PROVIDING YOUNG STAND MANAGEMENT ALTERNATIVES AND ENHANCING SPATIAL HETEROGENEITY THROUGH DAYLIGHT CLEANING IN MIXED-CONIFER FORESTS

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AUTHORIZATION TO SUBMIT THESIS

This thesis of Kyla Marie Berendzen, submitted for the degree of Master of Science with a major in Natural Resources and titled “Providing young stand management alternatives and enhancing spatial heterogeneity through daylight cleaning in mixed-conifer forests” has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

Throughout western North American forests, harvests of recent decades have created an abundance of young, even-aged stands. In the Inland Northwest over 120,000 ha of young western white pine plantations now urgently need management to maintain their health and resilience. Traditional precommercial thinning practices promote growth of desirable crop trees but are expensive and create homogeneous conditions. I compared the effectiveness, spatial heterogeneity, and growth environments of daylight cleaning treatments that cleared 4-m radii around crop trees to full cleaning treatments at regular spacings and to untreated controls across three replicates in 30-year-old western white pine plantations. The daylight cleaning method is a partial cleaning method that left portions of the stand untreated, cleaning just 27% of the stand areas with the remainder left as untreated matrix. However, similar densities of western white pine crop trees were released in the daylighted stands as in fully cleaned stands, and conditions were more heterogeneous in the daylighted stands. Around the daylighted crop trees, gap sizes, stand structure, fuels, predicted fire behavior, and microclimates were highly variable but more similar to fully cleaned conditions than to those of the control. Daylight cleaning can provide a cost-effective opportunity to conduct stand tending across more young forest plantations than would be possible with full cleanings. The partial cleaning concepts applied to daylight cleaning can be modified for different sites, species, and tree density objectives to provide a broad range of alternatives to maximize young stand spatial heterogeneity and resilience to disturbances and changing conditions at stand and landscape scales.

Keywords: precommercial thinning, variable-density thinning, plantations, western white pine, biocomplexity

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CHAPTER 1

PROJECT OVERVIEW: Daylight cleaning as a preliminary evaluation to inform western white pine forest restoration and young stand tending

This study is part of a larger project designed by the USDA Forest Service Rocky Mountain Research Station (RMRS) to inform management of western white pine plantations throughout the Inland Northwest before they lose their potential to contribute to western white pine restoration efforts. The western white pine forests that once comprised up to 50% of Inland Northwest forest area, as well as other early seral communities, are high priorities for forest restoration (Hessburg and Agee 2003, Harvey et al. 2008). Over 120,000 ha of young western white pine plantations have been planted on public lands since the 1960s to accomplish these restoration goals, but now most of these stands have reached or surpassed the ideal age for cleaning treatments (Graham et al. 2005, DeNitto and Helmuth 2007). Now, tree growth in these western white pine restoration assets is stagnating due to limited funding for young stand tending. On public lands, few cleaning treatments are done in the productive plantations that support western white pines due to the expense of fully cleaning such dense stands. Instead, resources are often allocated to other forest types where less intensive cleanings can treat more area per cost. Various alternative cleaning methods are already being implemented experimentally by managers throughout Inland Northwest forests with considerable success, but the lack of supporting research and consistent technical guidance, terminology, contract specifications, and evaluation methods makes implementation challenging (Hayes et al. 2005).

Rocky Mountain Research Station researchers are working with forest managers to implement and evaluate partial cleaning methods designed to release western white pines while leaving parts of the stands untreated. They hope to maximize benefits and ecosystem services across multiple spatial and temporal scales and to encourage western white pine restoration and heterogeneity throughout the landscape by managing for western white pine-dominated stands that contain healthy trees on a trajectory towards future old growth, future seed sources,and timber resources. Throughout the landscape, managers can use these young stands as part of a diverse mosaic of forest ages, compositions, and structures to increase resilience to disturbances and climatic stress, maintain watershed health, reduce potential fire spread, and support wildlife (Hartley et al. 2002, Hayes et al. 2005, Thompson et al. 2009). At the stand level, cleaning treatments that also increase within-stand spatial heterogeneity can encourage resilience to insects and pathogen outbreaks, climatic stressors, potential fire damage to crop trees, and other disturbances while supporting understory community and habitat diversity; this approach has been applied in older stands and could also work in plantations of young trees (Carey 2003, O’Hara et al. 2010). Treatments are intended to sufficiently increase light and moisture resources to encourage diameter growth needed to stabilize wind and snow damage-prone trees, improve resilience to white pine blister rust (*Cronartium ribicola*) and other diseases, and reduce ladder fuels and crown continuity (Oliver and Larson 1996, Graham et al. 2005, Schwandt et al. 2010).

In Chapter 2, I present my graduate project. I focused on daylight cleaning, the first partial cleaning treatment evaluated for the Rocky Mountain Research Station project and Idaho Panhandle National Forests. In the daylight treatments, cleaning crews selected healthy western white pine crop trees and cleaned a 4-m radius around them. I examined 1) stand-level treatment effectiveness and spatial heterogeneity, as well as differences in 2) growth environment, 3) fuel distribution, and 4) microclimate around the western white pine crop trees in the daylight cleaning compared to untreated controls and to full cleaning as commonly implemented with uniform spacing between crop trees (Graham et al. 2005).

The limited time-frame and resources confine my study to short-tern examination of the post-treatment crop tree- and stand-level impacts. It is part of a larger project evaluating alternative cleaning methods for western white pine forests, including costs and tree growth response. Thus this is the first step toward designing effective cleaning prescriptions, guiding research, and implementing treatments to maintain western white pine dominance of young stands. We consider how promoting increased biocomplexity in young stands earlier in the forest development process influences their potential contributions to functional heterogeneity and resilience and at the crop tree, stand, and landscape scales (Odion and Sarr 2007, Brockerhoff 2008, O’Hara et al. 2010). Examining heterogeneity and the crop tree growth environment helps to understand benefits and trade-offs in relation to full-cleaning techniques, so I consider but cannot quantify how variation in structure, fuels, and microclimates might scale up to the stand level based on the area and crop trees treated and spatial heterogeneity that we observed throughout the stand. I cannot examine landscape level impacts of daylight cleaning, but I hope this study will provide information to help managers contextualize treatments and prioritize stands to maximize landscape benefits. The Rocky Mountain Research Station scientists, Idaho Panhandle National Forests, and I hope to generate discussion and encourage manager feedback regarding research needs and treatment feasibility to best utilize young stand cleaning resources and restore western white pine forests.

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CHAPTER 2

PROVIDING YOUNG STAND MANAGEMENT ALTERNATIVES AND ENHANCING SPATIAL HETEROGENEITY THROUGH DAYLIGHT CLEANING IN MIXED-CONIFER FORESTS

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ABSTRACT

Throughout western North American forests, harvests of recent decades have created an abundance of young, even-aged stands. In the Inland Northwest over 120,000 ha of young western white pine plantations now urgently need management to maintain their health, resilience, and potential to restore western white pine-dominated stands. Traditional precommercial thinning practices release desirable crop trees but are expensive and create homogenous spacings. We compared the effectiveness, spatial heterogeneity, and growth environments of daylight cleaning treatments that cleared 4-m radii around crop trees to regularly-spaced full cleanings and to untreated controls across three replicates in 30-year-old western white pine plantations. Daylight cleaning treated 27% of the stand areas but released 69% of western white pine crop trees; conditions ranged from various-sized gaps to dense matrix. Around daylighted trees, stand structure, fuels, predicted fire behavior, and microclimates were highly variable but similar to fully cleaned conditions. Daylight cleanings have potential to release crop trees while treating less area, increasing spatial heterogeneity, and promoting resilience.

Keywords: precommercial thinning, variable-density thinning, plantations, western white pine, biocomplexity

INTRODUCTION

Young stand heterogeneity

Young managed stands comprise an increasing portion of forest landscapes worldwide yet their capacity to provide ecosystem services associated with heterogeneity are often overlooked (Hartley 2002, Odion and Sarr 2007, Brockerhoff et al. 2008). Young stands, including plantations, support forest structure, fuel conditions, and microclimates very different from that of mature and old-growth stands and therefore are important elements of functional heterogeneity in forest landscapes (Hartley

2002, Odion and Sarr 2007). They can provide important ecosystem services by supporting forest and understory community biodiversity, unique wildlife habitat, and landscape fire-resistance, and by influencing albedo, water balance, and local climatic adaptability (Hartley 2002, Carey 2003, Odion and Sarr 2007). Patterns of heterogeneity within young forests influence critical forest processes, stand development, and their role in the landscape, but young stand tending practices designed to maximize crop tree growth often result in homogenous forest structure with low biodiversity (Graham et al. 2005, Brockerhoff et al. 2008, O'Hara et al. 2010). Creating heterogeneity, encouraging crown class differentiation, and promoting diverse successional pathways earlier in the forest development process promotes these young stands as assets for restoration while accelerating and enhancing their potential contribution to landscape heterogeneity, resilience, and ecosystem services (O'Hara et al. 2010, Turner et al. 2012).

Traditional cleaning (also known as precommercial thinning) techniques are widely applied to increase crop tree growth and health in young planted forests, but alternative cleaning techniques may increase heterogeneity and reduce costs (Oliver and Larson 1996, Graham et al. 2005, O'Hara et al. 2010). Common cleaning methods release crop trees by thinning to a fairly regular spacing and cleaning out the competing saplings of the understory. However, cleanings can be very expensive, especially in dense stands, and homogeneous implementation of cleaning methods may not effectively support changing management objectives that envision crop trees primarily as mature seed sources or even old-growth stands and secondarily as timber resources. Techniques such as variable-density precommercial thinning and patch cleaning have been increasingly applied in young stands to foster heterogeneity and biocomplexity during the competitive exclusion phase of forest development. Biocomplexity is the combination of structural complexity, biodiversity, and spatial heterogeneity that can amplify with stand development (Carey 2003, O'Hara et al. 2010). In naturally regenerating stands, forest development processes and disturbances (e.g., mixed severity fires, post-fire snag recruitment, wind events, ice storms) of varying sizes and intensities create biocomplexity (Franklin et al. 2002, Odion and Sarr 2007). Forest biocomplexity across spatial and temporal scales improves resilience to diseases, insects, and fire to insure long-term growth and development and enhances ecosystem services such as wildlife habitat and watershed health (Franklin et al. 2002, Muir et al. 2002, Carey 2003). By leaving parts of each stand untreated and altering the structure and variability of the forest matrix as well as gap or patch sizes and frequencies, these partial cleaning methods enhance functional heterogeneity and biocomplexity that can influence stand development (Carey 2003, Odion and Sarr 2007, O'Hara et al. 2010). In young Pacific Northwest forests, variable-density pre-commercial thinning methods designed to enhance forest biocomplexity can enhance ecosystem services, support increased biodiversity, and accelerate development of old-growth forest characteristics (Muir et al. 2002, Carey 2003, Wilson and Puettman 2007, O'Hara et al. 2010). However, few studies have examined the implications of partial cleaning methods that release crop trees while only treating a small portion of the stand (but see Karlsson et al. 2002), and this is a new concept forwestern white pine forests. Local managers have implemented partial cleaning methods in hopes of releasing trees while saving money and maintaining dense stand conditions for wildlife habitat, but these treatments have not been evaluated. More research and technical guidance is needed to better understand variable-density and partial cleaning implications for stand-level heterogeneity, crop tree growth environment, treatment feasibility, and role in the landscape and to enable their application across a broader range of forest types and restoration objectives (Odion and Sarr 2007, O'Hara et al. 2010).

Inland Northwest early seral forests

In the Inland Northwest forests of the northern Rocky Mountains, there are over 120,000 ha of young western white pine (*Pinus monticola* Douglas ex D. Don) plantations that need urgent management to maintain western white pine dominance (Graham et al. 2005, DeNitto and Helmuth 2009). These early seral stands are assets for the restoration of western white pine-dominated forests, which once comprised up to 50% of the Inland Northwest forest area (Jain and Graham 2005, Harvey et al. 2008). Now, western white pine-dominated forests have declined to less than 5% of their historical extent after white pine blister rust (*Cronartium ribicola*) was accidentally introduced in 1910 (Fins et al. 2001, Hessburg and Agee 2003). Massive salvage harvest operations decimated western white pine populations and removed potential seed sources, and fire suppression has reduced regeneration opportunities. After Forest Service Research and Development developed blister rust-resistant western white pine in the 1960s, these more resistant seedling have been planted after harvests, along with western larch (*Larix occidentalis* Nutt.) and other early seral species (Bingham 1983). Resulting young stands are now dense with abundant grand fir (*Abies grandis* [Douglas ex D. Don] Lindl.) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and they are susceptible to blister rust, wind and snow damage, and stand-replacing fire (Watt 1960, Graham et al. 2005). Under current management guidelines, at 25 to 30 years these young plantations would be thinned to regular spacings crop trees and cleaned of grand fir and hemlocks, and the western white pines would be pruned of their blister rust infection-prone lower branches (Graham et al. 2005, Schwandt et al. 2010). These treatments release dominant, healthy, blister rust-free western white pines and western larch crop trees by increasing crown exposure and growing space to accelerate growth, maintain their health and dominance, and when combined with pruning can reduce impacts of white pine blister rust. However, current treatments generate homogeneous stands and are also expensive (Graham et al. 2005); most of these young stands have not been thinned due to limited funding on public lands and many have reached or surpassed the ideal age for cleaning (Graham et al. 2005).

Research objectives

We implemented and evaluated daylight cleaning in young early seral stands (Figure 1) as part of a larger study evaluating thinning costs and efficiency. Spacing was based on the ecology of western white pine and moist forests as well as established parameters typically used in cleaning contracts conducted by the Idaho Panhandle National Forests (Graham et al. 2005). We examined 1) stand-level treatment effectiveness and spatial heterogeneity, as well as differences in 2) growth environment, 3) fuel distribution, and 4) microclimate around the western white pine crop trees in the daylight cleaning compared to untreated controls and full cleaning as commonly implemented at uniform spacing between trees.

As the first stage of a larger project evaluating partial cleaning methods for western white pine forests, we hope the short-term, localized context of our observations can provide initial information for broader-scale, longer-term objectives, such as designing cleaning prescriptions, guiding research, and informing managers that may need to implement treatments immediately to maintain western white pine dominance of these young stand assets. Examining crop tree growth environments in the context of stand-level heterogeneity helps us understand benefits and trade-offs in relation to full-cleaning techniques at multiple spatial scales. We also consider how introducing biocomplexity in young stands earlier in the forest development process influences their potential contributions to functional heterogeneity and resilience and at the crop-tree, stand, and landscape scales.

METHODS

Study area and experimental design

The thirty-year-old study plantations are located in Deception Creek Experimental Forest (DCEF) on the Coeur d’Alene River Ranger District, Idaho Panhandle National Forest, about 32 km northeast of Coeur d’Alene, Idaho (Jain and Graham 1996, Figure 2a). DCEF was established in 1933 as a center for silvicultural research in the western white pine forest type. The area is dominated by an inland maritime climate, with short summers and cloudy autumns and winters. It is one of the wettest locations in Idaho, receiving an average of 140 cm of precipitation per year, 25% of which occurs as snow. Soils are very fertile Typic Vitrandepts with volcanic ash caps up to 1.5 m deep (Jain and Graham 1996). The study replicates are located on a north-facing aspect ranging from 960 to 1200 m in elevation, and the dominant habitat type is western hemlock/queencup beadlily (*Tsuga* *heterophylla* [Raf.] Sarg.)/ *Clintonia uniflora* [Menzies ex Schult. & Schult. f.] Kunth) (Cooper et al. 1991). Major tree species are grand fir, western hemlock, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), western larch, and western white pine with a diverse understory, including alder (*Alnus* spp.), ceanothus (*Ceanothus* spp.), and willow (*Salix* spp.). DCEF is at the heart of the historical distribution of western white pine and represents the climate, soils, and topography of the moist western hemlock forests of the northern Rocky Mountains (Jain and Graham 1996).

We used a completely randomized experimental design with three cleaning treatments replicated three times: 1) full cleaning, 2) no cleaning, and 3) daylight cleaning (Figure 1). In the full cleaning treatments, the entire stand was treated to create a uniform spacing of about 3 m between healthy western white pines (which were also pruned) and western larch, resulting in about 275 trees/ha. Daylight cleaning creates variable openings with radii of about 4 m around contractor-selected healthy western white pines, also pruned, without treating the remaining stand matrix. Prescriptions were based on canopy-opening thresholds and space requirements to optimize growth of western white pines and western larch as well as moist forest ecology and silviculture (Haig et al. 1941, Graham et al. 1983, Jain et al. 2004). No cleaning was done in the control treatment. The four plantations were harvested in 1984 and planted in 1986. Using natural topographic breaks or roads, the four plantations were partitioned into experimental units to which the three treatments were randomly assigned. Treatments were implemented in summer 2012 (replicate 1) and summer 2013 (replicates 2 and 3). We sampled during the season prior to treatment and the year following each treatment. We evaluated forest characteristics at multiple spatial scales: stand-level treatment outcomes (treatment effectiveness and spatial heterogeneity) and crop tree-level growth environment (treatment intensity, stand structure, surface fuel amounts, projected fire behavior, and microclimates) (Table 1). We use our localized, crop tree-scale observations in the context of stand-level treatment area and heterogeneity to better understand the daylight treatment's stand-level implications.

Data collection

To determine the stand-level treatment effectiveness and the variability among the treatments we used transects (Cressie 1993) (Table 1). At least one transect was sampled after cleaning treatment in each unit, and in daylight units two or more were sampled; at least one parallel to slope contours and one perpendicular to slope contours. In the largest replicate (replicate 1), transects parallel to slope contours were located at upper, middle, and lower slope strata to reflect the elevation gradient that may influence white pine blister rust sporulation and consequently the abundance of healthy western white pines (Van Arsdel et al. 2005). On transects we recorded all crop trees within the transect width, noting species and release status; trees were considered to be released if they were in a cleaned gap with their crowns at least partially exposed to increased light. We also noted health conditions and pruning status for western white pines (Van Arsdel et al. 2005); since pruning and cleaning are implemented separately, released trees are not necessarily pruned.

To quantify growth environment, structure, and fuel characteristics of the crop tree environment, we measured the number and size of crop trees on variable-radius plots, density and size classes of understory trees on fixed plots (Dilworth 1970), and fuels on planar intercept transects around plot center trees (Brown 1974, Lutes et al. 2006) (Figure 2b, Table 1). Prior to treatment, 6 plots per replicate were established around crop trees in each of the three replicates to be treated. Plots were randomly located using a grid system using GIS software (ArcGIS 10.0). In the forest we navigated to those coordinates and selected the nearest western white pine crop tree. These crop trees were dominant or codominant western white pines, healthy and free of blister rust, chosen for promoting their survival, growth, and potential as future seed sources (Graham et al. 2005). At each plot we obtained GPS coordinates, measured slope angle and aspect, and sampled the fixed and variable subplots using standard forest inventory procedures (Dilworth 1970).

The variable-radius crop tree plots were designed to examine crop trees conditions. They were centered around a western white pine crop tree and included at least four of the closest surrounding western white pine and western larch crop trees (Figure 2b). Rather than using a basal area factor, we measured distance to crop trees to calculate densities; thus, plot radii varied from 3 to 15 m. When we resampled these plots the year following treatment, we re-measured structural characteristics, recorded crown conditions (gap, edge, or matrix) of the five or more crop trees, and sampled fuel characteristics (Table 1). We used FVS and FFE-FVS to summarize stand structure characteristics and fire behavior. In the daylight treatment, we also calculated plot-level values to represent the spectrum of treatment intensities present. The treatment intensity proxy summarized the variable impacts of treatment intensities and gap configurations on crop tree release and light availability at the plot-level by averaging the crown conditions (gap, edge, or matrix) of the the crop trees:

$$\text{treatment intensity proxy} = \frac{\#\text{ trees in gap } + (0.5 * \#\text{ trees in edge conditions})}{\text{total }\#\text{ trees in plot}}$$

Microclimate conditions were sampled at three locations per treatment in replicate 1, which were stratified by elevation: lower (~1070 m), middle (~1120 m), and upper (~1160 m) slope strata. Three treatments at three slope strata totaled to 9 trees. At each location, a western white pine crop tree was randomly selected for installation of two HOBO® temperature/humidity data-loggers and for monthly pre-dawn water potential testing (Table 1).

Statistical analyses

We used general linear mixed models (Schabenberger and Pierce 2002) from the SAS GLMMIX procedure (SAS 9.3; SAS Institute, Inc. 2012) and evaluated the statistical significance ($\alpha \leq 0.05$) among the treatments for all stand-level treatment effectiveness, structure, fuels, and fire behavior variables (Table 1). To ensure model assumptions were met, we transformed several of the variables using a logarithm transformation (Kirk 1995). Prior to analyses of post-treatment data, we examined data for significant differences in pre-treatment conditions among replicates. Only western larch densities differed, so we analyzed total crop tree densities (western larch and western white pine combined) instead. Some variables examined did differ significantly among the replicates prior to and after treatments, so we used Tukey-Kramer approximation to account for differences among replicates when we conducted pairwise comparisons among the treatments (Schabenberger and Pierce 2002). To evaluate stand-level treatment effectiveness, we analyzed cleaned proportion (% of total stand area), total released crop tree densities (trees ha^{-1}), released western white pine densities (trees ha^{-1}), and pruned western white pine densities (trees ha^{-1}). Transect observations were also used to examine stand-level spatial heterogeneity within the daylight treatment by graphically portraying spatial distributions of gap and matrix to demonstrate gap frequencies. To test crop tree-level growth environment differences among the treatments we used the GLIMMIX procedure to compare structural variables (canopy cover, number of canopy layers, understory sapling densities, and the treatment intensity proxy) and fuels and fire behavior variables (canopy base height, fuel loadings in 1-hour, 10-hour, and 100-hour size classes, slash depths, and predicted crowning index and probability of torching). The microclimate variables were tested for statistically significant differences related to the transformed treatment intensity proxy rather than treatment, since the trees' growth environments in the daylight treatment were variable. Treatment intensity proxy values describe conditions surrounding the crop tree to which the sensors were attached. At crop trees in the control treatment intensity proxy values were always 0, for fully cleaned crop trees values were 1.0, but values ranged from 0.4 to 0.8 for the daylighted crop trees. Slope strata often significantly influenced microclimate ($p > 0.05$) and were used as a blocking variable (Figure 1).

RESULTS

The daylight cleaning created more heterogeneous conditions and released more trees per area cleaned than in the full cleaning, and the conditions around the crop trees were usually between those of the full cleaning and control but often more similar to the full cleaning.

Prior to treatment, there were no significant differences among stands in overstory western white pine densities (Fig. 3), proportions of healthy white pine, sapling densities, or canopy base heights. Pre-treatment canopy cover, number of tree canopy layers, and crowning and torching indices also did not vary among treatments. Overstory western larch densities did vary prior to treatment, and total overstory crop tree density did not differ but was quite variable, ranging from 238 (±112 trees ha^{-1} standard error, SE) in replicate 3, to 491 (±249 trees ha^{-1} SE) in replicate 2 and 858 (±38 trees ha^{-1} SE) in replicate 1 (Fig. 1).

Stand-level treatment effectiveness: daylight cleaning releases more trees per area cleaned

The proportion of treated area differed among treatments ($p = 0.0046$), but daylight cleaning released similar proportions of western white pine crop trees as the full cleaning ($p= 0.105$). Daylight treatment created a mosaic of gap and matrix conditions with an average of 27% (± 4.7% SE) of the stand area was cleaned to gap conditions (Fig. 4). In the daylight clean, 68% (± 6.0% SE) of the western white pine crop trees were released and 74% (± 3.9% SE) were pruned, but of total crop trees (western white pine and western larch), only 48% (± 4.1% SE) were released since western larch crop trees were not targeted and were only released if they grew near western white pine. In the full clean, 100% (± 4.1% SE) of the stand was cleaned so 100% of the trees were released, and 62% (± 3.9% SE) of western white pines were pruned. Thus, the densities or proportions of released or pruned western white pine did not differ between daylight and full cleaning treatments ($p > 0.2$), though proportions of total released crop trees were greater in the full clean than the daylight ($p = 0.012$) (Fig. 4). The frequency and spatial distribution of gaps – and therefore of treated trees – also varied within the daylight cleaned stands, throughout the lengths of transects as well as among transects (especially in Replicate 1 where transects were conducted at three elevation bands, Fig. 5). Daylight radii merged together at higher densities of crop trees, enlarging gaps and influencing the distribution of trees in gap, edge, and matrix conditions (Fig. 5). Pruned trees were generally – but not always – in daylighted gap; since cleaning and pruning are implemented separately, occasionally pruned trees were found in the matrix.

Daylight cleaning created structure and fuel conditions for crop trees similar to full cleaning

Full cleaning and daylight cleaning often created similar growing conditions for the released western white pine crop trees, although treatment intensity varied widely in the daylight treatment. While averages for the full clean and control are considered representative due to the homogeneous conditions in these stands, averages do not effectively portray daylight treatment conditions at the stand level; therefore, we must also consider the variability in the daylight compared to the variability of the full clean and control treatments.

Even at released crop trees in the daylight treatment, crown exposure and surrounding structural complexity (canopy cover, sapling densities, and tree canopy layers) varied (Figs. 6 and 7). In the daylight cleaning plots, on average 34% (± 29% SE) of crop trees were in gap, with 37% (± 25% SE) in edge and 29% (± 24% SE) in matrix (Fig. 7). The treatment intensity proxy calculated from these crop tree conditions varied from 0 (as in the control) to 1 (as in the full cleaning), with an average of 0.74 (± 0.08 SE) across all crop trees we sampled in the daylight cleaning due to the partial and irregular character of gaps in the daylight cleaning. Tree canopy cover and understory sapling densities in the daylight cleaning were between and similar to both the full cleaning and the control ($p > 0.05$), but canopy cover and sapling densities in the full cleaning and control differed from each other ($p = 0.034$ and $p = 0.019$, respectively). There were more tree canopy layers in the daylight cleaning than in the control ($p = 0.022$), similar to the full cleaning ($p = 0.777$, Fig. 6).

Fuels and projected fire behavior of the daylight cleaning also ranged between those of the full cleaning and control but were generally more similar to the full cleaning (Fig. 8). Slash depths and fuel loadings in the 1-hr and 10-hr size classes were similar to those of the full cleaning ($p > 0.3$) but greater than the control ($p < 0.05$). Fuel loadings in the 100-hour size classes were between and similar to both the full clean ($p = 0.390$) and the control ($p = 0.058$), which were significantly different from each other ($p = 0.018$). Canopy base heights did not differ among treatments ($p = 0.143$). Probability of torching in severe fire weather conditions did not differ among treatments ($p = 0.756$). Crowning index in the daylight was similar to the full clean ($p = 0.978$) but greater than the control ($p = 0.020$) (Fig. 8).

Intermediate, variable microclimate conditions throughout the daylight cleaning

Cleaning treatment intensity influenced microclimate conditions were influenced most in the understory and during more extreme conditions and slope location; the intermediate treatment intensities resulting from gap configurations in the daylight treatment resulted in microclimate conditions that ranged in between the full cleaing and the control (Table 2, Fig. 9). Microclimate variables were also influenced by elevation, differing among lower (~1070 m), middle (~1120 m), and upper (~1160 m) slope strata. At the 3-m height, temperatures and humidities showed little variation among treatments except during the coldest and dryest conditions we examined, including spring (May) average temperatures (nearly significant, $p = 0.056$) and summer (June through August) maximum relative humidities ($p < 0.05$) (Table 2). However, at the 1-m height, air temperature and relative humidity were generally warmer and drier as cleaning treatment intensities increased (Table 2). Spring temperatures were not significantly different, but most summer (June through September) temperature and humidity maximums, minimums, averages, and ranges were significantly related to treatment intensity. Temperatures were positively correlated and relative humidities were negatively correlated with treatment intensity ($p < 0.05$). Cumulative metrics, including growing degree days and vapor pressure deficits, were not significantly different at 3-m heights ($p > 0.1$), but at 1-m heights both growing degree days and average vapor pressure deficit showed a significantly positive relationship with treatment intensity during the summer ($p \leq 0.0003$) (Table 2, Fig. 9). Soil water potentials were only influenced by cleaning treatment intensity during dry conditions; after a dry August, September soil water potentials were significantly less negative (less moisture stressed) at higher treatment intensities ($p = 0.011$, Fig. 9).

DISCUSSION

Daylight cleaning released many crop trees and enhanced within-stand heterogeneity

Partial cleaning promotes crop tree growth and potential to serve as future seed sources while creating heterogeneity that promotes biodiversity and creates gaps or patches of different types of wildlife habitat (Carey 2003, O'Hara et al. 2010). Even though the daylight cleaning method treated so little of the stand relative to previously tested methods, our results suggest that daylight cleaning could have similar benefits for long-term western white pine restoration by releasing many crop trees. Canopy exposure of released trees in the daylight cleaning was more variable and less complete than that of the full cleaning, but released crop trees in the daylight cleaning generally had similar structure, fuels, and microclimates as in the full cleaning. Although we yet cannot evaluate long-term effects of the daylight cleaning in promoting crop tree growth, even western white pine crop trees in gaps and in edge conditions still benefit from increased solar radiation (Jain et al. 2004). Thus, we hypothesize that daylight cleaning will still support a growth response and competitive advantage for enough western white pines to promote a trajectory towards western white pine-dominated stands. Variable crown exposure to solar radiation may also encourage crown differentiation that could further enhance vertical complexity, as observed in other studies (O'Hara et al. 2010). Additionally, the broad range of conditions varied from dense matrix to open gaps to create a range of canopy coverage and increased vertical complexity (Fig. 7) to support objectives of biocomplexity and functional heterogeneity needed to enhance forest resilience, diversify understory forb, lichen, and shrub communities, and diversity of wildlife habitats (Oliver and Larson 1996, Odion and Sarr 2007). Dense matrix, thinned gaps, and edge conditions within young stands can support valuable – but different – wildlife habitat and understory communities (Carey 2003, Wilson and Puettman 2007).

Dense stands may provide habitat for hares and food source for their predators, including lynx and fischers, as well as habitat for many bird species (Thomas 1979).

Moderated microclimates could influence tree growth and resilience to disturbance

Although cleaned gaps in the daylight cleaning increased crop tree did not increase light and moisture resources as much as in the full cleaning, variable microclimate conditions may promote biocomplexity while shaded understories and decreased airflow will reduce desiccation throughout the untreated matrix, especially during extreme dry and warm conditions. The canopy-level differences we observed only during the coldest and driest conditions are consistent with observations that treatment and structural variability have the greatest impacts on microclimate and soil moisture in harsh conditions and may still influence timing and rates of transpiration (Sperry et al. 2002, von Arx et al. 2013). As we observed at more intensely cleaned crop trees in late summer (Fig. 9), reduced tree densities can increase available water for residual tree growth (Aussenac 2000, Weng et al. 2007, von Arx et al. 2013). However, dense canopies can also maintain soil moisture later into the year, and in years with dry soil conditions, dense canopies may have more microclimate moderating capacity due to hydraulic lift (von Arx et al. 2013). Warmer, drier conditions below thinned canopies may also influence crop tree growth as well as soil physical, chemical, and biological properties, understory communities, wildlife forage, and fuel moistures (Aussenac 2000, Thibodeau 2000, Carey 2003). The highly significant relationships of microclimate observations with the treatment intensity proxy in this small sample suggest that microclimate could be more variable across a greater range of gap sizes and configurations. Gap configurations further influence air flow and wind behavior, affecting snow deposition and timing of runoff, soil moisture, and plant uptake (Aussenac 2000, Weng et al. 2007, O’Hara et al. 2010). Thus, structural complexity that maintains shaded, mesic matrix conditions but uses gaps to promote crop tree growth can create microclimatic diversity that may enhance resilience to temporally variable climatic conditions (Aussenac 2000, O’Hara et al. 2010, Lyons-Tinsley and Peterson 2012).

Heterogeneous fuel conditions may moderate fire behavior

Dense young forests are susceptible to fires, especially under extreme conditions and where surface fuels are conducive (Stephens and Moghaddas 2005, Finney et al. 2010, Halofsky et al. 2011, Lyons-Tinsley and Peterson 2012). However, we hypothesize that discontinuity in fuels in the daylight treatment could potentially alter fire behavior and effects. In full cleaning treatments, continuous high slash loadings but wide spacing between trees and reduced ladder fuels enable increased wind speeds and could result in more intense surface fires. In dense, untreated stands, higher fuel moistures and reduced wind speeds sometimes smother fire behavior, particularly under mesic conditions in these moist mixed-conifer forests, but under extreme conditions the continuous ladder and crown fuels could lead to stand-wide crown fire (Lyons-Tinsley and Peterson 2012, Thompson et al. 2007). Although localized, crop tree-level fuels observations and fire behavior predictions do not portray stand-level fire behavior, they portray the heterogeneous conditions that may impact fire outcomes and spread (Finney et al. 2010). Daylight gap configurations reduced connectivity of the contiguous tree canopy present in the control and separated pockets of temporarily flammable slash that were continuous and deep in the full cleaning. Daylight cleaning may alter wind behavior and maintain high fuel moisture, slow fire spread, and generate spatially heterogeneous burn patterns and post-fire outcomes that would leave unburned islands of crop trees (Stephens and Moghaddas 2005). Furthermore, through modifying gap sizes and treatment intensities, alternative cleaning methods facilitate adjustment of canopy cover and densities as well as canopy base height, ladder fuels, and even slash distribution. Treatment strategies that increase fuel heterogeneity within stands while also varying cleaning prescriptions among stands could enhance fire resilience and increase landscape biocomplexity (Stephens and Moghaddas 2005, O’Hara et al 2012).

Heterogeneity: implications for treatment longevity

Many unpredictable factors will influence the futures of cleaned young stands – including post-cleaning tree and shrub growth responses, changing future climate conditions, and altered disturbance regimes (Graham et al. 2005, Turner et al. 2012). Although the daylight treatment created heterogeneous growth environments within stands, gap size and treatment intensity will influence stand development and treatment longevity. Based on previous studies of western white pine ecology (Jain et al. 2004), we hypothesize that the gaps and structural complexity created using daylight cleaning will last long enough to generate a response from the white pine crop trees and promote crown differentiation. Increased crown differentiation and lower densities of western white pine released may accelerate development of old-growth stand canopy complexity (O’Hara et al. 2010) and also reduce the need for consecutive thinning treatments (Graham et al. 2005), which may be especially advantageous in less accessible sites. However, the daylight gaps are small and little total area was treated relative to previous studies, so the benefits of stand-level heterogeneity, microclimate variability, and understory community diversity may be short-lived as small gaps may close in due to crown development of surrounding trees and competition from the residual understory. In these productive moist forests, even full cleanings on these moist sites promote crown closure and abundant understory conifer regeneration that would likely shade out post-cleaning shrub and forb regeneration within 10-20 years, and (Graham et al. 2005), but small gaps of the daylight cleaning may be short-lived may further increase western hemlock’s competitive advantage. However, understory community regeneration patterns may differ on harsher sites where shrubs, forbs, or grasses have a competitive advantage over tree seedlings.

Post-treatment disturbance dynamics will likely also differ among treatments (Franklin et al. 2002). Fully cleaned stands often experience post-cleaning tree mortality due to wind and snow damage, especially in stagnating stands thinned so late that increased height:diameter ratios reduce stability; however, after this initial loss cleaned stands generally experience little mortality for decades, until crown closure occurs (Oliver and Larson 1996, Graham et al. 2005). In untreated stands, intense competitive exclusion causes gradual, continuous mortality and gap creation throughout stand development. Introducing heterogeneous conditions at this young age or in stagnating stands may further alter disturbance patterns and long-term biocomplexity due to impacts on wind behavior, gap-induced snow deposition, potentially more concentrated wildlife browse patterns, and other factors that may influence growth and survival of crop trees within gaps (Franklin et al. 2002).

Implementing various cleaning treatments to maximize landscape benefits

The daylight cleaning method is just one alternative option to release more trees per area treated, but other partial cleaning methods may be more beneficial or feasible. Variable gap sizes and treatment intensities may more effectively amplify treatment-induced biocomplexity throughout stand development to approximate the variance and distribution of conditions created by natural regeneration and disturbance processes (Franklin et al. 2002, O’Hara et al. 2010). However, gap sizes may also need to be increased or varied to reduce costs, ensure treatment longevity, reduce the rate of crown closure, promote crown differentiation, increase disturbance resilience, and encourage shrub and understory community diversity (O’Hara et al. 2010). Additionally, cleaning small gaps is still expensive. Daylight cleanings at the densities prescribed for this study cost 70 – 75% of full cleaning costs, but we expect that contracting will become easier as managers and crews become accustomed to new cleaning strategies. Altering gap size and configuration and implementation methods may also make it possible to further reduce the costs of partial cleanings. For example, fully cleaning a few large patches around clumps of healthy crop trees in the most strategic locations could reduce the difficulty of finding randomly dispersed crop trees and potentially the cost per stand. Stand and site conditions may have more impact on the outcomes and implications of heterogenous treatments. In the daylight treatment, variation in healthy crop tree densities and contract crews’ crop tree selection influenced spacing patterns within stands, gap configurations, and implementation feasibility much more than in the full cleaning. Densities of healthy white pine crop trees varied throughout the stand (such as across the elevation gradient in Replicate 1) and were often clumped, likely due to microclimate-influenced variation in blister rust infection rates. Blister rust infection rates should be considered when choosing a cleaning method; evaluating blister rust status can be challenging in dense stands and make it difficult for crews to select randomly dispersed crop trees. Cleaning larger gaps of merged daylight radii around groups of healthy crop trees may be more feasible and further increase the numbers of trees released per area treated, reduce search time and costs, and ensure that western white pine crop trees are both cleaned and pruned. Gap sizes will also need to be adjusted for topography and site variation; slope and aspect will interact with gap dimensions to influence the sun angles reaching crop trees and the understory, affecting photosynthesis and moisture availability (Jain et al. 2002, Jain et al. 2004). Thus, partial cleanings may require more careful consideration of existing within-stand variability and site differences to design prescriptions and minimize costs, but they also provide the flexibility to create a wide range of conditions that can favor a broader range of species and structural conditions, drastically reduce treatment efforts to strategically release only the most important or strategically located crop trees, or achieve a wider range of objectives (Hartley et al. 2002, O'Hara et al. 2010).

Applying various partial cleanings as well as full cleanings to as many of these young stands as possible could begin earlier in the stand development trajectory to enhance heterogeneity and ecosystem services within stands and throughout the landscape. This study is part of a larger effort to provide Inland Northwest forest managers with flexible, affordable alternatives to strategically distribute resources and design prescriptions for the more than 120,000 hectares of western white pine plantations in need of tending to support timber production and broader landscape goals of restoring western white pine-dominated forests and promoting forest health, resilience, and ecosystem services. We hope that our crop tree- and stand-level observations will help inform selection of partial cleaning methods and their application to the landscape context to maximize benefits of cleaning operations. The partial cleaning concept may be useful in other forest types. A broader range of young stand management alternatives increases our options to advance our current young stand assets along a trajectory towards healthy, resilient future forests and to incorporate them into silvicultural objectives that promote biocomplexity and forest health spanning across spatial and temporal scales (Hartley 2002, Muir et al. 2002, Carey 2003).

KEY MANAGEMENT AND POLICY IMPLICATIONS

Over 120,000 ha of young western white pine plantations could be valuable assets for restoration of Inland Northwest landscapes, yet they need cleaning to maintain their productivity and resilience. However, tending methods commonly implemented in young planted stands are expensive and create homogenous conditions, resulting in stands with limited wildlife habitat, high fuel loadings, and exposed conditions. Daylight cleaning and other partial cleaning methods only treat portions of the stand, providing options to release more crop trees per area treated and likely encourage their growth and future seed production. Applying partial cleaning in some stands could allow managers to treat more stands. We found that daylight cleaning around crop trees created similar, but more diverse, conditions as full cleaning, including stand structure, fuels, fire hazard, and microclimates. We expect that these treatments will promote crown differentiation, improve stand health and resilience, and provide a greater variety of wildlife habitat. The partial cleaning concept can be modified to manage young stands across a broad range of forest types by create gaps of varying sizes to account for species requirements and stand and site variables while integrating objectives of restoration, timber, fuels, and wildlife goals into forest management plans to support forest landscape biodiversity, productivity, and resilience.

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CHAPTER 3

CONCLUSIONS AND IMPLICATIONS: Preliminary daylight cleaning observations, applications, and contributions to young stand cleaning research

Daylight cleaning provides an alternative cleaning method that can utilize young planted stands and contribute to western white pine restoration objectives, as the Rocky Mountain Research Station intended. Our crop tree- and stand-level observations indicate that daylight cleaning creates heterogeneity and reduces costs while releasing enough crop trees to encourage western white pine dominance throughout the stand, and that those released crop trees will experience relatively similar conditions as in the full cleaning. However, additional research will be needed to evaluate the long-term and broader-scale effectiveness and feasibility of daylight cleaning and other alternative cleaning methods (Hayes et al. 2005). The Rocky Mountain Research Station will continue monitoring these treatments to examine the growth response of released crop trees, structural change, slash decomposition and fuel continuity, microclimatic changes, white pine blister rust infection rates, and understory response. More treatments will be implemented across a broader range of habitat types and sites to include different species (especially western larch), ages, and stand densities.

The partial cleaning concept can be modified and applied to a broad range of species, sites, and objectives (Carey 2003, Hayes et al. 2005, O'Hara et al. 2010). The daylight treatment we implemented certainly cannot be applied broadly since daylight cleaning was designed primarily for dense stands of western white pine, which is more adapted to gap conditions than most pine species. However, larger gaps and different gap configurations including more trees could be used to release crop trees while creating different patterns of within-stand spatial heterogeneity that could increase implementation feasibility, better emulate conditions created by local disturbances, or accomplish other objectives such as habitat management. In the daylight treatment, pre-existing variation in healthy crop tree densities within stands influenced treatment patterns and implementation feasibility much more than in the full cleaning, and topographic variation had more influence over solar radiation reaching crop trees and understory. Thus, partial cleanings may require more careful consideration of existing within-stand variability and site differences to design prescriptions, but they also provide the flexibility to create a wide range of conditions that favor a broader range of species and structural conditions, drastically reduce treatment efforts to strategically release only the most important or strategically located crop trees, or achieve a wider range of objectives (Hartley et al. 2002, Hayes et al. 2005, O'Hara et al. 2010). Future partial cleaning experiments will involve cleaning patches of variable numbers of crop trees to create larger, more variable gaps or only cleaning the most strategic portions of stands. We will further examine management implementation processes, feasibility, and concerns to provide more information and technical guidance to managers as soon as possible to maintain the health and productivity of our young stand assets and their potential contribution to future forest landscapes.

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Table 1. Sampling methods. This sampling design, measurements, and calculations were used to quantify and compare response variables among the three treatments (full clean, daylight clean, and untreated control).

Response Variable	**Measurements and Calculations**
Stand-level treatment effectiveness: Belt transects, 2m wide (Cressie 1993)	
Proportion treated area	Treated or untreated conditions observed at 3 m intervals
Overstory trees ha^{-1}	Tallied on belt transects
Crop trees (western white pine + larch): released, total	Released/untreated
Western white pine: released, total, pruned	Released/untreated, pruned/unpruned
Crop tree treatment intensity and structure: Fixed and variable plots[1], FVS projections[2]	
Canopy release	Gap, edge, or matrix condition of crop tree crowns (from variable-radius plots)
Treatment intensity proxy (calculated for each plot using canopy release observations)	$= \frac{\#\text{ trees in gap } + (0.5 * \#\text{ trees in edge conditions})}{\text{total }\#\text{ trees in plot}}$
Canopy cover	Calculated in FVS from fixed and variable-radius plots
Number of structure classes	Calculated in FVS from fixed and variable-radius plots
Understory sapling densities (trees ha^{-1})	Tallied on fixed plots (3.6 m radius)
Fuels and fire behavior: fuel transects[3], fixed and variable-radius plots[1], FFE-FVS projections[4]	
Crop tree canopy base height (m)	Height of lowest live limb of crop trees
Downed woody fuels (tonnes ha^{-1}) of 1-hr, 10-hr, and 100-hr time lag size classes[4]	Two 7.3m fuel transects at the center crop tree
Slash heights (m)	Measured at 1.3 m intervals along transects
Probability of torching	FFE-FVS from fixed and variable-radius plots
Crowning index	FFE-FVS from fixed and variable-radius plots
Microclimate conditions: three trees per treatment in replicate 1	
Temperature and relative humidity (monthly averages, minimums, and maximums)	Hourly intervals from August 2013 to Sept. 2014[5]
Summer growing degree days for western white pine	June 22 to Sept. 4 2014 (Miller et al. 2001)
Average summer vapor pressure deficit (kPa)	June 22 to Sept. 4 2014 (Campbell and Norman 1998)
Soil moisture	Pre-dawn water potential (mPa) of crop tree foliage (fascicles of current year growth about 4 m high) measured monthly, June through Sept. 2014[6]

[1] Both 0.004-ha fixed plots (3.6 m radius) and variable radius plots (sizes varied to include at least 5 western white pine crop trees) were used to examine overstory and understory structure (Dilworth 1979).

[2] The use of FVS (Forest Vegetation Simulator) is described by Stage (1973) and Wykoff et al. (1982).

[3] Fuel transects are modified from Brown (1974) and Lutes et al. (2006).

[4] Fire behavior variables were modeled using data from fixed and variable plots and the fuel transects using the Fire and Fuels Extension of FVS (Reinhardt and Crookston 2003).

[5] Temperatures and relative humidities were measured at one-hour intervals from August 2013 to September 2014 using HOBO® data loggers attached at 1 m (below canopies) and 3 m (within canopies) above the ground and on the north side of white pine crop trees (Brooks and Kyker-Snowman 2008).

[6] Pre-dawn water potential of white pine crop tree foliage was measured with a PMS Pressure Chamber Instrument once per month June – September between 2 AM and 4 AM (Tyree et al. 1972).

Table 2. Microclimate models and significance. Microclimate variables were compared to the treatment intensity proxy at three elevation strata: lower (~1070 m), middle (~1120 m), and upper (~1160 m); and at 1 m and 3 m above the ground.

Height	Response Variable	Slope position	Significance	
		Upper Middle Lower	Treatment intensity proxy	Slope strata
3 m	May Average Air Temperature	y = 10.2971 + 4.3503x	0.0564	0.0567
		y = 9.0859 + 4.3503x		
		y = 9.2984 + 4.3503x		
3 m	August Maximum Relative Humidity	y = 86.4874 - 20.9319x	0.0117	0.0173
		y = 90.6623 - 20.9319x		
		y = 92.9414 + 0.9319x		
1 m	August Maximum Air Temperature	y = 22.8657 + 12.3113x	0.0082	0.0544
		y = 20.0564 + 12.3113x		
		y = 20.7071 + 12.3113x		
1 m	August Maximum Relative Humidity	y = 89.6829 - 12.9509x	<.0001	<.0001
		y = 95.5938 - 12.9509x		
		y = 97.5804 - 12.9509x		
1 m	Summer growing degree days (June 20 to Sept 4)	y = 912.77 + 333.61x	<.0001	0.0002
		y = 825.4599 + 333.61x		
		y = 810.02 + 333.61x		
1 m	Avg Summer vapor pressure deficit (June 20 to Sept 4)	y = 192.66 + 61.1804x	0.0003	0.0012
		y = 177.862 + 61.1804x		
		y = 176.308 + 61.1804x		
soil	Sept. 13 soil moisture (leaf water potential)	y = 0.9068 -1.4453x	0.011*	0.492*
		y = 0.81707 - 0.8991x		
		y = 0.82732 - 0.1072x		

*The interaction of treatment intensity proxy and slope strata was almost significant (p = 0.0715) in the soil moisture model and improved model performance.

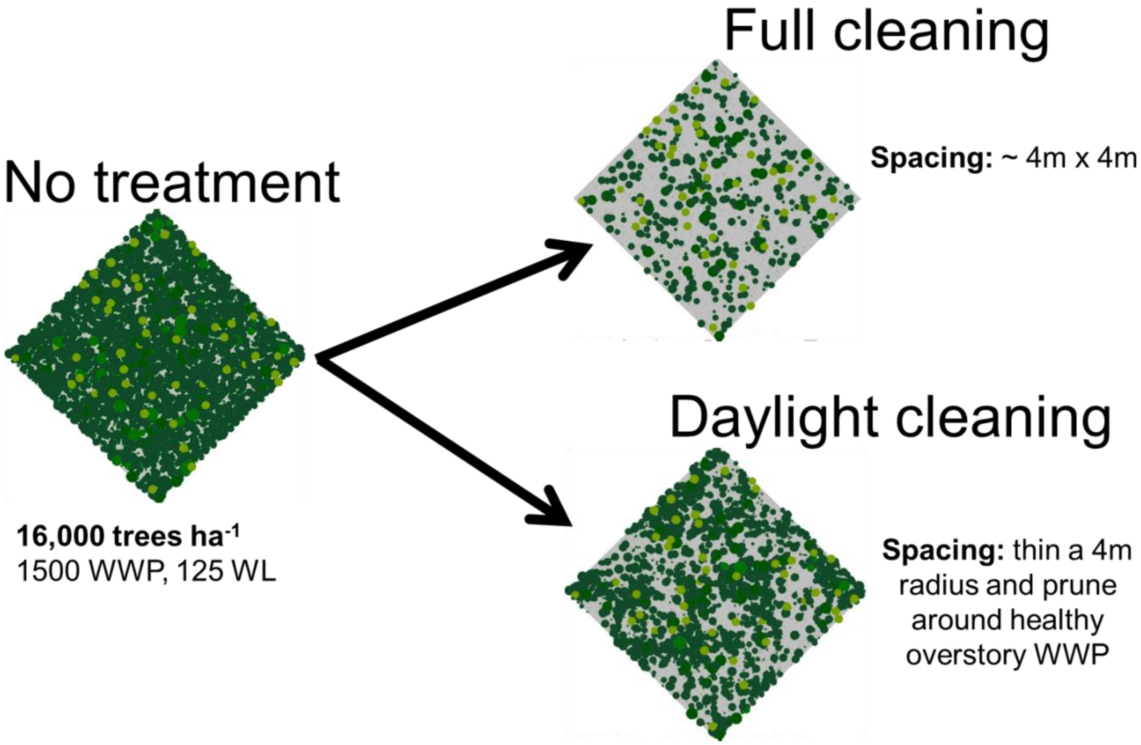

Figure 1. The three alternative cleaning treatments. Modeled spatial distributions of hypothetical post-treatment forest structure in young plantations managed with full cleaning, daylight cleaning, and no cleaning (control). Tree symbols include western white pine (WWP, dark green), western larch (WL, light green), and western red-cedar (blue-green); larger dots represent larger trees. Slash removed for visual clarity.

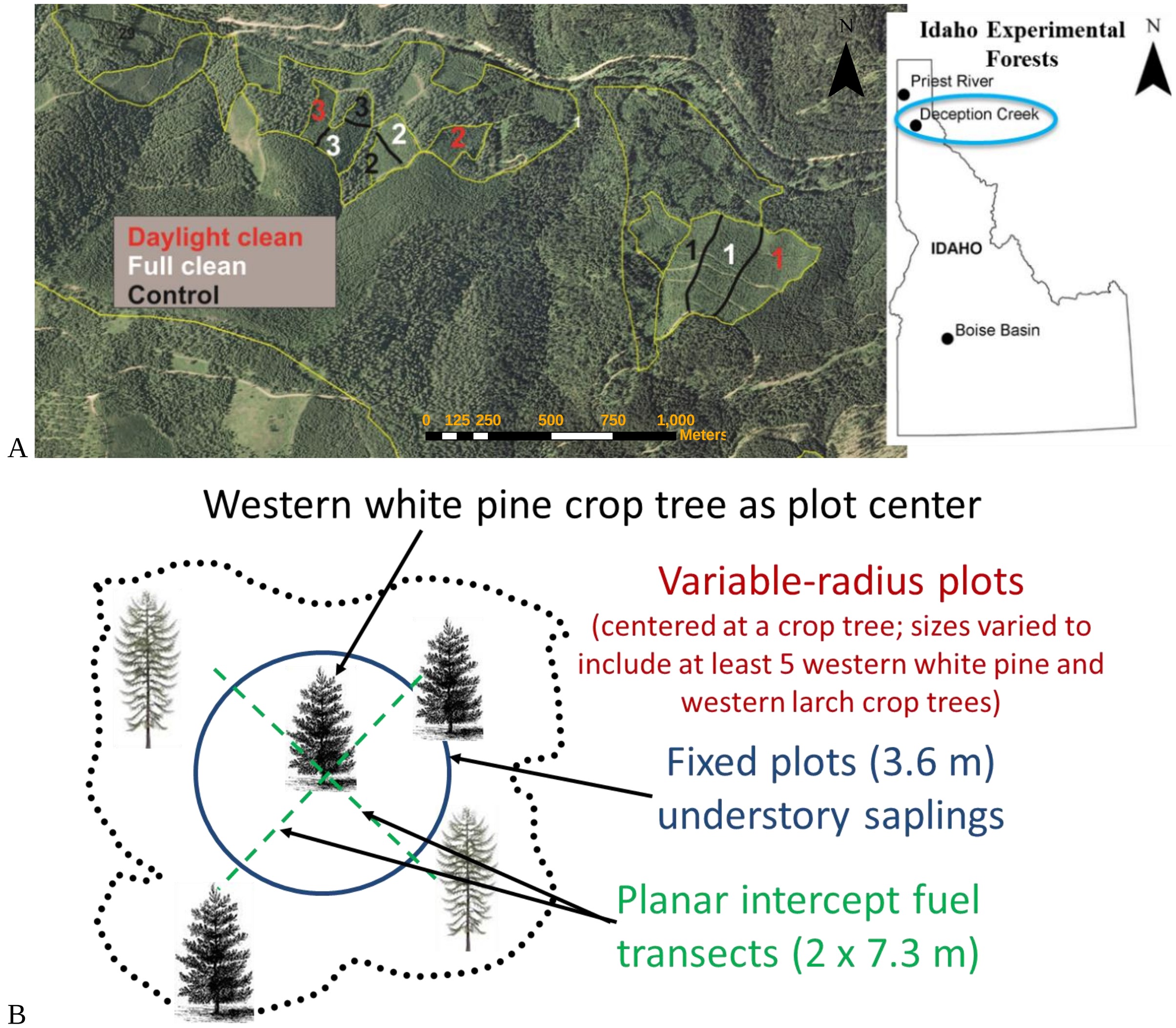

Figure 2. Study area and nested plot design. A) There were three cleaning treatments: Daylight clean (red), full clean (white), and untreated control (black) in Deception Creek Experiment Forest in northern Idaho. Replicates are numbered 1, 2, and 3 (nine units total). In each unit, stand-level treatment effectiveness and heterogeneity were measured with 2 m-wide belt transects across the unit. B) Crop tree-scale environments were examined in 6+ nested plots per unit. These included variable-radius plots, including the 4 nearest white pines or western larch around a white pine crop tree chosen as plot center; fixed plots to sample competing understory saplings; modified fuel transects; and gap measurements in eight directions. Microclimate conditions (temperature, humidity, and soil moisture) were examined at three locations per treatment in replicate 1.

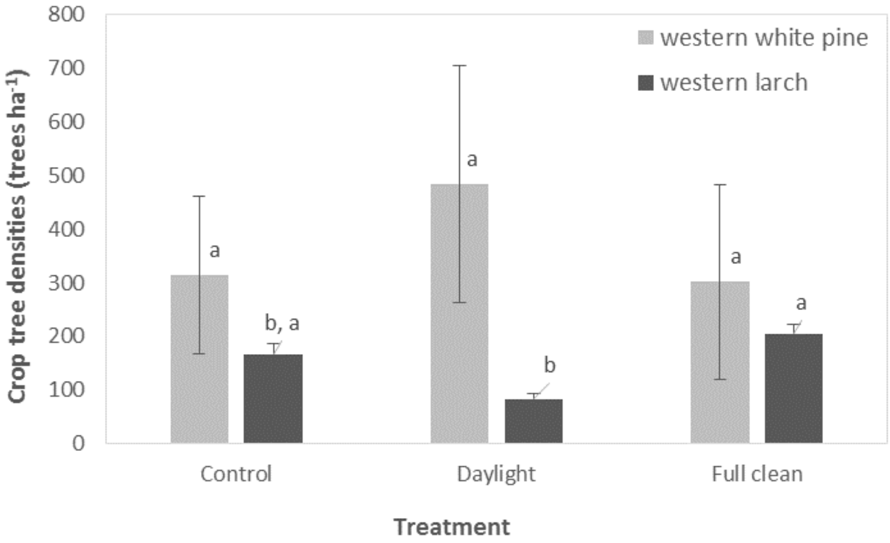

Figure 3. Overstory crop tree densities prior to treatment. There were no significant differences among treatments in densities of overstory western white pine crop trees ($p = 0.49$). Western larch densities did differ significantly ($p = 0.016$), but there were no significant differences in total crop tree densities (healthy western white pine and western larch combined) ($p = 0.85$).

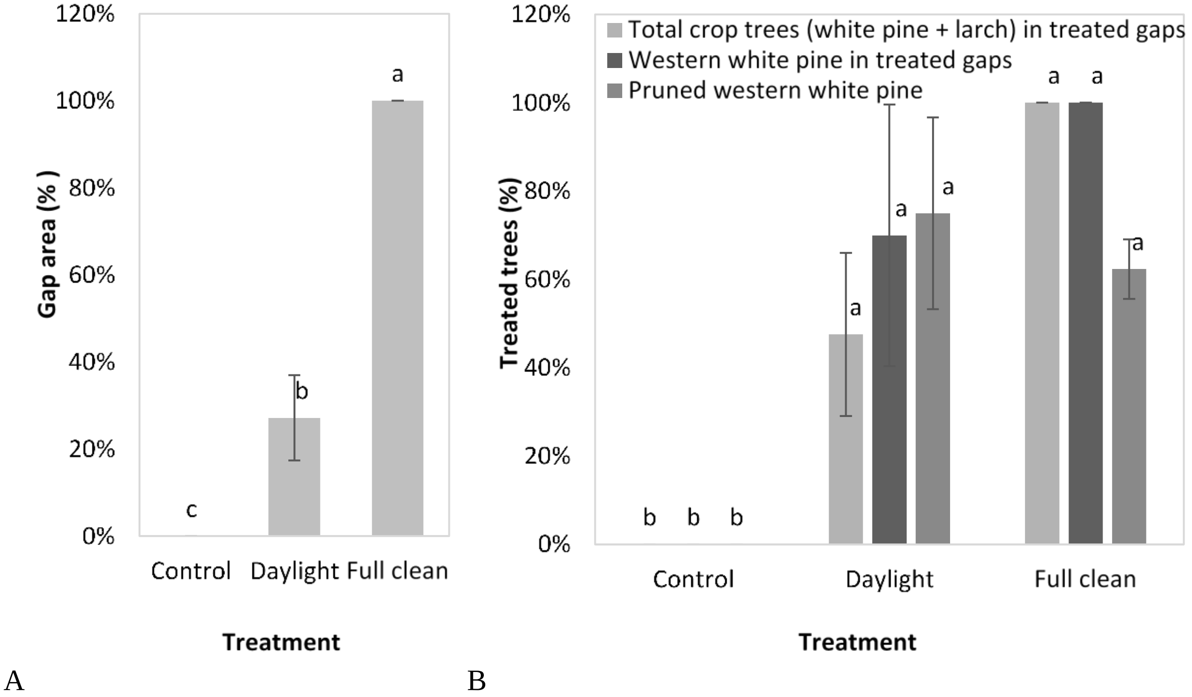

Figure 4. Stand-level treatment effectiveness. A) The proportions of area treated differed significantly among treatments ($p = 0.0011$), and varied within the daylight replicates. B) Proportions of released crop trees (western white pine and western larch), of released western white pine, and of pruned western white pine in the daylight treatment were not significantly different from those of the full clean ($p > 0.2$). Released crop trees were those in cleaned gap conditions, untreated trees were in matrix conditions.

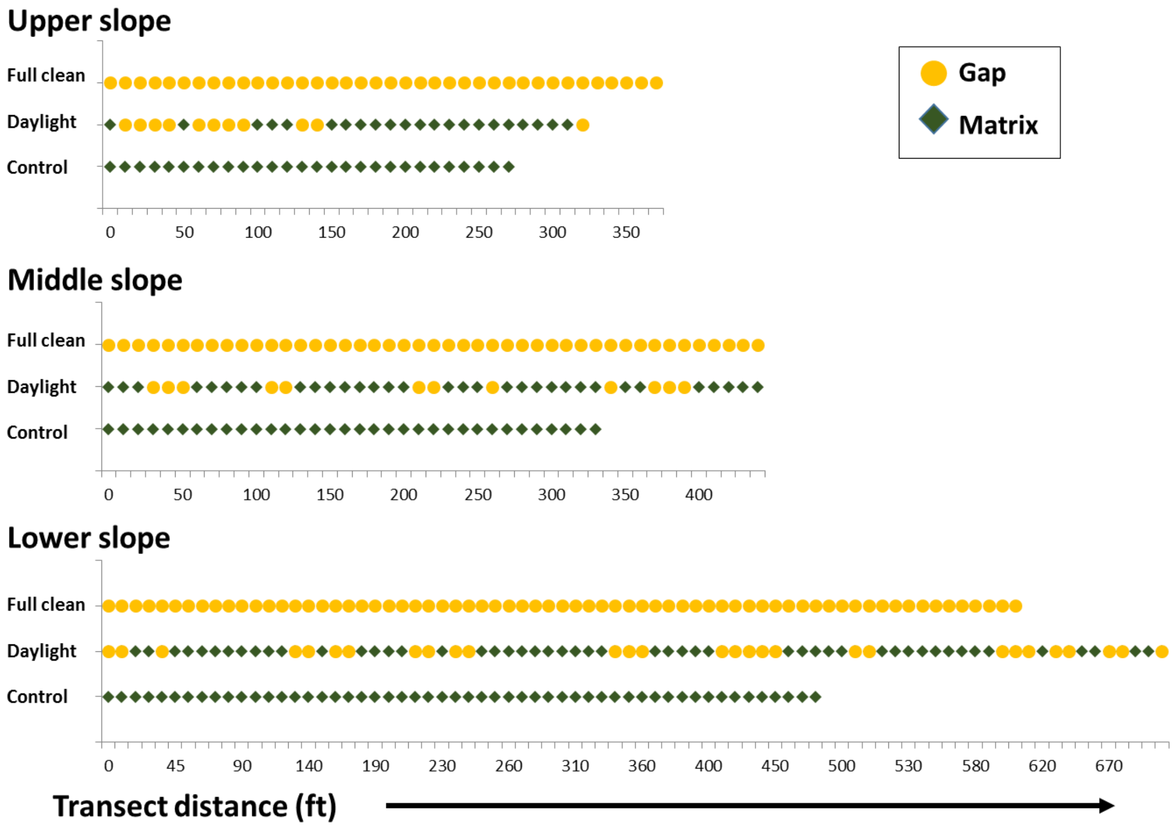

Figure 5. Daylight treatment stand-level heterogeneity. Transects demonstrate variable distribution among matrix and gap conditions for the cross-slope transects in replicate 1; in this replicate, transects were spaced at three elevations across the slope: lower (~1070 m), middle (~1120 m), and upper (~1160 m). Matrix (untreated) or gap (cleaned) conditions were recorded at 10-ft intervals in multiple transects through each treatment unit. Gaps were larger and more irregular in upper slope units where western white pine densities were more clumped, and more evenly distributed at lower slope positions where western white pine were spaced more randomly.

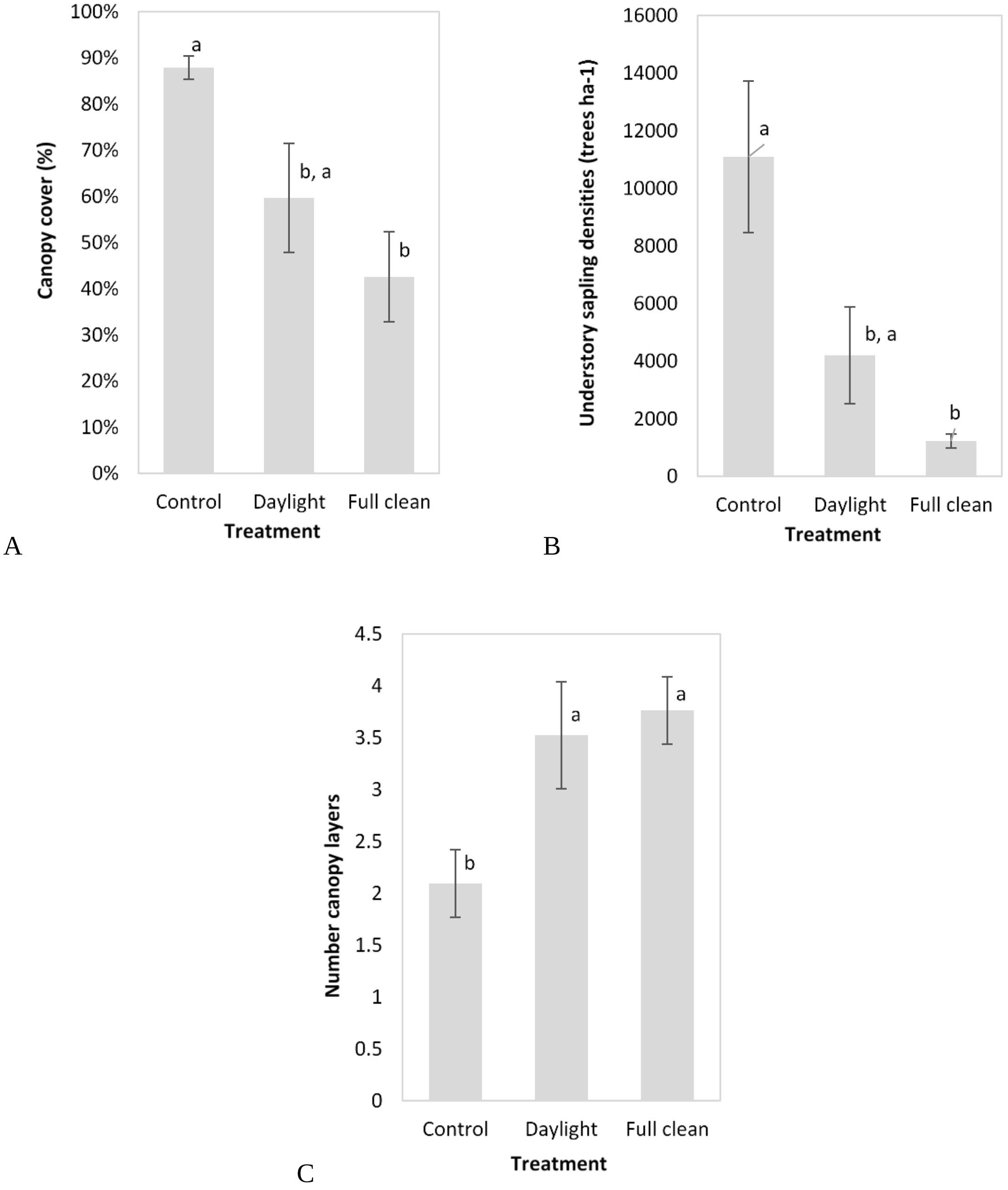

Figure 6. Structural complexity at crop trees. A) Canopy coverage (modeled in FVS), B) understory sapling densities, and C) numbers of canopy layers (modeled in FVS) around western white pine crop trees.

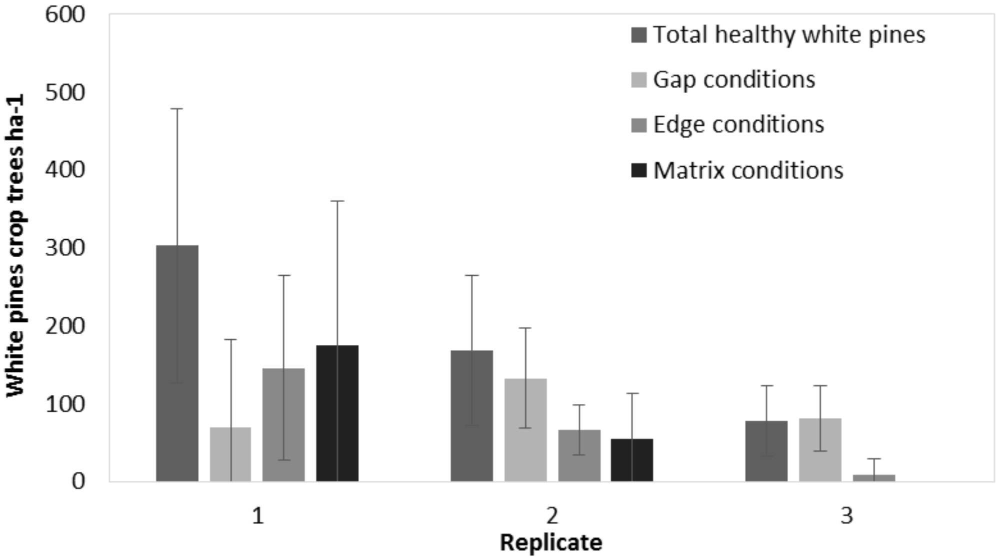

Figure 7. Variable western white pine crop tree crown release in the daylight treatment. The daylight treatment resulted in varying levels of crown exposure; crop tree crown conditions were categorized as cleaned gap, edge, or untreated matrix. The total abundance of western white pines, especially of healthy western white pines, appears to have influenced treatment patterns and gap configurations that caused this distribution. The plot-level distribution of crown conditions was also used to calculate the treatment intensity proxy for daylight treatment plots.

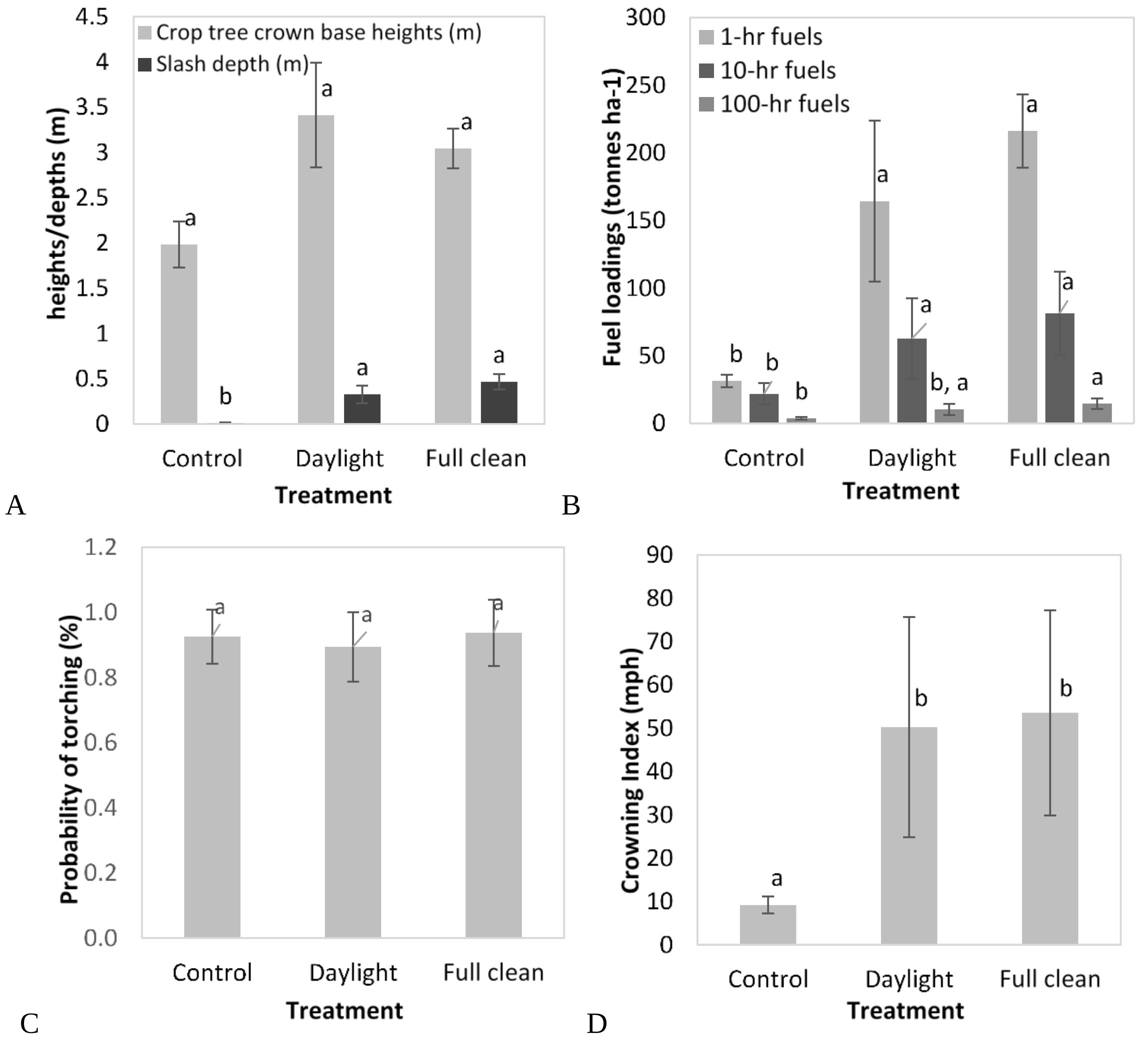

Figure 8. Fuel distribution and fire behavior at crop trees. Fire behavior was projected using the Fire and Fuels Extension to FVS (Reinhardt and Crookston 2003). A) Averaged canopy base heights of crop trees and average slash heights (m); B) fuel loadings of 1-hour (<0.6 cm), 10-hour (0.6 – 2.5 cm), and 100-hour (2.5 – 7.6 cm) fuel size classes (Brown 1974); C) probabilities of torching, and D) modeled crowning indices. Probability of torching is predicted for high-severity fire conditions. Crowning index is the predicted windspeed at which a crown fire would begin to spread through tree crowns.

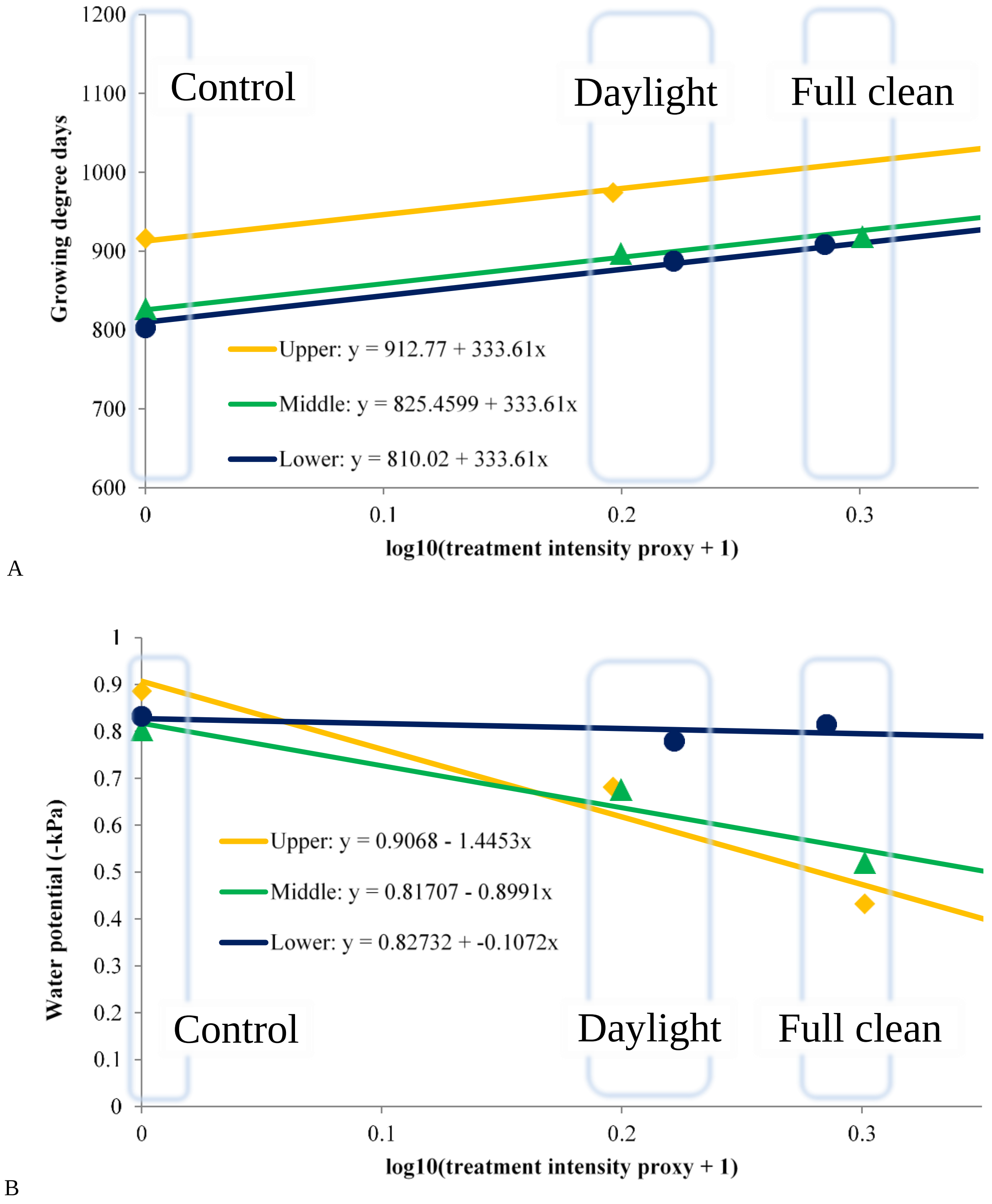

Figure 9. Microclimate conditions at crop trees. A) In the understory, growing degree days (Miller et al. 2001) throughout the summer (June 20 to September 4) increased with increasing cleaning treatment intensity ($p < 0.0001$). B) Soil moisture during dry soil conditions was greater at higher treatment intensities ($p = 0.0108$), but slopestrata may have influenced the relationship ($p = 0.0715$); upper slope strata were more influenced by treatment intensity. Soil moistures (units of negative kPa) were compared using pre-dawn water potentials of the western white pine crop trees foliage.

APPENDIX A: SUMMARY TABLE

Table A1: Stand-level and crop tree-level treatment outcomes for the three treatments. Different colors indicate statistically significant differences; gray text indicates no significant differences.

Response Variable	**No treatment**	**Daylight clean:** clean a 3m radius around the healthiest western white pine crop trees	**Full clean:** average 3m x 3m spacing
Stand-level treatment effectiveness			
Area treated	0% cleaned gap	27±9.8% cleaned gap	100% cleaned gap
Western white pine released	0%	69±30%	100%
Western white pine pruned	0%	74±22%	62±7%
Observations	Homogeneous, dense matrix: overstory western white pine, western larch, and Douglas-fir, slightly taller than the grand fir and western hemlock understory saplings. Many western white pine have rust, especially in lower branches.	Cleaned gaps and patches of various sizes surrounding one or more western white pines and western larches, variably distributed throughout matrix. Slash variable and concentrated within gaps. Pruning concentrated in gaps.	Homogeneous open conditions, understory eliminated, western white pines and western larch crowns fully exposed. Deep slash throughout entire stand. Pruning throughout stand.
Crop tree growth environment			
Structure			
Canopy cover	88±2.5%	60±11.8%	43±9.7%
Understory saplings (trees ha^{-1})	11,092±2630	4201±1683	1226±243
Canopy layers (number)	2.1±0.3	3.6±0.5	3.8±0.3
Fuels & fire behavior			
Canopy base height (m)	2.0±0.3	3.4±0.6	3.0±0.2
Fuels: 1hr/10hr/100hr (tonnes ha^{-1})	31±5/ 22±8/ 3.7±1	164±59/ 63±30/ 10±4	216±27/ 81±31/ 15±4
Slash depths (cm)	9±9	33±10	47±9
Crowning Index (windspeed, mph)	9±2	50±25	54±24
Probability of torching	92±8%	89±11%	93±11%
Microclimate variable	**Relationship with cleaning treatment intensity**		
Growing degree days (canopy)	no change		
Summer temperatures (canopy)	no change		
Summer relative humidity (canopy)	–		
Growing degree days (understory)	+		
Summer temperatures (understory)	+		
Summer relative humidity (understory)	–		
Soil moisture: moist conditions	no change		
Soil moisture: dry conditions (September)	+		

APPENDIX B: ADDITIONAL MICROCLIMATE METRICS

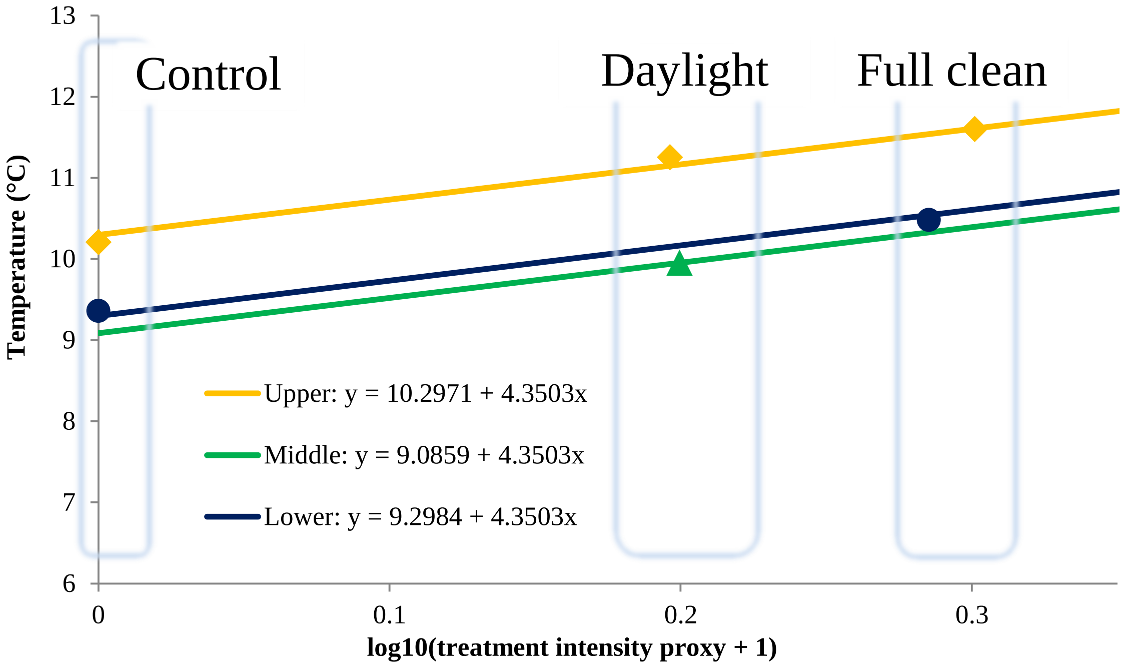

Figure A1: May average temperatures within crop tree crowns were influenced by cleaning treatment intensity at an almost significant level (p = 0.0564).

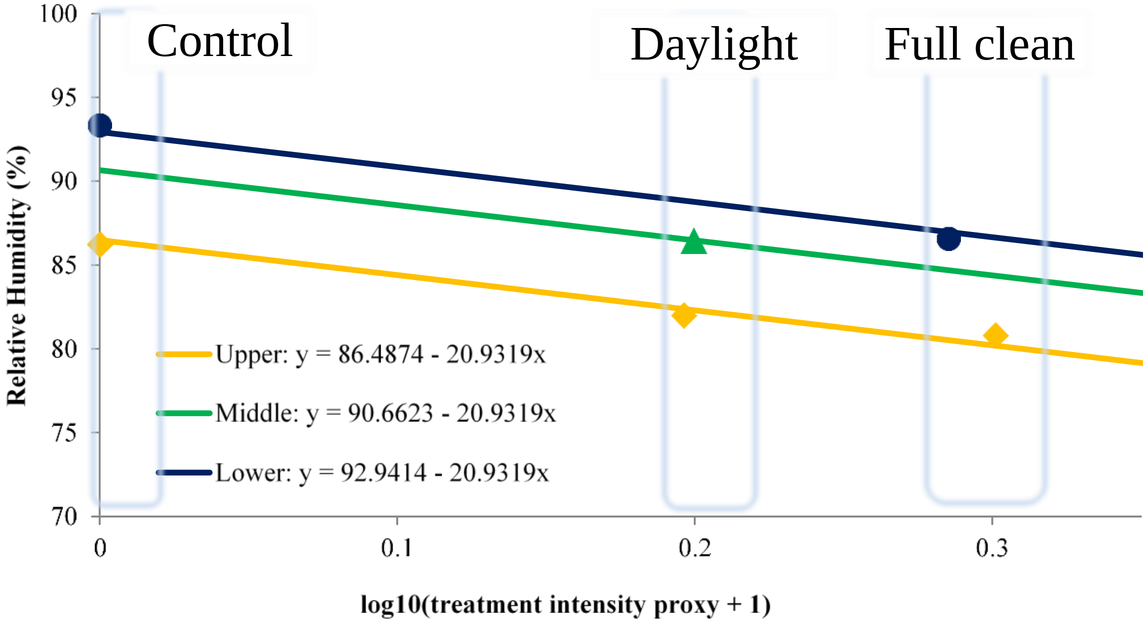

Figure A2: August maximum relative humidities within crop tree crowns were significantly influenced by cleaning treatment intensity (p = 0.0117).

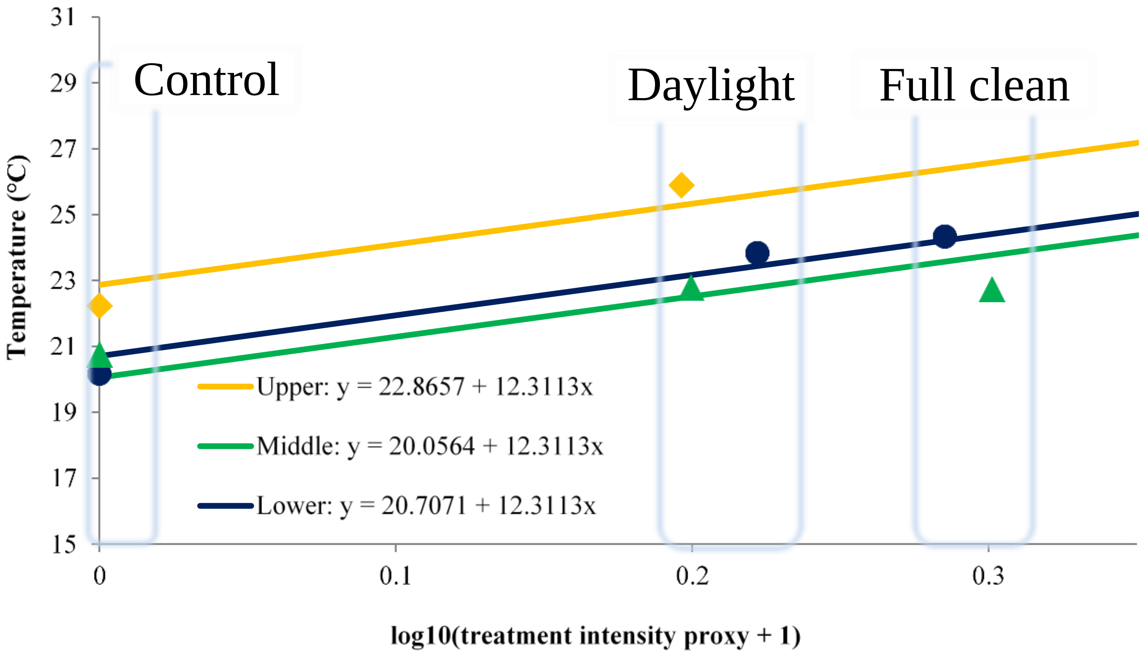

Figure A3: In the understory, maximum August air temperatures were significantly influenced by cleaning treatment intensity (p = 0.0082).

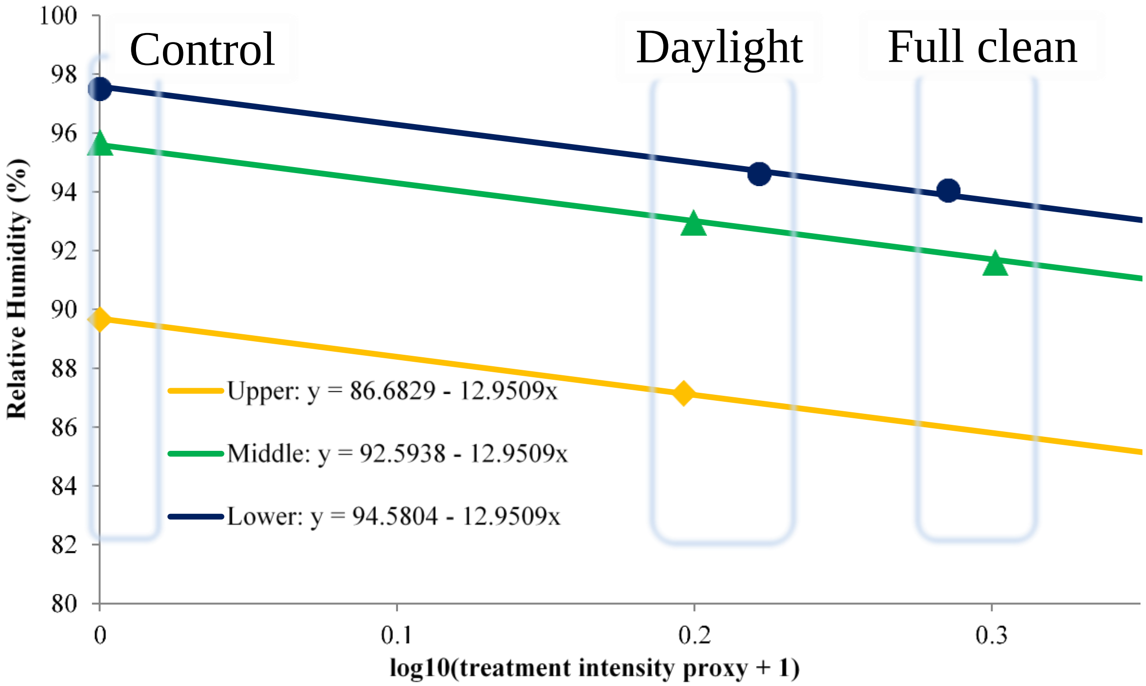

Figure A4: In the understory, maximum August relative humidities were significantly influenced by cleaning treatment intensity ($p < 0.0001$).

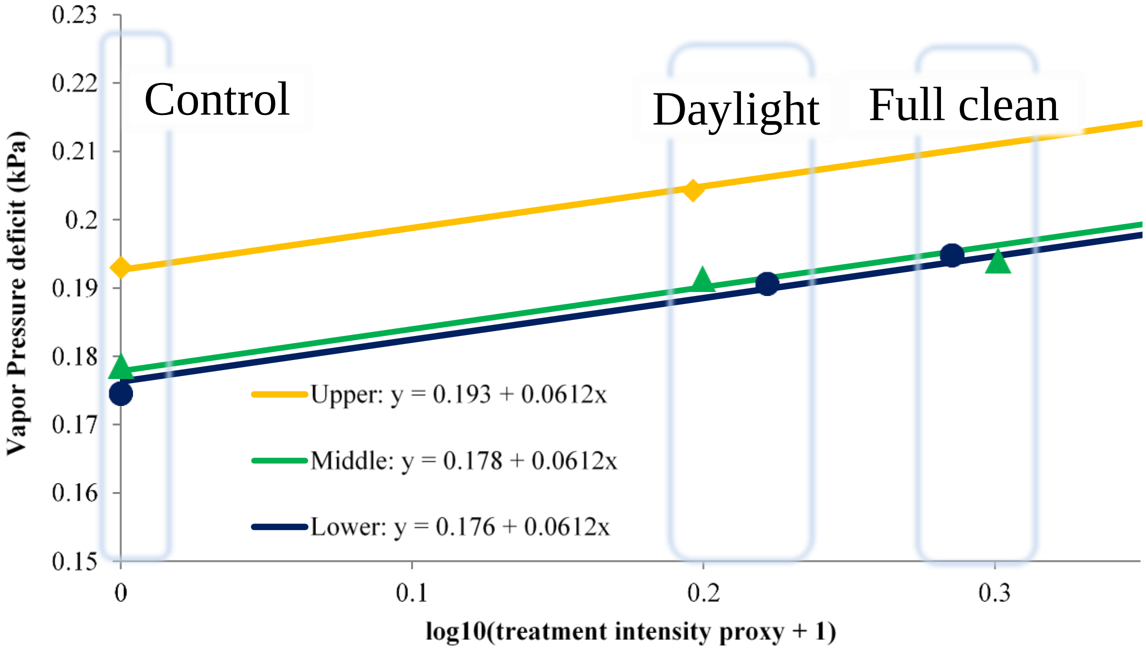

Figure A5: In the understory, summer (June 20 through Sept. 4) vapor pressure deficits (kPa) were significantly influenced by cleaning treatment intensity ($p = 0.0003$).