Bigleaf Maple Decline in Western Washington

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Science

University of Washington

2018

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Program Authorized to Offer Degree:

Environmental and Forest Sciences

University of Washington

Abstract

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Bigleaf maple (*Acer macrophyllum* Pursh) is a prominent component of the urban and suburban landscape in Western Washington, which lies at the heart of the native range of *A. macrophyllum*. *Acer macrophyllum* performs many important ecological, economic, and cultural functions, and its decline in the region could have cascading impacts. In 2011, increases in *A. macrophyllum* mortality were documented throughout the distributional range of the species. Symptoms of this decline included a systemic loss of vigor, loss of transpiration, and a reduction in photosynthetic potential, but did not display any signs or symptoms indicative of a specific causative agent. No pathogenic microbes, insects, or other biotic agents were initially implicated in causing or predisposing *A. macrophyllum* to decline. In my thesis research, I quantified the spatial extent and severity of *A. macrophyllum* decline in the urban, suburban, and wildland forests of western Washington, identified potential abiotic and biotic disturbance agents that are contributing to the decline, and conducted a dendrochronological analysis to ascertain the timing of the decline. I surveyed 22 sites that were previously reported as containing declining *A. macrophyllum*, and sampled 156 individual *A. macrophyllum*, of which 65 (41.7%) were observed to symptoms of declining health. In addition, I sampled 59 sites that were randomly selected from within the range of *A. macrophyllum* in western Washington, and sampled 132 individual *A. macrophyllum,* of which 29 (22.0%) were observed to symptoms of declining health. By comparing qualitative and quantitative measurements of *A. macrophyllum* decline severity, and dendrochronological patterns of tree growth and decline, elemental concentrations in soil and foliage, and geographic records of weather, landcover classes, and soil characteristics, I identified several environmental variables that are associated with mortality and loss of vigor in *A. macrophyllum*. Higher temperatures, vapor pressure deficits, decreased precipitation, high levels of developed land, low levels of forested or herbaceous land, and proximity to paved roads were all positively associated with increased prevalence of decline in *A. macrophyllum*. Ring widths of *A. macrophyllum* were negatively correlated with summertime temperatures, vapor pressure deficits, and drought, signifying reduced growth and vigor in the hotter, drier summers of the Pacific Northwest. Dendrochronologically-derived spatio-temporal estimations of *A. macrophyllum* decline did not indicate a spatially-correlated spread of symptoms characteristic of pathogen or disease introductions. Increased human habitation, activity, and development, as well as predicted increases in summer temperatures and drought, in the western coast of North America will likely continue, which could lead to increased mortality in *A. macrophyllum* in the future. The results of this study could be used to assist managers in their efforts to develop mitigating management strategies and adapt to changing conditions in the forest of the Pacific Northwest.

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ACKNOWLEDGMENTS

I would first and foremost like to thank my advisor Dr. Patrick C. Tobin, who was consistently good natured, patient, helpful, and creative. Patrick always went out of his way to help out, offer guidance, troubleshoot issues, and help with edits. He never showed anger or annoyance, even when it came to budgeting issues, project delays, or when I completed something at the last minute. I couldn't have asked for a better advisor.

I would also like to thank the members of my committee, Dr. Greg Ettl, Dr. Brian Harvey, and Dr. Robert Harrison. They were, likewise, always willing to take time out of their schedule to offer helpful advice, coach me through analytical issues I was struggling to comprehend, or provide a teacher's assistant position that provided some welcome funding.

I would like to thank my collaborators, Amy Ramsey and Dan Omdal, who were instrumental in getting this project off the ground, let me come along for sampling to get caught up on the issue, help me network at conferences, or keep me company while doing long days of field work.

I have to thank the many, many people who helped me along the way, from agency employees who took time out of their job to help me with mine, university employees who went above and beyond to help with hectic schedules and troubleshoot frustrating problems, and the employees of the School of Environmental and Forest Science who worked behind the scenes to make this program possible. I would like to specifically mention Dongsen Xue, Betsy Goodrich, Amy LeBarge, Joseph Gates, and David Zuckerman.

Thank you to the undergraduate employees who helped with the project, including Mikaela Balkind, Kendra Potoshnik, and especially Sabrina Gilmour, who volunteered her time for no pay, worked countless hours on tedious but necessary tasks, and provided fresh ideas. I appreciate all the company, advice, and help with homework that my lab mates, Michael Freeman, Riley Metz, Sean Callahan, Lila Westricht, Ryan Garrison, Alex Pane, and Michael Bradshaw provided.

I'd like to thank my parents, who were supportive and helpful, not the least of which by providing me with an education that helped me reach graduate school in the first place, the rest of my friends and family, and my fiancé Kaylyn Barnard, who put up weird work hours, a busy field season, and cooked countless meals for me while I was deep in thesis writing.

Finally, I would like to thank the USDA NIFA McIntire-Stennis Cooperative Forestry Program (Project #1009492), the University of Washington, and the Washington Department of Natural Resources for the funding that made this project possible.

Chapter 1. BIGLEAF MAPLE (ACER MACROPHYLLUM PURSH) ECOLOGY, THE PROCESS OF TREE DECLINE, AND STUDY SUMMARY

Bigleaf maple (*Acer macrophyllum* Pursh) is a deciduous, hardwood tree species native to the western coast of North America, with most populations west of the Pacific Coast Ranges in California, Oregon, Washington, and British Columbia (Fig. 1.1). It is typically associated with sites that have abundant soil moisture, such as river terraces, floodplains, and seepage sites on lower portions of slopes, often occurring in scattered patches within or on the streamside edges of conifer-dominated riparian communities (Peterson *et al*. 1999). It is commonly present along stream and roadside edges, interspersed with conifers such as western redcedar (*Thuja plicata* Donn) and Douglas-fir (*Pseudotsuga menziesii* Franco) (Kennedy & Spies 2005). *Acer macrophyllum* can also re-sprout from the stump or root crown after fire, cutting, or herbicide application, and are well adapted to rapid growth in canopy openings (Dobkowski 1995). They are often one of the early seral tree species inhabiting clear-cut Douglas-fir stands (Fried 1988). *Acer macrophyllum* is limited by lack of moisture and cold temperatures at higher elevations and does not grow where deep soil freezes occur before snowfall (Krajina *et al*. 1982), and is associated with soils of high nutrient concentration, high cation exchange capacity, high base saturation, and low C:N ratios (Peterson *et al*. 1999).

Acer macrophyllum is one of the few commercially important hardwood species from Pacific coast forests, where it can be harvested for furniture and piano frames (Minore & Zasada 1990). It is also considered a species of cultural importance in the Pacific northwest, including for the use in traditional medicines of the Saanich and Cowichan Coast Salish people (Turner &

Hebda 1990). As a component of urban and suburban forests, *A. macrophyllum* provides numerous ecosystem services and benefits, such as nutrient cycling, soil stabilization, successional relationships, and hydrology (Fried *et al*. 1990; Peterson *et al*. 1999). It is an aesthetically pleasing shade tree, which when grown in residential areas can contribute to reduced cooling costs to residents (Dwyer *et al*. 1992; McPherson *et al*. 1997). It also provides habitat and forage for the region's urban and suburban wildlife community, including birds, small mammals, and invertebrates (Neitlich & McCune 1997; Peterson *et al*. 1999). In heavily populated areas of Western Washington, it also is one of the few tree species seemingly able to support the region's iconic epiphytes, which are otherwise restricted on trees species growing in less populated areas and under lower levels of anthropogenic-derived pollution (Callahan 2017). These epiphytes contribute to several important and diverse ecosystem functions (Coxson & Nadkarni. 1995; Pettersson *et al*. 1995; Lindo & Gonzalez 2010) and are known to readily intercept atmospheric pollution (Reimann *et al*. 2005). Due to the dominance of *A. macrophyllum* as an over-story tree in many urban and suburban areas, its presence has a strong influence on plant and fungal communities (Halpern & Spies 1995).

Mortality events in trees are attributed to three interacting components, "predisposing", "inciting", and "contributing" factors (Sinclair 1965). Predisposing factors are environmental conditions that reduce a tree's ability to resist injurious agents or events, inciting factors are the events or agents responsible for the first general symptoms of decline, and contributing factors are secondary pathogens, herbivores, or other agents of mortality. According to Manion (1991), a decline in forest tree species, specifically, is characterized as a (1) dieback consisting of a usually slow, progressive deterioration in health and vigor, (2) phenomenon that primarily affects mature cohorts of trees, (3) condition of decreased growth and increased twig and branch dieback, and (4) complex etiology that may include contributions from abiotic and biotic factors.

This primarily differentiates a decline from a dieback caused by a specific cause, such as drought or an introduced pathogen or pest. A wide range of causal factors have been implicated in tree decline, including climatic changes, anthropogenic pollution, and biotic invasions (Hennon *et al*. 2006; Schulze 1998; Campbell & Antos 2000). Across western North America, there is evidence of recent increased mortality of trees (Van Mantgem *et al*. 2009), and documented instances of species-specific tree declines (D'Amore & Hennon 2006, Westing 1996).

Beginning in 2011, observations of a decline in *A. macrophyllum* health and vigor were reported by the public, land owners, forest land managers, and the Washington State Department of Natural Resources (WA DNR) (Ramsey 2016). This prompted the WA DNR to conduct an exploratory survey throughout the range of *A. macrophyllum* in western Washington in 2014, and collect leaf, branch, soil, root, and decayed wood samples of symptomatic, dying, or dead trees. This initial survey was conducted at 63 sites throughout western Washington and revealed decline across a large spatial gradient (Fig. 1.2). Symptoms of *A. macrophyllum* decline included yellow flagging of large branches, small leaf size, yellow and red leaf margins, partial or entire crown dieback, and mortality (Fig. 1.3). Symptoms of decline were present in both young and mature trees (Fig. 1.4). However, subsequent bioassays and sampling did not identify any pathogenic microbes, viruses, insect vectors or pests in or on enough of the declining trees to implicate that biotic agent as causative of the decline across the spatial extent in which it was observed.

To better understand the spatial extent and severity of *A. macrophyllum* decline, and to identify potential abiotic and biotic disturbance agents that are contributing to or causing the decline, I surveyed forest sites in the urban, suburban, and wildland forests of western Washington that contain *A. macrophyllum*. A random sample of 15 of the original 63 DNR sites, where *A. macrophyllum* decline was previously known to be present, was selected. I also used 7 sites reported by land owners where *A. macrophyllum* decline was also presumed to be present. In addition, I randomly selected 59 sites from the range of *A. macrophyllum* in western Washington where there was no a priori knowledge of *A. macrophyllum* decline presence of absence. At these study sites I collected tree and stand level data, conducted spatial analysis of the site locations, and associated the sites with weather data from the PRISM climate record dataset (PRISM Climate Group, Oregon State University 2017) and class land cover types from the National Land Cover Database (NLCD 2011) (Homer et al. 2015). In addition, I collected leaf and soil samples from study sites to measure elemental concentrations in each, which was then associated with *A. macrophyllum* decline presence or absence. This component of my thesis is presented in Chapter 2.

The use of dendrochronology has been successfully used to explore the temporal dynamics of decline in forest tree species, and in some cases, the cause of decline. While tree mortality can occur quickly after a major disturbance event, in general it is more often presaged by a decline in tree vigor, which is apparent through reduced annual tree growth. Dendrochronology, which is the measurement and analysis of tree growth rings, can be an essential tool in quantifying the reduced vigor preceding mortality (Cailleret *et al*. 2017). Dendrochronology can be used to monitor the spread and impact of biotic agents on host trees by quantifying the timing of tree decline expressed as reduced year-to-year growth (Agrawal 1995, Siegert *et al*. 2014), and can be an essential tool linking weather conditions to tree vigor and growth, revealing the impact of climate on tree health (Amoroso *et al*. 2015, Mclane *et al*. 2011, Helama *et al*. 2009). To determine the temporal pattern of *A. macrophyllum* decline in western Washington, I took tree cores from both healthy and declining *A. macrophyllum* from the study sites described previously, as well as from nearby coniferous trees, including *P. menziesii*, western hemlock (*Tsuga heterophylla* Sargent), and *T. plicata*, in which signs of decline were not apparent. Cores were used to contrast the growth patterns of *A. macrophyllum* relative to coniferous trees grown under similar environmental conditions, reconstruct the temporal aspect of the decline, and to associate growth patterns with environmental variables. This component of my thesis is presented in Chapter 3.

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Chapter 2. BIOTIC AND ABIOTIC FACTORS ASSOCIATED WITH DECLINE IN BIGLEAF MAPLE (ACER MACROPHYLLUM PURSH) IN WASHINGTON STATE

2.1 ABSTRACT

Bigleaf maple (*Acer macrophyllum* Pursh) is an important, native, broadleafed tree in the Pacific northwest. Decline in *A. macrophyllum* has been witnessed throughout out its entire range, beginning around 2011, with symptoms indicative of a systemic reduction in vigor, photosynthetic capability, and ability to resist secondary pathogens. To date, no pathogens, pests, or pollutants have been positively identified as a primary inciting factor in the decline. The goal of this project is to elucidate a disturbance agent, or group of interacting agents, or abiotic factors responsible for or associated with the reported *A. macrophyllum* decline. To do this, I sampled 103 40.47 m^2 (10^{th} acre) forest plots throughout western Washington, the range of *A. macrophyllum* in Washington state, and collected site descriptions, visually quantified decline in *A. macrophyllum*, and collected leaf and adjacent-soil samples from *A. macrophyllum*. I also attributed weather records, landcover, and other landscape characteristics to sites. Sites consisted of resampled opportunistically-chosen sites, randomly selected sites containing *A. macrophyllum*, and single-tree roadside opportunistically-chosen sites. The majority of lots were on publicly administered land. By comparing sites and trees with decline and without, as well as elemental concentrations in soil and foliage, and geographic records of weather, landcover classes, and landscape characteristics, I determined the relationship between *A. macrophyllum*

decline and a wide range of abiotic and biotic factors, which suggest that *A. macrophyllum* decline is associated with recent summer drought conditions and human development.

2.2 INTRODUCTION

Bigleaf maple (*Acer macrophyllum* Pursh) is a deciduous, hardwood maple tree species native to North America (Fig. 1.1), with populations in the Sierra Nevada, Cascades, western lowland of Oregon and Washington, and coastal ranges of California, Orgon, Washington, and British Columbia (Ruth *et al*. 1958). It is typically associated with sites that have abundant soil moisture, such as river terraces, floodplains, and seepage sites on lower portions of slopes, often occurring in scattered patches within or on the streamside edges of conifer-dominated riparian communities (Peterson *et al*. 1999). It is also prevalent on the edges of coniferous forests, along clearings, roadsides, and rivers and streams, interspersed with conifers such as western redcedar (*Thuja plicata* Donn) and Douglas-fir (*Pseudotsuga menziesii* Franco) (Kennedy & Spies 2005). Because of *A. macrophyllum*'s high moisture requirements and low frost tolerance, it is most likely limited by cold, freezing temperatures in the northern end of its range, and by drought in the east and south. It is killed by deep soil freezes that occur before snowpack (Haeussler & Coates 1986). *Acer macrophyllum* has relatively low nutrient requirements, although it expresses higher growth rates on rich, alluvial soils (Minore & Zasada 1990). In the Pacific Northwest, soil pH beneath *A. macrophyllum* averaged 5.5 (Tarrant *et al*. 1951). *Acer macrophyllum* is associated with soils of high nutrient concentration, high cation exchange capacity, high base saturation, and low C:N ratios (Peterson *et al*. 1999). It is found from sea level to 900 m over a range of topographic positions. In Washington it primarily grows on flat, riparian terraces and alluvial outwashes, with scattered trees on steep, rocky slopes (Minore & Zasada 1990).

Acer macrophyllum is thin-barked (1.3 cm), deciduous, reaching heights of 15-20 m when mature, often with multiple, joined boles, and wide, spreading branches (King 1991). The leaves are the largest of the maples, commonly reaching widths of 10-25 cm. Female and male flowers form on a raceme, with fruit consisting of a 3-5 cm long samara (Minore & Zasada 1990). *Acer macrophyllum* has deep roots, and is resistant to windthrow, but highly susceptible to fire-caused mortality. After fire, logging, or herbicide damage, however, *A. macrophyllum* is proficient at resprouting, and is common in clear cuts and other early seral communities (Dale *et al*. 1986; Dobkowski 1995).

Common pathogens of *A. macrophyllum* include *Sawadaea* spp., *Verticillium* spp., *Armillaria* spp. (Staude), *Ganoderma* spp. (P.Karst), *Phytophthora* spp. (de Bary), *Neonectria* spp. (Wollenw), and *Nectria* spp. (Tode). Insect pests include *Prionoxystus robiniae* (Peck) (Lepidoptera: Cossidae) and *Leptocorus trivittatus* (Say) (Hemiptera: Rhopalidae), but these insects are seldom mentioned as causal agent of mortality (Minore & Zasada 1990). Drought, frost damage, competitive shading, and flooding are all known to cause damage and mortality in *A. macrophyllum* as well. The maximum age of *A. macrophyllum* is around 200 years, with trees older than this succumbing to heart rot, overt-topping, and other age-related causes of mortality (Peterson et al. 1999).

Beginning in 2011, observations of a decline in *A. macrophyllum* health and vigor were reported throughout the range of the tree. Most of these trees had no obvious pathogens, pests, or other causative agents. Symptoms of this decline were varied but included a combination of deformed, wilted, and shrunken leaves, partial to entire crown dieback, and complete tree mortality. Recent symptoms also include leaves with yellow edges, red to brown scorched tips (Fig. 1.3) (Ramsey 2016).

In 2014-2015, the Washington State Department of Natural Resources (WA DNR) surveyed 63 sites distributed throughout western Washington at which *A. macrophyllum* decline was observed to ascertain a causative agent for the decline (Fig. 1.2). In collaboration with colleagues from Oregon State University and Washington State University-Puyallup, bioassays from leaf, branch, soil, root, and decayed wood samples of symptomatic, dying, or dead trees were collected in Washington State. However, to date, all samples have tested negative for many of the usual pathogen suspects that are often associated with the general symptoms of *A. macrophyllum* decline. *Verticillium* spp. was not found in any of the declining trees, *Armillaria* was only found in 11% of the declining trees, *Ganoderma* was only found in 3% of the declining trees, and results for *Xylella fastidiosa* were inconclusive (Ramsey 2016; USFS 2017). Furthermore, species of *Phytophthora*, *Neonectria*, and *Nectria* was not substantially abundant enough to be the causal agent across the landscape (USFS 2017). *Acer macrophyllum* decline in California is often referred to as Maple Leaf Scorch and is attributed to drought and suspected to be caused by *X. fastidiosa*, which is also the causative pathogen of Pierce’s disease in cultivated grape (Hopkins & Purcell 2002). However, attempts to screen samples from western Washington for *X. fastidiosa* DNA have been inconclusive (CFPC 2016).

Unidentified leafhoppers (Hemiptera: Cicadellidae) have also been found on several *A. macrophyllum*. As a family, leafhoppers are mostly generalist herbivores that use piercing mouthparts to feed on plant sap, and feed as both nymphs and adults. Due to their feeding behavior, leafhoppers can be competent vectors for plant pathogens, such as bacteria and viruses.

To date, it is not known if leafhoppers are responding to *A. macrophyllum* decline and taking advantage of a stressed host, and/or if they are contributing to *A. macrophyllum* decline by vectoring a plant pathogen (USFS 2017), although they tend not to significantly associated with tree decline.

Anthropogenic-induced changes to nutrient cycling and the introduction of toxins could have profound impacts on tree vigor and forest health. Anthropogenic influences on global nutrient cycling, such atmospheric nitrogen deposition as a byproduct of fertilization, has drastically increased (Galloway 2008). The increase in nitrogen deposition has also had dramatic influences on forest health and composition (Vitousek 1997), including decreased plant diversity (Clark & Tilman 2008). Pollution leading to increased introduction of toxic chemicals such as heavy metals (Hauck *et al.* 2001), as well as shifts in the pH balance of precipitation (Duchesne *et al*. 2002; Tomlinson 1983; Tomlinson *et al*. 1987), have been shown to cause significant increases in forest dieback and declines in tree vigor.

Climate change and weather events have been blamed on increased levels of mortality, disease, and reduced growth rates in forests (Allen et al. 2010; Sturrock et al 2011), and as the primary cause the decline in specific tree species (Beier et al. 2008; Cook & Johnson 1987; Sanchez et al. 2011).

In this paper, I surveyed the urban, suburban, and wildland forests of western Washington to identify possible causative disturbance agents responsible for the decline. By comparing sites and trees with decline and without, as well as elemental concentrations in soil and foliage, and geographic records of weather, landcover classes, and landscape characteristics, I determined the relationship between *A. macrophyllum* decline and a wide range of abiotic and biotic factors. A goal of this project is to elucidate a disturbance agent, or group of interacting agents, or abiotic factors responsible for or associated with reported *A. macrophyllum* decline. Such knowledge is particularly important in efforts to develop mitigating management strategies.

2.3 MATERIALS AND METHODS

Sampling Locations and Sampling Schedule

The WA DNR surveyed 63 roadside sites in 2014-2015 at which symptoms of *A. macrophyllum* decline were observed; 15 of these sites were randomly selected for inclusion in this study, and sites were selected within 10 regional subdivisions of western Washington (1 or 2 sites per regional subdivision; Fig. 2.1). Because DNR sites were purposively selected due to the presence of symptoms of decline, it was important to select additional sites at random. Thus, 59 sites on public land were randomly selected from areas known to contain *A. macrophyllum*. In addition, 7 sites were located on private land (these landowners have contacted me or the WA DNR and volunteered to take part in the study). Lastly, 36 roadside partial sites were purposively selected based on the presence of decline. All study sites are located within western Washington and within the range of *A. macrophyllum*, based on distributional data from the USDA Forest Service Forest Inventory Analysis (Fig. 2.2). Of the 59 Randomized sites, 17 sites were within the Mount Baker-Snoqualmie National Forest, 7 sites within the Gifford-Pinchot National Forest, 7 sites within the Olympic National Forest, 6 sites within Olympic National Park, 1 site within North Cascades National Park, 3 sites within Columbia River Gorge National Scenic Area, 7 sites within King County i-90 Corridor lands, 3 Sites within the Washington Park Arboretum, and 8 sites within the Cedar River Municipal Watershed.

Description of Study Sites

At each of the 15 resampled DNR sites, sampling was conducted in three, 40.47 m2 (10th acre), circular plots. One plot was centered on the previously tagged *A. macrophyllum,* which was sampled by DNR in 2014-15. If the tagged tree could not be located, the largest diameter stem of *A. macrophyllum* within 30 meters of the georeferenced location of the tagged tree was selected. Up to two additional plots, treated as additional replicates, were placed ~500 meters away from the center plot in opposite directions along the road. The center location of these two additional plots were determined by choosing the largest diameter stem of *A. macrophyllum* within a radius of 30 meters, centered around the point on the road 500 meters from the center plot. In cases where the road did not extend to 500 m, the plot was located at the end of the road centered on the largest diameter stem of *A. macrophyllum*. If there was no *A. macrophyllum* in one direction of the center plot, the additional plot was not taken.

At each of the 59 randomized sites on public land, sampling was conducted at one, 40.47 m^2 (10th acre), circular plot, centered on a target tree. Target trees were chosen by selecting the largest diameter stem of *A. macrophyllum* within 30 meters of a randomly generated spatial location, located within sites known to contain *A. macrophyllum*. These sites were chosen by contacting land managers at the responsible state or Federal agencies. Furthermore, all randomly selected sites were within 200 meters of a road or trail for ease-of-access purposes. If the randomly generated spatial location was inaccessible or had no *A. macrophyllum* within 30 meters of it, another randomly generated spatial location was chosen. At each of the 7 landowner sites, there was one 40.47 m^2 (10^{th} acre), circular plot, centered on a *A. macrophyllum* with symptoms of *A. macrophyllum* decline.

The 36 roadside partial sites consisted of only a single *A. macrophyllum*. Criteria for selecting a roadside partial site included visible symptoms of *A. macrophyllum* decline and an accessible location. *Acer macrophyllum* trees were designated as declining if they have higher than nominal levels of dieback, thinning, discoloration, or reduced leaf size. All sites were sampled between 13 June 2017, and 8 September 2017, which was after *A. macrophyllum* budbreak and before leaf senescence in all study locations (Campbell & Franklin 1979).

Study Site Measurements

Within each 40.47 m^2 (10^{th} acre) plot, the managing agency, site descriptor, date sampled, spatial location of center tree, elevation, slope, aspect, and WA DNR stand structure code (Amy Ramsey, personal communication, 19 June 2017) were recorded. In addition, the three most dominant understory species, percent of surrounding trees that are deciduous (as opposed to coniferous), signs of noticeable disturbance (e.g., windthrow, past logging, etc.), distance to nearest road, brief description of soil, number of *A. macrophyllum* saplings (<5cm DBH (diameter at breast height)), and percent of *A. macrophyllum* trees in surrounding area showing symptoms of decline were recorded. Each stem (≥5 cm DBH) had the following variables recorded: species, which multi-stemmed tree it is a part of (if applicable), DBH, mortality class (Bradford *et al.* 1996), and dominance class (Nyland 2016).

For each *A. macrophyllum* tree in the plot, the following variables were recorded: regeneration (sprouting from the base of the tree), presence of epicormic branching, presence of visible disease (e.g., heart-rot discovered after coring), presence of insect herbivores, approximate density of per leaf, and (if the tree was declining) whether *Armillaria* spp. were present at the base of the tree. Symptoms of decline, including extent of crown dieback, extent and severity of thinning, extent and severity of discoloration, extent and severity of reduced leaf size, were recorded on a 1-100% scale for extent and 1-5 scale for severity.

In the roadside partial sites, the following variables were recorded: date sampled, spatial location of center tree, distance to nearest road, the multi-stemmed tree of which it was a part (if applicable), DBH, mortality class, dominance class, regeneration, presence of epicormic branching, extent of crown dieback, extent and severity of thinning, extent and severity of discoloration, extent and severity of reduced leaf size, if there was a visible disease present, presence of insect herbivores on the leaves, approximate number of insects per leaf, whether *Armillaria* spp. was present at the base of the tree, and what percentage of surrounding *A. macrophyllum* trees were declining.

Soil and Foliar Elemental Analyses

In each 40.47 m^2 (10th acre) plot, soil samples for elemental analysis consisted of 2 kg of soil collected using 2.54 cm diameter and 30 cm deep soil cores. Cores were extracted at 2, 4, 8, and 10 m from the center tree, located along the four cardinal directions, and combined into one aggregate sample. Soil samples to estimate bulk density consisted of two samples taken 5 m east and west from the center tree using a corer with a 10.15 cm diameter and collected to a depth of 8.25 cm. In the roadside partial sites, the elemental soil samples consisted of 1 kg of soil, collected using 2.54 cm diameter and 30 cm deep soil cores. Cores were extracted at 2 and 4 m from the center tree, arrayed along the four cardinal directions, for a total of 8 samples per roadside partial plot.

Following collection, elemental soil samples were stored at ~4 °C until sieved at 2 mm, dried at ambient temperature, and ground and homogenized using a mortar and pestle. Elemental soil had wet weight, dry weight, and root/rock weight recorded. Samples for estimating bulk density were dried, sieved at 2 mm, and had wet and dry weight recorded. This information was used to estimate soil water content, soil bulk density (Carter & Gregorich 2008).

Foliar samples were collected in each 40.47 m^2 (10th acre) plot, and consisted of loosely compacted leaves, ~2 liters in volume. Foliar samples were collected from the cored *A. macrophyllum* trees, resulting in up to three foliar samples per 40.47 m^2 (10th acre) plot. A foliar sample were also taken from each of the roadside partial site trees. Leaves were collected by hand or through the use of an extendable pole clipper. *Acer macrophyllum* trees with foliage located > 5.5 m from ground level were not accessible by the pole clipper, and thus samples were not collected. Foliar samples were dried at ambient temperature, then ground and homogenized using a mortar and pestle.

The elemental soil sample and the foliar samples were analyzed using the CHN Analyzer 2400 Model, PERKIN ELMER Co., the ICAP 61E Model, Thermo Jarrell Ash Co., and the Denver Instruments Model 220 pH Conductivity Meter, all operated by the Analytical Service Center within the School of Environmental and Forest Sciences, University of Washington.

Concentrations of Ag, Al, As, B, Ba, C, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Mo, N, Na, Ni, P, Pb, S, Se, Si, and Zn were quantified for foliar and soil samples, as well as pH of soil samples.

Complementary Metrics

Climate data that included precipitation, mean temperature, minimum temperature, maximum temperature, mean dew point temperature, minimum vapor pressure deficit, and maximum vapor pressure deficit in monthly increments from January 1981 to July 2017 were obtained from the PRISM Climate Group (PRISM Climate Group 2017). Data from the National Land Cover Database 2011 (NLCD 2011) (Homer *et al.* 2015), which provides a 16-class land cover classification scheme that has been applied consistently across the United States at a spatial resolution of 30 meters, was also collected for the entire study region.

Analyses

Severity of decline (hereafter referred to as “Tree Severity”) was calculated based on four metrics of decline: crown dieback, thinning, discoloration, and reduced leaf size. Tree Severity ranged from 0 for a completely healthy tree to 1, which corresponded to a tree with a 5/5 severity and 100% extent for all four metrics. In actuality, the observed range of Tree Severity was 0 to 0.75. A tree was noted as declining (hereafter referred to as “Tree Declining”) if the Tree Severity measured > 0. These values were used to designate a binary response variable (e.g., presence of absence of Tree Declining). Additionally, “Site Severity” was calculated by averaging Tree Severity of all *A. macrophyllum* in the plot, and sites were defined as “Site

Declining” when Site Severity was >0. These four metrics represent tree- and site-level continuous and binary response values.

Monthly precipitation, monthly average temperature, monthly mean temperature, and monthly maximum vapor pressure deficit from PRISM climate record dataset (PRISM Climate Group 2017) was tabulated for each site. June, July, and August data were averaged to represent a summer mean. Moreover, means were estimated from the summers of 2015-2017 and considered as a recent summer metric, and while means were estimated from the summers of 1981-2014 and considered as a historical summer metric. Means from the recent summers were divided by the means from the historical summers to estimate summer change values.

To analyze the NLCD 2011 data, land cover classes 41 (Deciduous Forest), 42 (Evergreen Forest), 43 (Mixed Forest), 71 (Grasslands/Herbaceous), 91 (Woody Wetlands), 92 (Emergent Herbaceous Wetlands) were combined into the category “Forested/Herbaceous”, and 21 (Low Intensity Residential), 22 (High Intensity Residential), and 23 (Commercial/Industrial/Transportation) were combined into the category “Developed”. A grid (1×1 km^2), which was chosen as a compromise between having proximate effects on sites and having enough variability for analysis, was centered around every site, and the fraction of “Forested/Herbaceous” land and fraction of “Developed land with each grid was estimated.

Generalized linear models were computed, using Tree Declining and Site Decline as a binary response variables, Tree Severity and Site Severity as a continuous response variables, and a range of environmental variables as predictor variables. These predictor variables included summer means for all four weather metrics, and summer change values for all four weather metrics from the random sites were considered as main effects. Also, the main effects of elevation, slope, aspect, latitude, longitude, soil pH, distance from closest dirt or paved road, distance from closest paved road, fraction of developed land cover surrounding the site, Curtis Relative Density (Curtis 1982), and *A. macrophyllum* saplings per plot were calculated. Tree basal area and number of stems was calculated with respect to Tree Decline and Tree Severity, and basal area declining and healthy (Tree Declining) *A. macrophyllum* of were plotted.

Mixed stepwise logistic regression models were computed, with concentrations of each element collected from the Random sites considered predictor variables and tested for significance, using Tree Declining and Site Decline as a binary response variables, Tree Severity and Site Severity as a continuous response variables. Separate analyses were conducted for foliar and soil samples. In addition, a principal component analysis (PCA) was also performed on all elements for foliar and soil samples, and when using only the elements identified as significant, in relation to Site Declining for soil concentrations and Tree Declining for foliar concentrations, from the final mixed stepwise logistic regression model. Concentrations were log transformed prior to the PCA, with 0.000000001 added to each concentration to eliminate zeros, to account for the variation in absolute concentrations of different elements. Summary statistics included box-and-whisker plots based on normalized elemental concentrations for both foliar and soil samples, for all Random, DNR, and Landowner sites, to show the range and variability in all sites.

In the analyses of landscape characteristics and elemental concentrations, individual trees were considered the experimental unit where the response variable was Tree Declining or Tree Severity, even though some data were collected on an individual tree basis regarding decline, while other data (i.e., fraction of forested or herbaceous land cover surrounding site) were collected on the level of the site. This was done to weight the sites with more *A. macrophyllum*, compared to sites with less *A. macrophyllum*. It is foreseeable that this may be criticized as pseudo-replication, however, site-level response variables (Site Declining and Site Severity) were also analyzed for all site-level predictor variables. Only data from the Random sites were used because the DNR and Landowner sites were chosen with bias since they were a priori known to contain declining *A. macrophyllum*.

Lastly, the spatial autocorrelation of the Site Severity and Site Declining was estimated using both Random and DNR sites using the ncf package (Bjornstad 2018) in R. DNR sites, as well as Random sites, were used in these analyses to show the autocorrelation at both long and short distances.

All statistical analyses were conducted using R (R Core Team 2018).

2.4 RESULTS

There was a higher percentage of declining *A. macrophyllum* in DNR resampled sites and Landowner sites than in Random sites (Table 2.1), with 18% of *A. macrophyllum* in Random sites experiencing some level of decline, and 42% and 38% of *A. macrophyllum* in DNR and Landowner sites, respectively, experiencing decline. There were similar rates of symptoms among the site types, although there were somewhat higher incidences of thinning and reduced leaf size in Random sites than in DNR or Landowner sites. Furthermore, decline in both the random and DNR sites were located across western Washington (Fig. 2.2; Fig. 2.3; Fig. 2.4), indicating that the decline is widespread throughout the range of *A. macrophyllum* in Washington.

The probability of *A. macrophyllum* decline in individual trees increased with recent maximum summer monthly temperatures, mean summer monthly temperatures, maximum summer monthly vapor pressure deficits, and decreased with recent mean summer monthly precipitation (Table 2.2; Table 2.3; Fig. 2.5; Fig. 2.6). The average site clearly showed reduced summer precipitation and increased summer temperatures and vapor pressure deficits (Fig. 2.7; Fig. 2.8). The probability of decline also increased in sites with higher fractions of Developed land and decreased with higher fractions of Forested/Herbaceous land (Table 2.2; Table 2.3; Fig. 2.9). The probability of decline also increased in sites closer to paved roads (Table 2.2; Table 2.3; Fig. 2.10), and when located in a more northerly site, indicating a directional gradient in decline (Table 2.2; Table 2.3). Lastly, *A. macrophyllum* in sites at lower elevations had a higher predicted probability of decline (Table 2.2; Table 2.3). Basal area of trees, number of *A. macrophyllum* saplings per plot, Curtis-Bray stand density index, and soil pH were not significantly correlated with either Tree Declining, Tree Severity, Site Declining, or Site Severity.

The range of soil (Fig. 2.11) and foliar (Fig. 2.12) element concentrations are presented, including total concentrations divided by site type (Table 2.7; 2.8), with foliar concentrations unique to individual trees and soil concentrations specific to sites. Despite the overlap in many element concentrations, stepwise regression of soil elemental concentrations of As, Ba, Ni, and P were positively associated with *A. macrophyllum* Tree Decline, while B, Cd, Mn, Mo, S, and Zn were negatively associated with *A. macrophyllum* Tree Declining (Table 2.4; Table 2.5). The stepwise regression of foliar elemental concentrations (Table 2.6) also found significant positive relations between *A. macrophyllum* Tree Declining and concentrations Al and Si, while As and B are negatively correlated with *A. macrophyllum* Tree Declining. The PCA analyses (Fig. 2.13; Fig. 2.14; Fig. 2.15; Fig. 2.16) of the elemental content of leaves and soil failed to show any clearly defined groupings of sites, or different associations between declining or healthy sites and *A. macrophyllum*.

When considering spatial autocorrelation in the pattern of Average Site Severity and Site Declining, which are site specific, in neither case was significant spatial autocorrelation observed (Fig. 2.17), suggesting that even at local spatial scales, Site Severity and Site Declining were spatially random.

2.5 DISCUSSION

The greater incidence of decline in DNR and Landowner sites than in Random sites (Table 2.1) is to be expected, as DNR sites and Landowner sites were chosen based on containing declining *A. macrophyllum*. However, even by disregarding the declining *A. macrophyllum* originally identified by the DNR, there was a higher prevalence of decline in the *A. macrophyllum* in the DNR sites. This would indicate that there is some local-scale spatial autocorrelation of decline even though there was no detectable spatial autocorrelation in decline at larger distances (Fig. 2.17). Indeed, the presence of decline in sites that were more developed and closer to main roads would suggest some spatial pattern. Although sites were located throughout western Washington, which provides a spatially broad perspective of *A. macrophyllum* decline (Fig. 2.18), it is likely that small scale processes were not accounted for in this data set. Unfortunately, it was not feasible to conduct both a broad-scale and local-scale sampling effort in this study, but future efforts could address local scale processes through the use of intensive plots. Given that a goal of my thesis was to quantify the spatial extent of *A.*

macrophyllum decline, sampling efforts focused on spatially extensive sites throughout western Washington.

There was also a significant association between *A. macrophyllum* decline and latitude, with more northerly sites more likely to containing declining trees. While it is possible that biogeographic processes are a factor, it is more likely a spurious correlation that is an artifact of the different types of landscapes that were sampled in the northern and southern part of the study area. The map of declining and healthy sites (Fig. 2.3; Fig. 2.4), and the reports of decline in British Columbia, Oregon, and California (Ramsey 2016), would seem to suggest that the decline does not necessarily follow a latitudinal gradient.

The lack of relationship between basal area and decline (Fig 1.4) would suggest that the decline is not specific to large, small, young, or old trees. This likely rules out senescence a single aged cohort of *A. macrophyllum* across the Washington. Nor is stand-age related exclusion responsible for decline in *A. macrophyllum*, as evidenced by the non-significant relationship between decline and stand density. While there is insufficient evidence to conclusively determine whether *A. macrophyllum* is regenerating at a sustainable rate across Washington, there is no evidence to suggest that increased regeneration is occurring in declining sites, as shown by the lack of relationship between decline and number of saplings.

Climate change and increased development are both identified as associated with *A. macrophyllum* decline (Fig. 2.5; Fig. 2.6). Recent summer have been marked by severe drought conditions and rising temperatures in Washington State (Marlier *et al*. 2017; Watts *et al*. 2018; Fig. 2.7; Fig. 2.8). My research suggests recent higher-than-average heat and drought are positively associated with decline of *A. macrophyllum* (Fig. 2.5; Fig. 2.6). Other studies have found links between climate change, increased temperatures, and changes in precipitation, to increased tree mortality (Allen *et al*. 2010; Intergovernmental Panel on Climate Change 2014; Van Mantgem *et al*. 2009), and *A. macrophyllum* seems to be experiencing negative impacts from this pattern as well. *Acer macrophyllum* closer to roads, developed areas, and impervious surfaces are reported to be more predisposed to decline than trees in more remote, forested areas (Dale *et al*. 2016; Sjöman *et al*. 2015). Furthermore, *A. macrophyllum* is more likely to be declining on lower elevation sites (Table 2.2; Table 2.3), where higher temperatures and more evapotranspiration are to be expected, suggesting climate change-caused range shifts along an elevational gradient (Lenoir & Svenning 2015; Savage & Vellend 2015). Together, this indicates an anthropogenic component of decline, with increased human habitation, activity, and development in the western coast of North America (Pendall *et al*. 2015) continuing to cause increasing mortality in *A. macrophyllum* in the future, even in the absence, at least to date, of a specific biotic agent or agents.

Other researchers (Case & Lawler 2016; Crookston *et al*. 2010) have created models of the susceptibility of tree species to climate change, and due to the extensive north-south range of *A. macrophyllum*, it is considered to be highly adaptable to climate change (Hamann & Wang 2006; Crookston *et al*. 2010). However, the reported recent decline in *A. macrophyllum* vigor throughout its range suggests that *A. macrophyllum* is could more susceptible to the higher temperatures and more intense droughts projected under climate change scenarios than currently known. One plausible explanation is that while *A. macrophyllum* does has a wide geographical range with different climate regimes throughout this range, individual trees and populations are still locally-adapted and in some areas, may be more susceptible to recent trends in climate. This is supported by other studies that have found differing climate preferences between populations of the same species (Johnson *et al*. 2004; McLachlan *et al*. 2007; Thomas *et al*. 2014).

The finding of several significant relationships between soil elemental concentration and reduced vigor in *A. macrophyllum* (Table 2.2; Table 2.3; Table 2.4; Table 2.5; Fig. 2.13; Fig. 2.14) would suggest that pollution could be a cause of decline, or that higher pollutant concentrations are tangential to other factors leading to decline. Because the DNR resampled and Landowner sites were chosen with bias, they were omitted in the analysis. However, elemental concentrations were different depending on site type (Table 2.4; Table 2.5; Table 2.6). The lack of well-defined groupings of sites within the PCA analyses (Fig. 2.13; Fig. 2.14; Fig. 2.15; Fig. 2.16) of the elemental content of leaves and soil, combined with the significant associations found by stepwise regression, can perhaps be explained by the fact that there is substantial variation in relative levels of elements between sites and *A. macrophyllum*, and no apparent relationship between concentrations of individual elements. This, however, does not suggest that an individual element's concentration does not influence the presence of decline in *A. macrophyllum*.

Pollution of certain heavy metals has increased in recent decades, primarily along urban roadways and areas (Donovan *et al*. 2016; Gatziolis *et al*. 2016; Geiser & Neitlich 2007; Bidwell 2017), due to traffic-derived pollution. However, the decline of *A. macrophyllum* has been documented across the range of the species, in both urban and rural locations (Ramsey 2016), while the recent influx in immigration has primarily been to urban areas in the Pacific Northwest (Bae 2017; Gately *et al*. 2015). While the significant relationships between elemental concentrations and mortality in *A. macrophyllum* (Table 2.4; Table 2.5; Table 2.6) may indicate pollutant levels as a predisposing or additive agent responsible for decline, the substantial overlap between elemental concentrations within healthy and declining sites suggests that other drivers may be the primary causal factor. Furthermore, it is theoretically possible that a pollutant may not have a clear elemental concentration signature or is uniformly spread across the entire study area. Though the results of this study do not clearly demonstrate a pollution component to reported cases of *A. macrophyllum* decline, due to the scope of the study, they also fail to conclusively rule out a relationship between a pollutant and decline.

The widespread decline of an integral and native component of the urban and natural forests of western Washington poses immediate concerns. For example, hazard tree removal in urban and suburban areas can be a substantial cost to municipalities and individuals (Aukema et al. 2011). Restoration and replanting efforts conducted by governmental and nongovernmental organizations could be forced to consider species other than *A. macrophyllum*, which reduces the presence of an important native tree and the ecological roles it plays (Peterson et al. 1999). Moreover, the loss of *A. macrophyllum* would also represent a loss to an important cultural resource (Minore & Zasada 1990). Although this research did not identify a “smoking gun” with regard to a specific biotic agent that could be implicated as a cause of *A. macrophyllum* decline, the presence of variables associated with *A. macrophyllum* decline, such as recent summer drought conditions and human development, provides an opportunity for future research.

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Chapter 3. A DENDROCHRONOLOGICAL ANALYSIS OF THE SPATIOTEMPORAL PATTERNS OF DECLINE IN BIGLEAF MAPLE (ACER MACROPHYLLUM PURSH) IN WASHINGTON STATE

3.1 Abstract

Bigleaf maple (*Acer macrophyllum* Pursh) is an important, native, broad-leafed tree in the Pacific Northwest. Decline in *A. macrophyllum* has been reported throughout its distributional range since 2011, with symptoms indicative of a systemic reduction in vigor, photosynthetic capability, and ability to resist secondary pathogens. To date, no pathogens, pests, or pollutants have been positively identified as a primary factor in the decline. I sampled 103 40.47 m^2 (10th acre) forest plots throughout western Washington, which encompasses the range of *A. macrophyllum* in Washington state, and cored healthy and declining *A. macrophyllum*. I also cored adjacent coniferous species for comparative purposes, which were primarily Douglas-fir (*Pseudotsuga menziesii* Franco). Sites consisted of resampled opportunistically -chosen sites, randomly selected sites containing *A. macrophyllum,* and single-tree roadside opportunistically -chosen sites. The majority of lots were on publicly administered land. I used several dendrochronological methods and analyses to identify the primary cause of *A. macrophyllum* decline. Specifically, I associated climate records to the ring widths of healthy and declining *A. macrophyllum* to measure its response to climate variables and to quantify the role of climate variables in the recent decline. I also used tree ring width records of healthy and declining *A. macrophyllum* to reconstruct the spatio-temporal patterns of decline and compared the ring widths of *A. macrophyllum* to nearby coniferous trees to determine to what extent the decline is species-specific. Ring widths of *A. macrophyllum* are negatively correlated with summertime temperatures, vapor pressure deficits, and drought, signifying reduced growth and vigor in comparatively hotter, drier summers. Spatio-temporal estimations of *A. macrophyllum* decline do not indicate a spatially-correlated spread of symptoms characteristic of pathogen or disease introductions. When compared with *P. menziesii*, *A. macrophyllum* ring widths contain comparatively more amongst-tree variance in ring-widths, with both species having increasing variance beginning around 2000. Dendrochronological analysis of *A. macrophyllum,* specifically the negative correlation between ring width and summer temperatures and drought, and the lack of spatial correlation of decline dates indicative of the spread of a pathogen, suggests that *A. macrophyllum* decline is associated with changes in weather patterns and not the result of a biological agent.

3.2 INTRODUCTION

Bigleaf maple (*Acer macrophyllum* Pursh) is a broad-leafed, deciduous tree native to the Pacific Northwest (Fig. 1.1), and is a prominent component urban and suburban forests, as well as wildland and managed forests (McLain *et al*. 2012; Mills *et al*. 2016). It provides many ecosystem services (Fried *et al*. 1990; Peterson *et al*. 1999), as well as providing cultural and economic functions (Dwyer *et al*. 1992; McPherson *et al*. 1997; Turner & Hebda 1990). An important role that *A. macrophyllum* serves on private property and in public spaces is as a shade tree, and as such can be a primary component of urban forests in the Pacific Northwest (McBride 2017).

Acer macrophyllum has been reported as declining in health and vigor throughout its entire range in Washington State since 2011. Symptoms of decline include deformed, wilted, and shrunken leaves, partial to entire crown dieback, yellow edges, red to brown scorched tips (Fig. 1.3), and complete tree mortality. Subsequent inquiries by the Washington Department of Natural Resource (WA DNR) have found reports of declining *A. macrophyllum* in California, Oregon, and British Columbia (Ramsey 2016).

Plant pathogens and insects are commonly implicated in widespread, rapid forest decline (Gandhi and Herms 2010; Maloy 2001; Rizzo & Garbelotto 2003; Swingle *et al*. 1949). To initially determine if a pathogen was responsible for the recent decline in *A. macrophyllum*, the WA DNR completed a survey of the range of *A. macrophyllum* in Washington in 2014-15. The WA DNR sampled 63 declining *A. macrophyllum* in Washington (Fig. 1.2), and after assaying leaf, branch, soil, root, and decayed wood samples through Oregon State University and Washington State University-Puyallup, all samples were negative for pathogens commonly associated with *A. macrophyllum* decline. For example, *Verticillium* spp. were not found in any of the declining trees, *Armillaria* was only found in 11% of the declining trees, *Ganoderma* was only found in 3% of the declining trees, and results for *Xylella fastidiosa* were inconclusive (Ramsey 2016; USFS 2017). Furthermore, species of *Phytophthora*, *Neonectria*, and *Nectria* were not substantially abundant enough to be considered as causal agents of decline across the landscape (USFS 2017). Decline of *A. macrophyllum* in California, often referred to as Maple Leaf Scorch, was first attributed to a combination of drought and *Xylella fastidiosa*, which is also the causative pathogen of Pierce’s disease in cultivated grape (Hopkins & Purcell 2002). However, attempts to screen samples from western Washington for *X. fastidiosa* DNA have been inconclusive (CFPC 2016).

Another potential cause of forest decline is climate change. Climate change has been implicated in causing increased incidence of mortality and disease, and reduced growth rates in forests (Allen *et al*. 2010; Sturrock *et al* 2011), as well as being the primary causative agent in the decline of several specific tree species (Beier *et al*. 2008; Cook & Johnson 1987; Sanchez *et al*. 2011). Washington is projected to become significantly warmer with more summer droughts in the future. On average, Washington is projected to be 1.8°C warmer by the 2040s and 3.0°C warmer by the 2080s, compared to 1970-1999, with wetter autumns and winters, and a slight increase in overall precipitation (Adair & Reeder 2009). However, summer precipitation is expected to decrease by 22% compared to historical levels, increasing drought risks for the region (Mauger *et al*. 2015). Insect outbreaks and forest disease dynamics in the Pacific Northwest are expected to change for many species as well (Stone *et al*. 2008; Sturrock *et al*. 2011; Thomson *et al*. 1984), which could facilitate disease outbreaks, reduce overall fitness, and potentially cause the decline of some tree species.

Dendrochronology has been used to investigate the link between climate history and tree growth (Briffa *et al*. 2002; Cook *et al*. 1999; Fritts & Shao 1992). Tree growth is a function of tree size, genetics, and environmental conditions. These environmental conditions can include precipitation, temperature, soil nutrients, herbivory, disease, and levels of sunlight (Schweingruber 1996). By detrending tree growth over time, it is possible to account for the growth patterns of individual trees (e.g., initial rapid growth and decreasing ring-width with age) and isolate the role that external, environmental factors play in annual tree growth (Biondi & Qeadan 2008). By averaging the annual growth of a suitable sample size of trees, it is possible to account for localized events, such as forest gaps that open or individual tree injury. After accounting for localized events, it is then possible to quantify the effects of landscape-level factors on tree growth patterns (Duchesne *et al*. 2017; Speer 2010). Climate is often one of the most influential factors affecting tree growth, causing the highest amount of variability in ring width from year to year (Fritts 1976; Oberhuber & Kofler 2000). In sites where climate limits growth, it is possible to construct past climate growth relationships, and to use this as a proxy to determine the effect that climatic variables, such as precipitation, growing season length, and seasonal temperature, have on tree growth (Fritts & Swetnam 1989; Grudd *et al*. 2002). By linking past climatic records with tree growth, and extrapolating into the future using climate predictions, it is possible to estimate the current and future climate change effects on tree growth, (Allen & Breshears 1998; Theurillat & Guisan 2001), and whether the effects that trees are experiencing now can be linked to a change in climate (Jump *et al*. 2006).

By examining declining trees and determining the original year that reduced-growth was recorded, it is also possible to estimate the beginning of the decline in that tree (Siegert *et al*. 2014; Swetnam & Lynch 1993; Welsh *et al*. 1992). By examining the local spatial dynamics of a decline in a tree species, it could be possible to determine whether the pattern of decline matches the pattern of a biotic agent, or other localized cause of decline, moving across a landscape. In contrast, the lack of a localized spatial structure to the decline could indicate regional weather patterns or region-scale disturbance events. Researchers have also been able to determine whether a declining tree species is experiencing a species-specific disturbance event, such as a species-unique pathogen or climate response, or a more general disturbance agent, such as drought or reduced growing season, by comparing the target species growth against nearby trees of a different species (Desplanque *et al*. 1999; Rubino & McCarthyz 2004).

In this chapter, I use three dendrochronological methods to (1) compare climate records to the ring widths of *A. macrophyllum* to construct climate growth relationships, and use those relate recent weather events and the reported decline in *A. macrophyllum*; (2) use tree ring width records of healthy and declining *A. macrophyllum* to reconstruct the spatio-temporal patterns of the reported decline; and (3) compare the ring widths of *A. macrophyllum* to nearby coniferous trees to determine to what extent the reported decline is species-specific.

3.3 MATERIALS AND METHODS

Sampling Locations and Sampling Schedule

The WA DNR surveyed 63 roadside sites in 2014-2015 at which symptoms of *A. macrophyllum* decline were observed; 15 of these sites were randomly selected for inclusion in this study, and sites were selected within 10 regional subdivisions of western Washington (1 or 2 sites per regional subdivision; Fig. 2.1). Because DNR sites were purposively selected due to the presence of symptoms of decline, it was important to select additional sites at random. Thus, 59 sites on public land were randomly selected from areas known to contain *A. macrophyllum*. In addition, 7 sites were located on private land (these landowners have contacted me or the WA DNR and volunteered to take part in the study). Lastly, 36 roadside partial sites were purposively selected based on the presence of decline. All study sites are located within western Washington and within the range of *A. macrophyllum*, based on distributional data from the USDA Forest Service Forest Inventory Analysis (Fig. 2.2). Of the 59 Randomized sites, 17 sites were within the Mount Baker-Snoqualmie National Forest, 7 sites within the Gifford-Pinchot National Forest, 7 sites within the Olympic National Forest, 6 sites within Olympic National Park, 1 site within North Cascades National Park, 3 sites within Columbia River Gorge National Scenic Area, 7 sites within King County i-90 Corridor lands, 3 Sites within the Washington Park Arboretum, and 8 sites within the Cedar River Municipal Watershed.

Description of Study Sites

At each of the 15 resampled DNR sites, sampling was conducted in three, 40.47 m2 (10th acre), circular plots. One plot was centered on the previously tagged *A. macrophyllum*, which was sampled by DNR in 2014-15. If the tagged tree could not be located, the largest diameter stem of *A. macrophyllum* within 30 meters of the georeferenced location of the tagged tree was selected. Up to two additional plots, treated as additional replicates, were placed ~500 meters away from the center plot in opposite directions along the road. The center location of these two additional plots were determined by choosing the largest diameter stem of *A. macrophyllum* within a radius of 30 meters, centered around the point on the road 500 meters from the center plot. In cases where the road did not extend to 500 m, the plot was located at the end of the road centered on the largest diameter stem of *A. macrophyllum*. If there was no *A. macrophyllum* in one direction of the center plot, the additional plot was not taken.

At each of the 59 randomized sites on public land, sampling was conducted at one, 40.47 m^2 (10th acre), circular plot, centered on a target tree. Target trees were chosen by selecting the largest diameter stem of *A. macrophyllum* within 30 meters of a randomly generated spatial location, located within sites known to contain *A. macrophyllum*. These sites were chosen by contacting land managers at the responsible state or Federal agencies. Furthermore, all randomly selected sites were within 200 meters of a road or trail for ease-of-access purposes. If the randomly generated spatial location was inaccessible or had no *A. macrophyllum* within 30 meters of it, another randomly generated spatial location was chosen. At each of the 7 landowner plots, there was one 40.47 m^2 (10th acre), circular plot, centered on a *A. macrophyllum* with symptoms of *A. macrophyllum* decline.

The 36 roadside partial sites consisted of only a single *A. macrophyllum*. Criteria for selecting a roadside partial site included visible symptoms of *A. macrophyllum* decline and an accessible location. *Acer macrophyllum* trees were designated as declining if they have higher than nominal levels of dieback, thinning, discoloration, or reduced leaf size. All sites were sampled between 13 June 2017, and 8 September 2017, which was after *A. macrophyllum* budbreak and before leaf senescence in all study locations (Campbell & Franklin 1979).

Study Site Measurements

In each 40.47 m^2 (10th acre) plot, up to three *A. macrophyllum* and three coniferous stems were cored using a 61 cm long, 5.15mm wide, Haglöf increment borer (Forestry Suppliers, Jackson, MS). No trees were cored if they were <5cm DBH (diameter at breast height). In each plot, three *A. macrophyllum* with largest-diameter stems were chosen, as well as the three conifers with the largest-diameter stems. In trees with multiple stems, only the largest stem was selected to be cored. All tagged *A. macrophyllum* from the initial DNR survey, when located, were cored. An additional two *A. macrophyllum* stems were also cored from each plot, and when possible, one healthy and declining tree was cored. Of the conifers, *Pseudotsuga menziesii* was given first preference, but other conifer species were selected if less than three *P. menziesii* were present. If three *A. macrophyllum* or three conifers that met these criteria were not present within the plot, as many acceptable trees as possible were cored. In total, across 59 Random sites, 40 DNR sites, and 7 Landowner sites, 232 *A. macrophyllum*, 9 *Picea sitchensis*, 106 *P. menziesii*, 69 *Tsuga heterophylla*, and 47 *Thuja plicata* trees were cored. An additional 37 *A. macrophyllum* were cored in Roadside sites, and at these plots the largest stem *A. macrophyllum* was cored. Each selected stem was cored twice, on opposite sides of the stem, both perpendicular to the direction of the slope (Stokes & Smiley 1968). Cores extended to the pith of the tree, or up to 46 cm, whichever was shorter. If the core passed near the pith, but did not directly intercept it, it was still accepted. For each cored tree the following metrics were recorded: species, which multi-stemmed tree it is a part of (if applicable), DBH, mortality class (Bradford et al. 1996), and dominance class (Nyland 2016). For each cored *A. macrophyllum* tree in the plot, the following variables were recorded: regeneration (sprouting from the base of the tree), presence of epicormic branching, presence of visible disease (e.g., heart-rot discovered after coring), presence of insect herbivores, approximate density of per leaf, and (if the tree was declining) whether *Armillaria* spp. were present at the base of the tree. Symptoms of decline, including extent of crown dieback, extent and severity of thinning, extent and severity of discoloration, extent and severity of reduced leaf size, were recorded on a 1-100% scale for extent and 1-5 scale for severity.

After collection, cores were air dried at room temperature, mounted on wooden runners, and sanded, using 80, 150, and 300 grit sandpaper, until rings were visible. Cores were digitally scanned at 1200 dpi, and the annual tree ring widths, with early wood and late wood differentiated, were measured, using the CooRecorder and CDendro software (Cybis Elektronik 2017).

Analysis

Core measurements were crossdated using COFECHA (Holmes 1983), with cores visually checked and edited to fix missing and duplicate rings. Cores from trees with <50 years were omitted to provide an adequate sample depth of core measurements. Furthermore, since two cores were extracted from each tree, the core with the least correlation to the series was discarded. A summary of dendrochronological characteristics for the full core depth is presented in Table 3.1, the 50-most-recent-year truncated core depth is presented in Table 3.2 . A total of 177 *A. macrophyllum* and 82 *P. menziesii* trees were recorded.

Ring measurements were detrended using a negative exponential model of biological growth according to:

$$f(t) = a\ exp(^{bt}) + k\ , \qquad \text{(Eq. 1)}$$

where y is radial increment, t is cambial age, and a, b, and k are fitted parameters (Fritts 1976), using the dplR package (Bunn 2008) in R (R Core Team 2018). Ring widths were then normalized by subtracting the mean and dividing by the standard deviation (Pedersen 1998; Bigler & Bugmann 2003).

An experimental response function analysis, similar to previous research (Fritts 2001; Briffa & Cook 1990) but with several key differences, was performed to quantify growth responses of *A. macrophyllum* and *P. menziesii* due to climate. For each site, precipitation, mean temperature, minimum temperature, maximum temperature, and maximum vapor pressure deficit, in monthly increments from January 1981 to July 2017, were obtained from the PRISM Climate Group (PRISM Climate Group 2017). Each weather variable was normalized by subtracting the mean and dividing by the standard deviation, for each site. (Fritts et al. 1971) citation May-August were treated as that year’s growing season, the September-April preceding the growing season were treated as that year’s dormant season (Campbell & Franklin 1979). For each individual tree, ring widths for each year within the timeframe (1981-2016) were compared with monthly values of that years’ growing season, and the values of the dormant season preceding it, for all five climate variables, using a basic bootstrapping regression model with 1000 replications (Fritts et al. 1990, Efron 1979, Guiot 1991). 95% confidence intervals for each monthly climate variable's correlation coefficient was constructed based on the totality of each species' ring widths. Thus, each individual ring in each tree was treated as a unique sample units. Correlation coefficients that were estimated with 95% confidence, and correlation coefficient error bars entirely above or below zero were treated as significantly positive or negative relationships.

In addition to this, the total number and percentage of individual *A. macrophyllum* and *P. menziesii* whose ring widths were positively and negatively associated, at 95% confidence, with temperature, precipitation, and vapor pressure deficit, for all twelve months, was calculated using a basic bootstrapping function with 1000 replications. Thus, instead of treating all ring widths of a species as a common pool, each tree was treated as an individual pool and whether or not that specific tree was correlated with a monthly weather variable was indicated as either yes or no, and if yes, whether the relationship was positive or negative. Monthly weather variables with at least 10% difference between proportions of positively and negatively associated trees were selected (i.e., 15 positive associations and 4 negative associations would pass this test). Then, climate variables with relationships that agreed for both methods, the bootstrapping of all rings and the bootstrapping of each tree individually, (i.e., positive for both), were identified.

The most recent year of above-average-growth for each tree was estimated by determining the last year when growth exceeded the tree's negative exponential model. This most recent year of above-average-growth was then used as a proxy to determine the beginning of decline in *A. macrophyllum*. It is important to note that the most recent year of above-average-growth does not, in and of itself, indicate decline in a tree's health. However, for comparative purposes, if two populations of trees with declining health had differing average years of above-average-growth, it should theoretically be possible to determine that one population began declining in health before the other. Thus, using this information, the temporal process of decline in *A. macrophyllum* was reconstruction, and an attempt was made to locate an epicenter of the decline in (Siegert et al. 2014), to determine whether decline in *A. macrophyllum* fits a biotic or abiotic pattern of incidence. A spatial autocorrelation was constructed to describe the degree of spatial dependence of a spatial random field (Reams 1989), in this case the year of above-average-growth for both *A. macrophyllum*.

Ring measurements, after being detrended with a negative exponential model (Eq. 1) and normalized, were used to determine whether growth rates of *A. macrophyllum* were reduced compared to the *P. menziesii* sampled across the study area. Differences in yearly ring width for each species were averaged across all recorded trees, for the period of 1967 to 2016, to identify any divergences in growth rates. Variance in ring widths, across all trees of the same species, for each year, was calculated for *A. macrophyllum* and *P. menziesii*, to determine if variability in growth differed amongst species across time.

All statistical analyses were conducted using R (R Core Team 2018).

3.4 RESULTS

Significant relationships between *A. macrophyllum* and *P. menziesii* ring widths and several climate variables were observed using the whole-population-pool bootsrapping (Table 3.3; Table 3.5; Fig. 3.1; Fig. 3.2; Fig. 3.3; Fig. 3.4; Fig. 3.5; Fig. 3.6; Fig. 3.7; Fig. 3.8; Fig. 3.9;

Fig. 3.10). These included positive associations between *A. macrophyllum* ring widths and maximum temperature in September, December, and April, mean temperature in September and December, precipitation in December, January, February, June, and July, and maximum vapor pressure deficit in September. Negative associations between *A. macrophyllum* ring widths and maximum temperature in October, January, February, June, July, and August, minimum temperature in October, February, May, April, March, June, July, and August, mean temperature in October, January, February, May, June, and August, precipitation in September and March, and maximum vapor pressure deficit in November, January, June, July, and August were also evident. *Pseudotsuga menziesii* was positively associated with maximum temperature in September, November, and December, minimum temperature in November, mean temperature in September and December, precipitation in January, June, and July, and maximum vapor pressure deficit in September and December, while it was negatively associated with maximum temperature in April, May, June, July, and August, minimum temperature in October, March, April, May, and June, mean temperature in May, June, July, and August, precipitation in September, and maximum vapor pressure deficit in April, June, July, and August.

However did not seem to be consistent agreement between the significant climate variable correlation coefficients and the proportion of individual trees significantly correlated with climate variables (Table 3.4; Table 3.6; Table 3.7; Fig. 3.1; Fig. 3.2; Fig. 3.3; Fig. 3.4; Fig. 3.5; Fig. 3.6; Fig. 3.7; Fig. 3.8; Fig. 3.9; Fig. 3.10). Only negative correlations between *A. macrophyllum* ring widths and March, February, April, and June minimum temperature, between *P. menziesii* June minimum temperature, and between *P. menziesii* April vapor pressure deficit, were in agreeance between the two methods.

Differences in detrended and normalized ring width between *P. menziesii* and *A. macrophyllum* varied during the last fifty years (Fig. 3.11), with some years favoring *P. menziesii* growth, and some favoring *A. macrophyllum* growth. Variation in ring widths of *A. macrophyllum* was consistently higher than variation in ring widths of *P. menziesii* over the last 100 years (Fig. 3.12), with a recent increase in the variation of both *A. macrophyllum* and *P. menziesii*, that still maintains the higher *A. macrophyllum* relationship.

3.5 DISCUSSION

The growth responses of *A. macrophyllum* to climate (Table 3.3; Fig. 3.1; Fig. 3.2; Fig. 3.3; Fig. 3.4; Fig. 3.5) shows several patterns. Summer mean, minimum, and maximum temperatures were negatively correlated with ring width, indicating that *A. macrophyllum* grows more in years with cooler summers. There seemed to be some positive correlations between *A. macrophyllum* growth and months in the very beginning and end of the growing season, such as March and September. This could potentially be a response to higher temperatures increasing metabolic processes, thawed snowpack producing more available soil moisture, or correlation between higher temperatures and clearer skies with more available sunlight. Likewise, summer precipitation was positively correlated with ring width, and summer maximum vapor pressure deficit was negatively correlated with ring width. March and September precipitation was negatively correlated with ring width in *A. macrophyllum*. Combined with the temperature results, this seems to show that *A. macrophyllum* prefers cooler, moister summers. Additionally, hot, dry summers, and summer-drought events negatively affecting the health and vigor of *A. macrophyllum*. *Pseudotsuga menziesii* growth also showed several significant relationships to climate variables (Table 3.5; Table 3.6; Fig. 3.5; Fig. 3.6; Fig. 3.7; Fig. 3.8; Fig. 3.9; Fig. 3.10) and had wider ring widths in years with lower summer mean, minimum, and maximum temperatures, higher with summer precipitation, and lower maximum vapor pressure deficits. Like *A. macrophyllum, P. menziesii* seemed to prefer warmer and drier autumns and dormant seasons, except for a positive correlation between ring width and January precipitation. This could, potentially, be related to increased growth in years with higher snowpack and subsequently more soil moisture available in the following spring and summer.

However, the lack of consistent agreement between the significant climate variable correlation coefficients and the proportion of individual trees significantly correlated with climate variables, could either be due to statistical limitations of examining single trees compared to looking at region-scale climate responses, or that the processes of measuring climate variable correlation coefficients from a pool of ring widths tied to geographically unique climate records may mask the underlying local relationships. However, past research has highlighted the relationship between summer drought and *A. macrophyllum* and *P. menziesii* growth (Hermann & Lavendar 1990; Minore & Zasada 1990). In addition, I considered the relationship for all individual trees, regardless of their location, and future studies could examine these correlations along significantly important landscape characteristics, such as distance to road (Fig. 2.9) and fraction of forested or developed land cover (Fig. 2.10).

The correlogram sites for *A. macrophyllum* (Fig. 3.13), do show an increase in correlation at closer distances, indicating a local-scale positive spatial correlation of the most recent year of above-average-growth, which is acting as a proxy for date of decline. However, no significant correlation is evident at larger (10+ km) scales, nor is any spatio-temporal pattern of decline visually evident when mapped across Washington State (Fig. 3.14). Importantly, *A.*

macrophyllum does not show the recognizable inverse curve characteristic of pathogen or disease introductions (Rouvinen et al. 2003).

There seemed to be a high amount of variability between higher and lower relative ring width to each species' detrended and normalized growth curves, which is logical given that detrending forces the detrended growth curves together for *A. macrophyllum* and *P. menziesii* (Fig. 3.11). Comparisons of the relative growth of the two species, and the recent divergence of detrended growth rates of *A. macrophyllum* and *P. menziesii* indicate higher variance in ring widths of one or both the two species in recent years. Although the differences in growth between these two species appears to be within the historical variation of differences and is challenging to draw conclusive inferences from, the recent trend towards comparatively reduced *A. macrophyllum* growth agree with reports of recent declines in *A. macrophyllum* health. There was an increase in variation among ring widths of different *A. macrophyllum* individuals in recent years (Fig. 3.12). This could be due to an increase in individual *A. macrophyllum* experiencing decline, which could increase the overall variability.

Recent changes in the weather patterns, including the 2014-15 drought in the Pacific Northwest (Blunden & Arndt 2016), have had dramatic effects on forest disturbances (McKenzie et al. 2008), tree growth (Loehle & LeBlanc 1996), and community distribution (Iverson & Prasad 2001). Climate change with have wide-reaching and significant impacts on forests in Washington. This will result in community structure, species distribution, and range shifts of tree species. *A. macrophyllum* appears to be experiencing negative outcomes, due to climate, based on summer weather events in recent years. Increases in summertime temperatures, vapor pressure deficits, and drought (Fig. 2.7; Fig. 2.8), combined with climate responses to those factors (Table 3.3; Table 3.4; Fig. 3.1; Fig. 3.2; Fig. 3.3; Fig. 3.4; Fig. 3.5) predict reductions in growth, and likely reduced vigor and increased mortality (Bigler & Bugmann 2003).

Based upon modeling work that combined climate projections with current species range limits, future climate conditions are forecasted to be more favorable to *Acer macrophyllum* than the majority of other species (Case & Lawler 2016; Crookston *et al*. 2010). Although such modeling projections are useful in prioritizing forest management decisions in response to climate change, these projections do not always consider the intricacies that are specific to a single species, such as local scale genetic structure of populations and population-level responses to climate (Bridle & Vines 2007). Moreover, attempts to link climate change with other anthropogenically-derived stresses, such as increased urbanization and pollution, in *A. macrophyllum* are lacking. The results of this study suggest a potential climatic factor responsible for the decline of *A. macrophyllum* in western Washington that could be exacerbated by other biotic and abiotic stresses present in the environment.

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TABLES

Table 2.1 Percent of *A. macrophyllum* decline and percentage of declining trees experiencing specific decline conditions by site type. Data recorded from the initial DNR survey in 2014 are not included.

Site Type	Percent in Decline	Crown Dieback	Thinning	Discoloration	Reduced Leaf Size
Random	29/132 (22%)	37.04%	70.37%	62.96%	59.26%
DNR	56/132 (42%)	32.20%	33.90%	47.46%	20.34%
Landowner	9/24 (38%)	11.11%	44.44%	44.44%	11.11%

Table 2.2 Significant predictor variables of *A. macrophyllum* decline as identified by general linear regression model. A binary response of individual *A. macrophyllum* as sample units (Tree Declining), as well as a continuous response of individual *A. macrophyllum* as sample units (Tree Severity) were both calculated for comparison. Only Random sites used for analysis.

	Tree Declining			Tree Severity		
Predictor Variable	Parameter Estimates	Z Value	P Values	Parameter Estimates	T Value	P Values
2015-17 Summer Mean Monthly Maximum Temperature (C)	0.477	3.255	**0.001**	0.002	2.215	**0.028**
2015-17 Summer Mean Temperature (C)	0.548	3.01	**0.003**	0.003	2.017	**0.045**
2015-17 Summer Mean Monthly Precipitation (cm)	-0.046	-1.847	0.065	>-0.001	-2.09	**0.038**
2015-17 Summer Mean Monthly Maximum Vapor Pressure Deficit (kPa)	0.171	2.558	**0.011**	0.001	2.233	**0.027**
Elevation (m)	-0.002	-2.134	**0.033**	>-0.001	-0.331	0.741
Slope (degrees)	0.053	3.143	**0.002**	<0.001	3.416	**<0.001**
Proximity to Any Road (m)	>-0.001	-2.498	**0.014**	>-0.001	-1.853	0.066
Proximity to Any Paved Road (m)	>-0.001	-2.358	**0.018**	>-0.001	-1.825	**0.07**
UTM Northing	>-0.001	-3.035	**0.002**	>-0.001	-2.528	**0.012**
Fraction/Forest Herbaceous	-4.344	-3.932	**<0.001**	-0.035	-3.917	**<0.001**
Fraction Developed	3.885	3.689	**<0.001**	0.037	4.019	**<0.001**

Table 2.3 Significant predictor variables of *A. macrophyllum* decline as identified by general linear regression model. A binary response site averages as sample units (Site Declining), as well as a continuous response of site averages as sample units (Site Severity) were both calculated for comparison. Only Random sites used for analysis. Predictor variables significant in relation to one response variable shown for all, for comparative purposes.

	Site Declining			Site Severity		
Predictor Variable	Parameter Estimates	Z Value	P Values	Parameter Estimates	T Value	P Values
2015-17 Summer Mean Monthly Maximum Temperature (C)	0.695	2.652	**0.008**	0.003	1.388	0.171
2015-17 Summer Mean Temperature (C)	0.762	2.603	**0.009**	0.003	1.167	0.248
2015-17 Summer Mean Monthly Precipitation (cm)	-0.063	-1.845	0.065	>-0.001	-1.667	0.101
2015-17 Summer Mean Monthly Maximum Vapor Pressure Deficit (kPa)	0.203	1.916	0.055	0.002	1.708	0.093
Elevation (m)	-0.003	-1.826	0.068	<0.001	0.204	0.839
Slope (degrees)	0.028	1.189	0.234	<0.001	2.624	**0.011**
Proximity to Any Road (m)	-0.004	-1.164	0.245	>-0.001	-1.232	0.223
Proximity to Any Paved Road (m)	>-0.001	-2.169	**0.03**	>-0.001	-1.431	0.157
UTM Northing	>-0.001	-2.486	**0.013**	>-0.001	-1.890	0.064
Fraction/Forest Herbaceous	-8.276	-2.47	**0.014**	-0.036	-2.007	**0.049**
Fraction Developed	9.202	2.204	**0.028**	0.041	2.251	**0.028**

Table 2.4 Soil elemental concentrations as predictor variables of *A. macrophyllum* decline as identified by the mixed stepwise logistic regression model, with only elements showing a significant relationship. A binary response of individual *A. macrophyllum* as sample units (Tree Declining), as well as a continuous response of individual *A. macrophyllum* as sample units (Tree Severity) were both calculated for comparison. Only Random sites used for analysis.

Tree Declining	Tree Severity

Element	Parameter Estimates	AIC	P Values	Parameter Estimates	AIC	P Values
Ag				0.001	-1254.8	0.047
As	0.483	146.31	<0.001			
B	-0.016	138.42	0.032			
Ba	0.044	143.17	0.002			
Cd	-1.324	145.58	0.001	-0.004	-1250.5	0.004
Cu				<0.001	-1253.7	0.024
Mn	-0.022	165.03	<0.001	>-0.001	-1251.3	0.006
Mo	-1.509	149.21	<0.001			
Ni	0.173	139.76	0.015	0.001	-1253.7	0.024
P	0.003	143.36	0.002	<0.001	-1245.2	<0.001
S	-0.003	138.02	0.041	>-0.001	-1254.4	0.037
Zn	-0.116	146.26	<0.001	>-0.001	-1253	0.016

Table 2.5 Soil elemental concentrations as predictor variables of *A. macrophyllum* decline as identified by the mixed stepwise logistic regression model, with only elements showing a significant relationship. A binary response of site averages as sample units (Site Declining), as well as a continuous response of site averages as sample units (Site Severity) were both calculated for comparison. Only Random sites used for analysis.

	Site Declining			Site Severity		
Element	Parameter Estimates	AIC	P Values	Parameter Estimates	AIC	P Values
Ag	0.225	69.154	0.048			
Cd				-0.004	-453.37	0.035
K				>-0.001	-452.28	0.018
Mg				<0.001	-449.69	0.004
Mn	-0.005	72.496	0.007	>-0.001	-451.41	0.011
Mo	-0.516	70.302	0.024			
P	0.002	71.446	0.013	<0.001	-447.99	0.002
S	-0.005	70.182	0.026			
Se	0.078	70.347	0.024			
Zn				-0.001	-449.79	0.005

Table 2.6 Foliar elemental concentrations as predictor variables of *A. macrophyllum* decline as identified by the mixed stepwise logistic regression model, with only elements showing a significant relationship. A binary response of individual *A. macrophyllum* as sample units (Tree Declining), as well as a continuous response of individual *A. macrophyllum* (Tree Severity) were both calculated for comparison. Only Random sites used for analysis.

	Tree Declining			Tree Severity		
Element	Parameter Estimates	AIC	P Values	Parameter Estimates	AIC	P Values
Al	0.001	57.11	0.042			
As	-0.357	66.955	<0.001			
B	-0.018	69.928	<0.001	>-0.001	-589.94	0.013
Si	0.007	75.36	<0.001	<0.001	-585.88	0.001

Table 2.7 Elemental concentrations in soil (μ/g) per type of site (Random, DNR, and Landowner)

Element	Random		DNR		Landowner	
	Average Concentration (μ/g)	Standard Deviation	Average Concentration (μ/g)	Standard Deviation	Average Concentration (μ/g)	Standard Deviation
Ag	0.63	3.05	0.41	2.24	0	0
Al	21517.75	10357.9	22448.24	11661.1	28168.64	12873.74
As	106.09	44.69	119.33	49.25	139.86	31.87
B	246.58	56.59	258.61	34.59	268.39	31.42
Ba	90.19	64.86	99.91	65.03	143.48	79.55
C	79529.15	40325.97	67183.57	36687.28	71208.33	41588.19
Ca	5822.15	4099.21	5215.58	3550.12	6139.38	3903.99
Cd	1.38	2.11	2.1	2.36	2.15	2.37
Cr	24.6	15.46	31.05	17.25	45.17	8.55
Cu	31.72	27.09	38.18	20.89	33.48	9.72
Fe	19038.43	8563.9	21989.89	7671.58	25814.75	3192.74
K	783.16	1632.75	724.13	469.39	650.98	301.03
Mg	4408.41	2763.91	5637.73	2754.03	5822.62	2192.71
Mn	648.44	394.28	699.99	462.05	861.52	383.41
Mo	34.08	14.68	37.71	16.6	45.25	13.5
N	4200.17	3587.14	3332.38	1459.56	3690	1829.17
Na	643.66	255.13	653.16	168	692.45	158.42
Ni	32.19	16.13	40.79	18.59	63.13	23.21
P	1014.45	675.97	984.22	495.46	1333.86	555.68
Pb	0	0	0	0	0	0
S	477.91	405.65	427.24	166.72	469.38	116.14
Se	258.14	108.35	291.44	125.47	345.62	95.74
Si	1175.16	347.37	1256.33	232.7	1313.12	130.7
Zn	58.73	25.63	68.82	28.23	76.19	14.32

Table 2.8 Elemental concentrations in foliage (μ/g) per type of site (Random, DNR, and Landowner)

Element	Random		DNR		Landowner	
	Average Concentration (μ/g)	Standard Deviation	Average Concentration (μ/g)	Standard Deviation	Average Concentration (μ/g)	Standard Deviation
Ag	0.07	0.66	0.25	1.51	0	0
Al	8278.17	8433.96	6255.8	7426.52	9731.89	7962.06
As	35.46	22.07	31.84	22	39.93	20.9
B	233.94	45.94	237.12	47.31	264.01	35.33
Ba	57.62	37.22	45.78	50.15	52.25	36.24
C	455857.88	12145.63	454289.36	15354.33	479844	71945.34
Ca	13938.25	4488.53	13443.6	6034.26	18240.2	4290.65
Cd	0	0	0	0	0	0
Cr	0.4	3.65	0	0	1.01	3.91
Cu	10.43	2.92	9.51	4.94	9.33	1.36
Fe	414.57	1563.69	427.76	1584.92	173.4	59.38
K	12999.41	4179.9	12562.01	5871.22	10284.28	2925.22
Mg	3044.12	695.11	3043.28	1172.1	3548.52	1191
Mn	237.37	192.81	174.59	113.25	170.29	73.21
Mo	9.79	10.38	7.52	9.42	12.31	9.43
N	32041.76	5970.51	29850.38	6653.35	27840	5238.11
Na	651.43	144.25	635.24	170.45	760.69	177.68
Ni	5.53	5.23	4.74	2.57	5.51	2.7
P	3134.87	1267.51	2744.83	1318.9	2552.78	855.95
Pb	0	0	0	0	0	0
S	2141.54	565.77	1996.57	644.49	1914.02	388.14
Se	53.46	72.87	38.31	64.11	73.63	62.97
Si	813.89	206.26	812.58	257.89	975.85	270.34
Zn	54.36	45.84	42.9	28.54	41.02	16.78

Table 3.1 Dendrochronological characteristics of chronologies developed from two species of trees analyzed, *Acer macrophyllum* (ACMA), *Pseudotsuga menziesii* (PSME), with the full record of cores shown. Series represents individual trees, using the best fitting of two cores taken.

Species	ACMA	PSME
Series (number)	173	82
Chronology range (years)	1821-2016	1712-2016
Chronology length (years)	196	305
Series intercorrelation	.260	.316
Average mean sensitivity	.325	.218
Mean length of series (years)	73.9	80.9

Table 3.2 Dendrochronological characteristics of chronologies developed from two species of trees analyzed, *Acer macrophyllum* (ACMA), *Pseudotsuga menziesii* (PSME), with all tree rings truncated to 50 years, which was the period used for all analyses. Series represents individual trees, using the best fitting of two cores taken.

Species	ACMA	PSME
Series (number)	173	82
Chronology range (years)	1949-2016	1952-2016
Chronology length (years)	68	65
Series intercorrelation	.310	.361
Average mean sensitivity	.337	.226
Mean length of series (years)	50.0	50.0

Table 3.3 Correlation coefficients for temperature, precipitation, and vapor pressure deficit, for all twelve months, as a predictor of ring widths of *A. macrophyllum*. September-December were associated with the following year's growing season. Lower and upper estimates of response coefficients listed, with 95% confidence of either wholly positive or negative relationships indicated with sign of relationship. Response coefficients were calculated using a basic bootstrapping function with 1000 replications.

Variable	Month	Lower Estimate	Upper Estimate	Significant Relationship
Maximum Temperature	September	0.133611	0.263058	+
	October	-0.14365	-0.001	-
	November	-0.03103	0.099171	
	December	0.114415	0.254773	+
	January	-0.26022	-0.11034	-
	March	-0.14958	-0.01952	-
	February	-0.06067	0.079412	
	April	0.007285	0.155471	+
	May	-0.12085	0.022479	
	June	-0.17092	-0.04403	-
	July	-0.1121	-0.00485	-
	August	-0.2246	-0.04575	-
Minimum Temperature	September	-0.05924	0.063733	
	October	-0.29314	-0.17713	-
	November	-0.05551	0.022244	
	December	-0.05845	0.024595	
	January	-0.07206	0.023073	
	March	-0.13044	-0.05235	-
	February	-0.27348	-0.15629	-
	April	-0.36412	-0.23339	-
	May	-0.21416	-0.07155	-
	June	-0.3303	-0.17804	-
	July	-0.25867	-0.11316	-
	August	-0.22061	-0.06749	-
Mean Temperature	September	0.083826	0.228219	+
	October	-0.23686	-0.08058	-
	November	-0.03205	0.069092	
	December	0.080902	0.191476	+
	January	-0.16512	-0.03687	-
	March	-0.14436	-0.03456	-
	February	-0.12553	0.012821	
	April	-0.0616	0.09573	
	May	-0.15446	-0.00647	-

	June	-0.21939	-0.06657	-
	July	-0.13621	0.000662	
	August	-0.28662	-0.08753	-
Precipitation	September	-0.0845	-0.01048	-
	October	-0.0033	0.038867	
	November	-0.02479	0.003156	
	December	0.004353	0.046403	+
	January	0.020247	0.060339	+
	March	0.002457	0.046503	+
	February	-0.08078	-0.0262	-
	April	-0.05083	0.022649	
	May	-0.00467	0.072394	
	June	0.081504	0.178644	+
	July	0.024364	0.11943	+
	August	-0.02737	0.063755	
Maximum Vapor Pressure Deficit	September	0.031073	0.096436	+
	October	-0.05003	0.052848	
	November	-0.28808	-0.04921	-
	December	-0.14728	0.204272	
	January	-0.52814	-0.26537	-
	March	-0.19387	0.009285	
	February	-0.02053	0.14722	
	April	-0.03095	0.094005	
	May	-0.06407	0.023638	
	June	-0.10746	-0.03889	-
	July	-0.06982	-0.01998	-
	August	-0.12995	-0.05906	-

Table 3.4 Number and percentage of individual *A. macrophyllum* whose ring widths are positively and negatively associated (at 95% confidence) with temperature, precipitation, and vapor pressure deficit, for all twelve months, as a predictor of ring widths of *A. macrophyllum*. Monthly weather variables with at least 10% difference between proportion of positively and negatively associated trees indicated with sign of relationship. September-December were associated with the following year's growing season. Results were calculated using a basic bootstrapping function with 1000 replications.

Variable	Month	Total Positively Associated Trees	Total Negatively Associated Trees	Percentage of Total Trees Positively Associated	Percentage of Total Trees Negatively Associated	10% Difference Between Proportions
Maximum Temperature	September	0	18	0%	11%	-
	October	0	7	0%	4%	
	November	7	11	4%	7%	
	December	7	10	4%	6%	
	January	4	7	2%	4%	
	March	3	16	2%	10%	
	February	1	4	1%	2%	
	April	3	11	2%	7%	
	May	14	4	8%	2%	
	June	10	3	6%	2%	
	July	3	3	2%	2%	
	August	18	1	11%	1%	+
Minimum Temperature	September	2	7	1%	4%	
	October	1	16	1%	10%	
	November	1	22	1%	13%	-
	December	2	30	1%	18%	-
	January	5	21	3%	13%	-
	March	4	28	2%	17%	-
	February	6	29	4%	17%	-
	April	12	36	7%	22%	-
	May	17	23	10%	14%	
	June	6	39	4%	23%	-
	July	4	5	2%	3%	
	August	8	13	5%	8%	
Mean Temperature	September	0	9	0%	5%	
	October	0	7	0%	4%	
	November	3	7	2%	4%	
	December	8	10	5%	6%	
	January	3	11	2%	7%	

	March	4	11	2%	7%	
	February	2	9	1%	5%	
	April	3	21	2%	13%	-
	May	10	5	6%	3%	
	June	3	14	2%	8%	
	July	1	3	1%	2%	
	August	18	2	11%	1%	+
Precipitation	September	3	4	2%	2%	
	October	12	2	7%	1%	
	November	4	19	2%	11%	
	December	8	7	5%	4%	
	January	4	1	2%	1%	
	March	9	2	5%	1%	
	February	14	0	8%	0%	
	April	1	2	1%	1%	
	May	5	7	3%	4%	
	June	3	1	2%	1%	
	July	2	1	1%	1%	
	August	12	3	7%	2%	
Maximum Vapor Pressure Deficit	September	5	20	3%	12%	
	October	6	16	4%	10%	
	November	12	11	7%	7%	
	December	4	8	2%	5%	
	January	5	4	3%	2%	
	March	5	14	3%	8%	
	February	0	12	0%	7%	
	April	2	22	1%	13%	-
	May	5	0	3%	0%	
	June	8	2	5%	1%	
	July	5	18	3%	11%	
	August	12	6	7%	4%	

Table 3.5 Correlation coefficients for temperature, precipitation, and vapor pressure deficit, for all twelve months, as a predictor of ring widths of *P. menziesii*. September-December were associated with the following year's growing season. Lower and upper estimates of response coefficients listed, with 95% confidence of either wholly positive or negative relationships indicated with sign of relationship. Response coefficients were calculated using a basic bootstrapping function with 1000 replications.

Variable	Month	Lower Estimate	Upper Estimate	Significant Relationship
Maximum Temperature	September	0.074472	0.227871	+
	October	-0.13729	0.053768	
	November	0.014878	0.156093	+
	December	0.10354	0.283452	+
	January	-0.1019	0.069069	
	March	-0.03725	0.100883	
	February	-0.14857	0.006739	
	April	-0.21045	-0.04273	-
	May	-0.21917	-0.06108	-
	June	-0.29218	-0.15771	-
	July	-0.15324	-0.03586	-
	August	-0.23745	-0.041	-
Minimum Temperature	September	-0.01477	0.124509	
	October	-0.20867	-0.08055	-
	November	0.001227	0.097195	+
	December	-0.08766	0.018645	
	January	-0.07894	0.02962	
	March	-0.0776	0.016246	
	February	-0.24452	-0.0795	-
	April	-0.24811	-0.09545	-
	May	-0.22173	-0.079	-
	June	-0.26368	-0.07449	-
	July	-0.10642	0.073366	
	August	-0.14018	0.017395	
Mean Temperature	September	0.083386	0.243411	+
	October	-0.18447	0.003611	
	November	-0.0006	0.109894	
	December	0.054752	0.189511	+
	January	-0.05678	0.082543	
	March	-0.03694	0.084458	
	February	-0.15228	0.005179	
	April	-0.20523	-0.01013	
	May	-0.2512	-0.086	-

	June	-0.35851	-0.18575	-
	July	-0.18521	-0.03689	-
	August	-0.25331	-0.05226	-
Precipitation	September	-0.09274	-0.01869	-
	October	-0.04252	0.006415	
	November	-0.02165	0.014949	
	December	-0.01456	0.029618	
	January	0.023591	0.06643	+
	March	-0.00726	0.044431	
	February	-0.03393	0.019492	
	April	-0.00194	0.070192	
	May	-0.05544	0.037489	
	June	0.0394	0.13443	+
	July	0.065383	0.178761	+
	August	-0.08046	0.101748	
Maximum Vapor Pressure Deficit	September	0.002861	0.079884	+
	October	-0.01703	0.103542	
	November	-0.05808	0.217222	
	December	0.286294	0.702441	+
	January	-0.0783	0.2253	
	March	-0.02014	0.18718	
	February	-0.11027	0.061274	
	April	-0.18726	-0.06251	-
	May	-0.1095	0.000325	
	June	-0.14977	-0.07653	-
	July	-0.08474	-0.0306	-
	August	-0.10484	-0.03533	-

Table 3.6 Number and percentage of individual *P. menziesii* whose ring widths are positively and negatively associated (at 95% confidence) with temperature, precipitation, and vapor pressure deficit, for all twelve months, as a predictor of ring widths of *P. menziesii*. Monthly weather variables with at least 10% difference between proportion of positively and negatively associated trees indicated with sign of relationship. September-December were associated with the following year's growing season. Results were calculated using a basic bootstrapping function with 1000 replications.

Variable	Month	Total Positively Associated Trees	Total Negatively Associated Trees	Percentage of Total Trees Positively Associated	Percentage of Total Trees Negatively Associated	10% Difference Between Proportions
Maximum Temperature	September	3	2	4%	2%	
	October	1	0	1%	0%	
	November	1	4	1%	5%	
	December	3	7	4%	9%	
	January	2	6	2%	7%	
	March	0	18	0%	22%	-
	February	1	4	1%	5%	
	April	1	6	1%	7%	
	May	10	3	12%	4%	
	June	4	2	5%	2%	
	July	3	1	4%	1%	
	August	9	1	11%	1%	+
Minimum Temperature	September	0	1	0%	1%	
	October	3	4	4%	5%	
	November	0	8	0%	10%	-
	December	0	11	0%	14%	-
	January	2	12	2%	15%	-
	March	1	5	1%	6%	
	February	4	7	5%	9%	
	April	5	8	6%	10%	
	May	6	1	7%	1%	
	June	1	16	1%	20%	-
	July	5	0	6%	0%	
	August	4	8	5%	10%	
Mean Temperature	September	3	0	4%	0%	
	October	1	0	1%	0%	
	November	0	3	0%	4%	
	December	1	6	1%	7%	
	January	1	9	1%	11%	-

	March	0	14	0%	17%	-
	February	1	7	1%	9%	
	April	0	7	0%	9%	
	May	6	1	7%	1%	
	June	3	6	4%	7%	
	July	1	0	1%	0%	
	August	5	1	6%	1%	
Precipitation	September	7	0	9%	0%	
	October	2	2	2%	2%	
	November	3	3	4%	4%	
	December	9	1	11%	1%	+
	January	3	1	4%	1%	
	March	12	0	15%	0%	+
	February	11	1	14%	1%	
	April	3	0	4%	0%	
	May	5	4	6%	5%	
	June	0	1	0%	1%	
	July	0	1	0%	1%	
	August	2	2	2%	2%	
Maximum Vapor Pressure Deficit	September	4	7	5%	9%	
	October	4	1	5%	1%	
	November	2	7	2%	9%	
	December	0	8	0%	10%	-
	January	2	1	2%	1%	
	March	0	15	0%	19%	-
	February	1	8	1%	10%	
	April	2	11	2%	14%	-
	May	8	4	10%	5%	
	June	7	3	9%	4%	
	July	5	2	6%	2%	
	August	6	1	7%	1%	

Table 3.7 Comparison of monthly weather variable correlation coefficients based on all rings with 95% confidence of either wholly positive or negative relationships, and at least 10% difference between proportion of positively and negatively associated individual trees, for both *A. macrophyllum* and *P. menziesii*. Agreements between the two methods shown with boxes. September-December were associated with the following year's growing season. Results were calculated using a basic bootstrapping function with 1000 replications.

		A. macrophyllum		*P. menziesii*	
Variable	Month	Significant Correlation Coefficient	10% Difference Between Proportions	Significant Correlation Coefficient	10% Difference Between Proportions
Maximum Temperature	September	+	-	+	
	October	-			
	November			+	
	December	+		+	
	January	-			
	March	-			-
	February				
	April	+		-	
	May			-	
	June	-		-	
	July	-		-	
	August	-	+	-	+
Minimum Temperature	September				
	October	-		-	
	November		-	+	-
	December		-		-
	January		-		-
	March	-	-		
	February	-	-	-	
	April	-	-	-	
	May	-		-	
	June	-	-	-	-
	July	-			
	August	-			
Mean Temperature	September	+		+	
	October	-			
	November				
	December	+		+	
	January	-			-
	March	-			-

	February				
	April		-		
	May	-		-	
	June	-		-	
	July			-	
	August	-	+	-	
Precipitation	September	-		-	
	October				
	November				
	December	+			+
	January	+		+	
	March	+			+
	February	-			
	April				
	May				
	June	+		+	
	July	+		+	
	August				
Maximum Vapor Pressure Deficit	September	+		+	
	October				
	November	-			
	December			+	-
	January	-			
	March				-
	February				
	April		-	-	-
	May				
	June	-		-	
	July	-		-	
	August	-		-	

FIGURES

Fig. 1.1 Range of bigleaf maple (*Acer macrophyllum* Pursh) in western North America (Little & Vierick 1971)

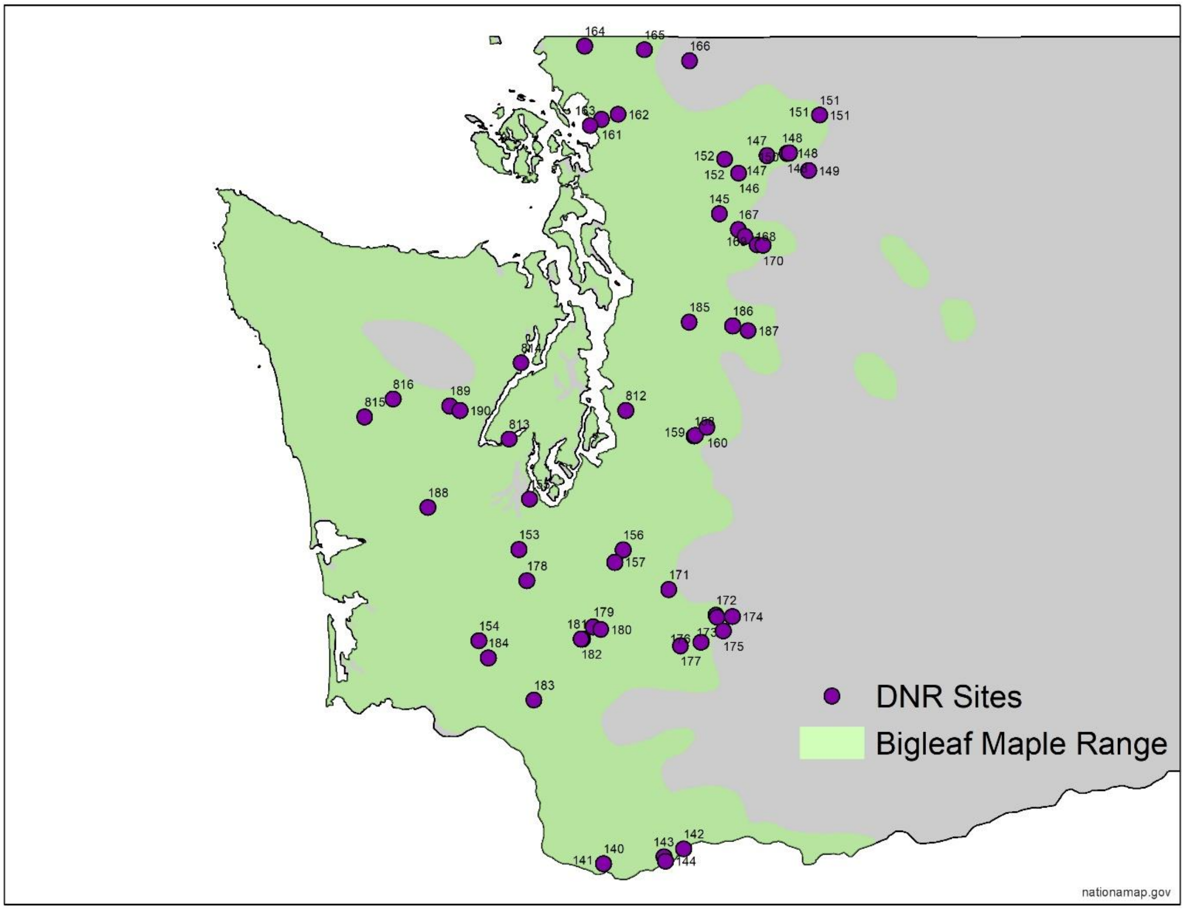

Fig. 1.2 Initial survey sites (N=63) sampled by the Washington State of Natural Resources in 2014. All locations contained a declining *A. macrophyllum*.

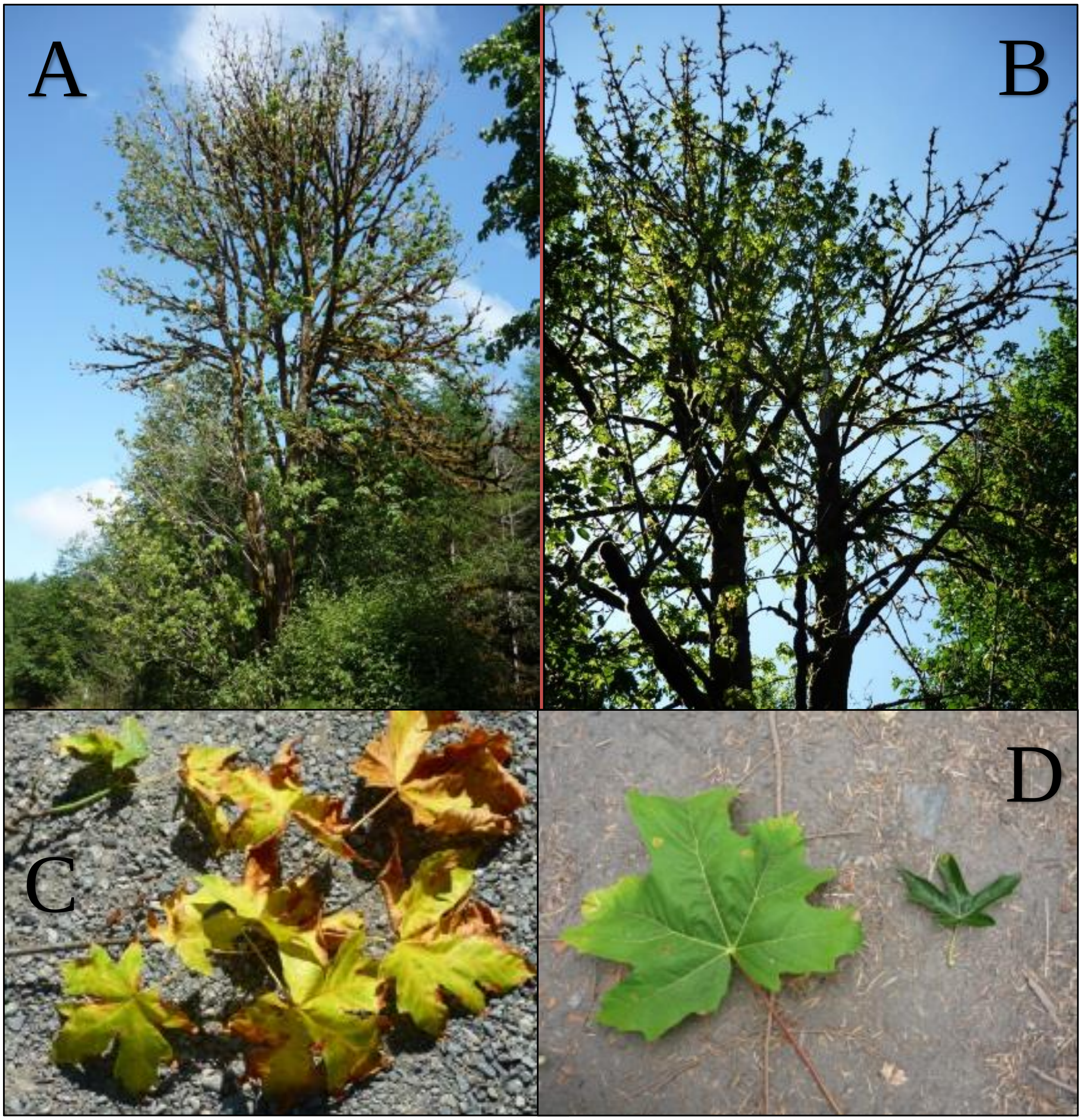

Fig. 1.3 *Acer macrophyllum* with dieback and substantial thinning (A), partial crown dieback and shrunken leaves (B), leaves with yellowing and leaf scorch (C), and healthy (left) and declining leaf (right) (D)

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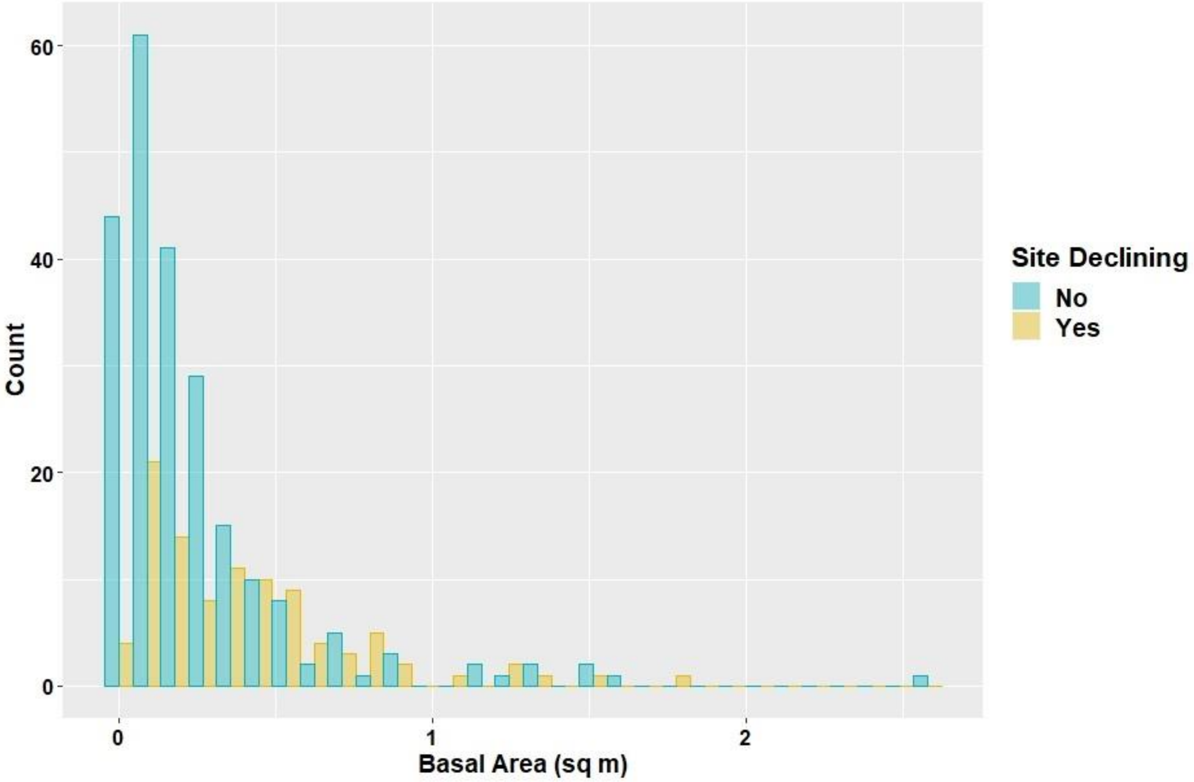


Fig. 1.4 Distribution of basal area (m^2) of all declining *A. macrophyllum* sampled from Random sites.

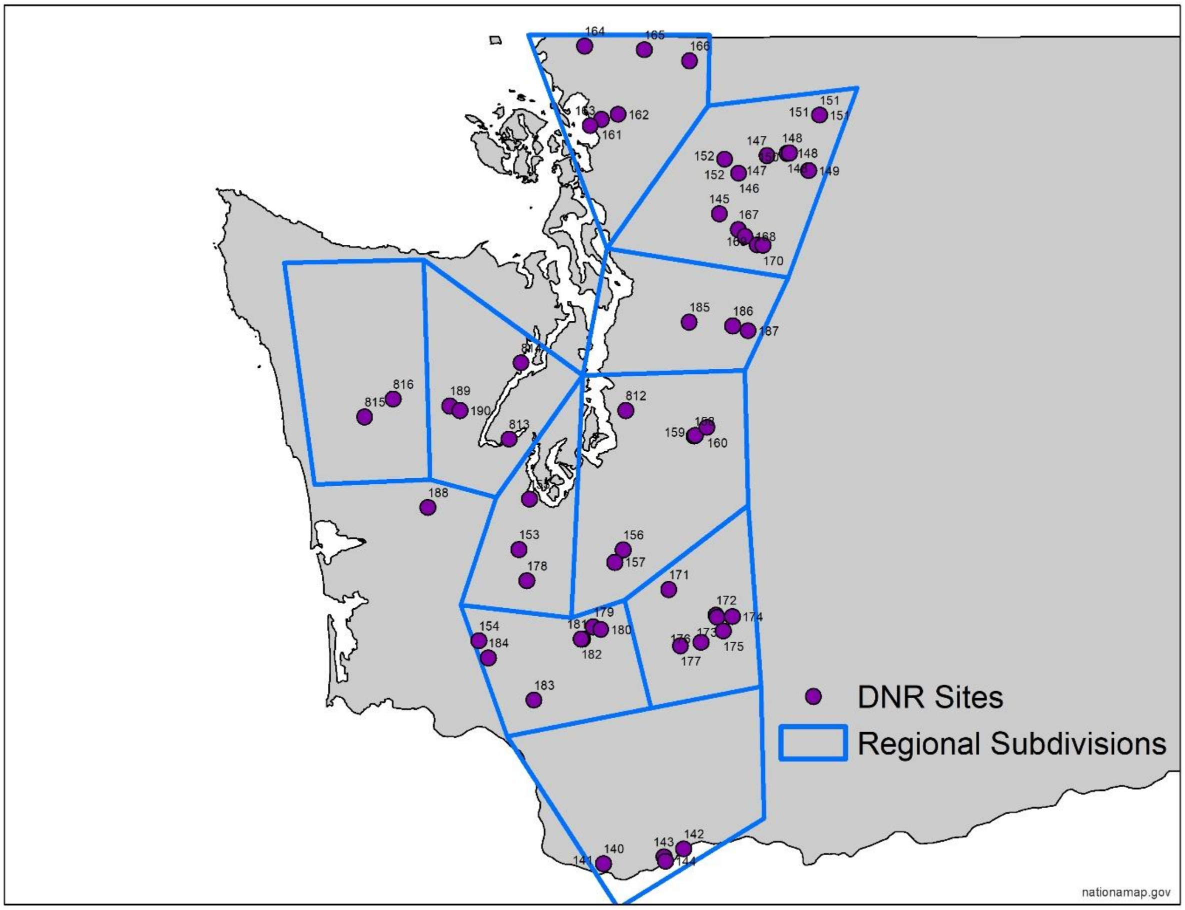


Fig. 2.1 Ten sub-regions in Washington, within which 15 DNR survey sites were randomly reselected to be more intensively sampled.

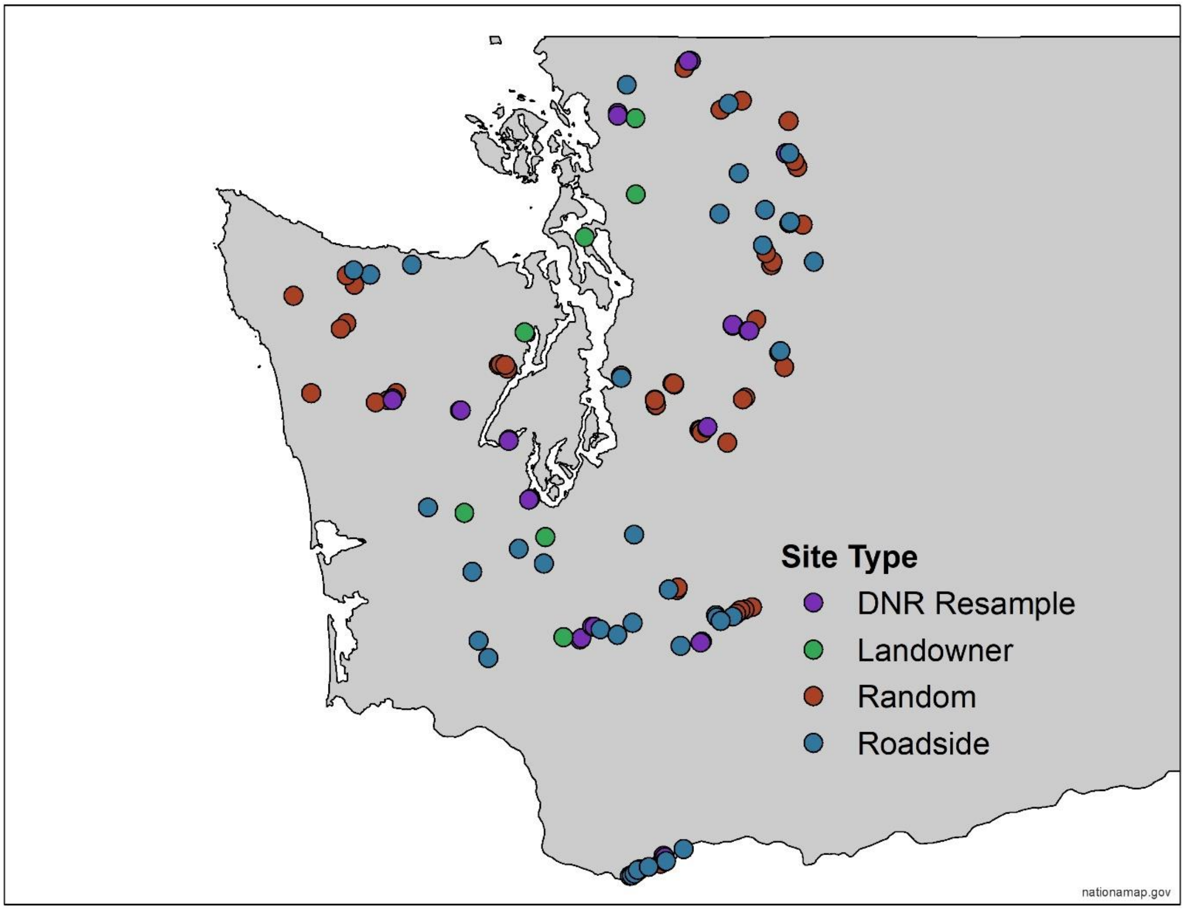


Fig. 2.2 Spatial locations of the sampled DNR sites (N=15), Random sites (N=59), Landowner Sites (N=7), and Roadside sites (N=34), overlaid on the range of *A. macrophyllum* in Washington.

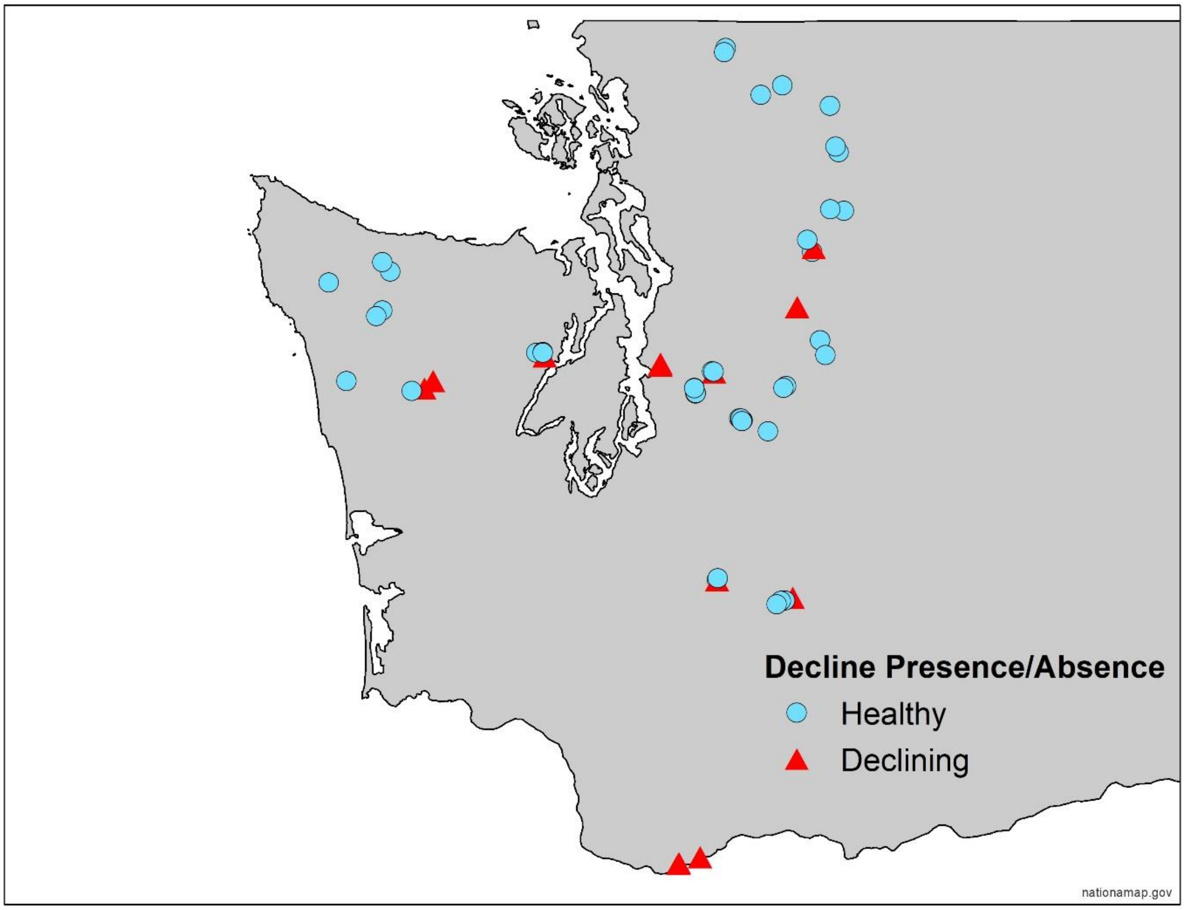


Fig. 2.3 Presence of healthy or declining *A. macrophyllum* from the 59 Random sites

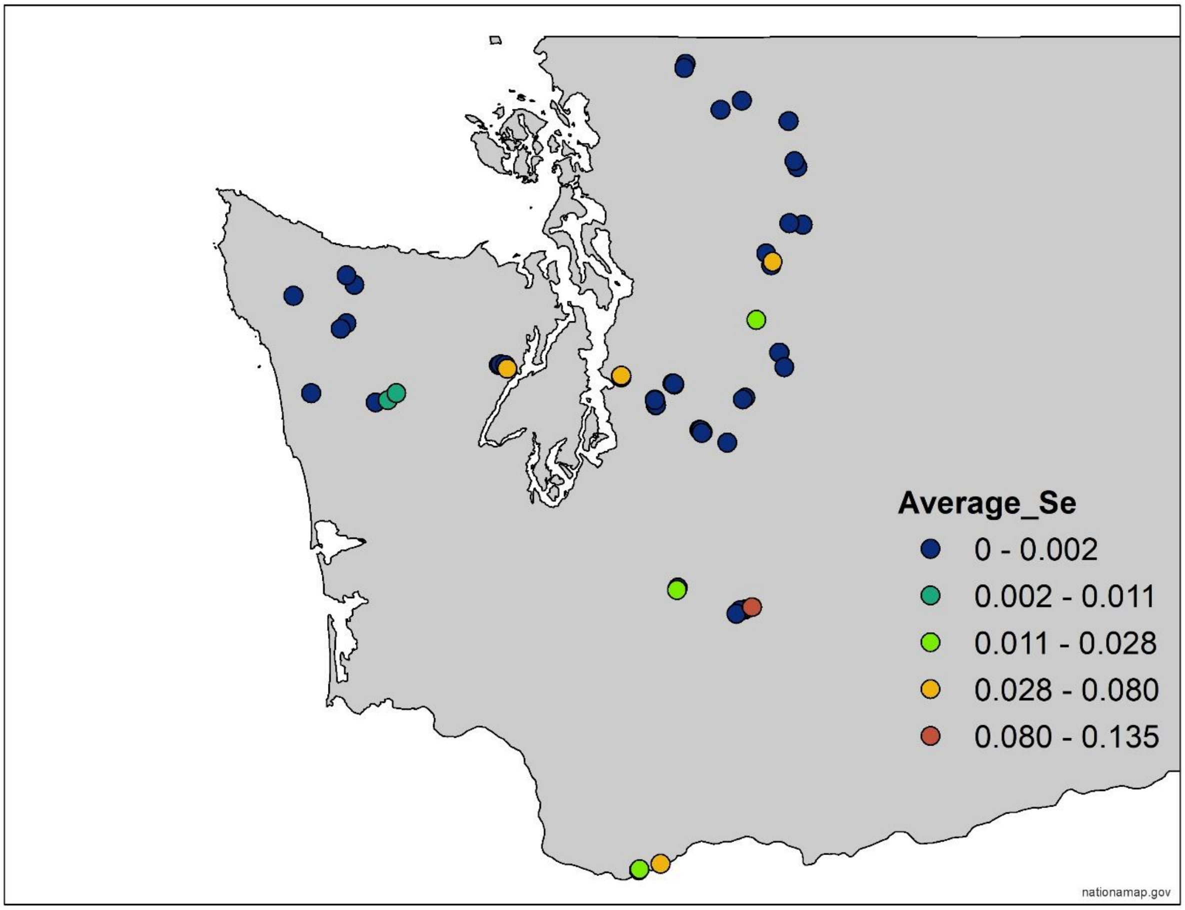


Fig. 2.4 Site Severity of decline from Random sites.

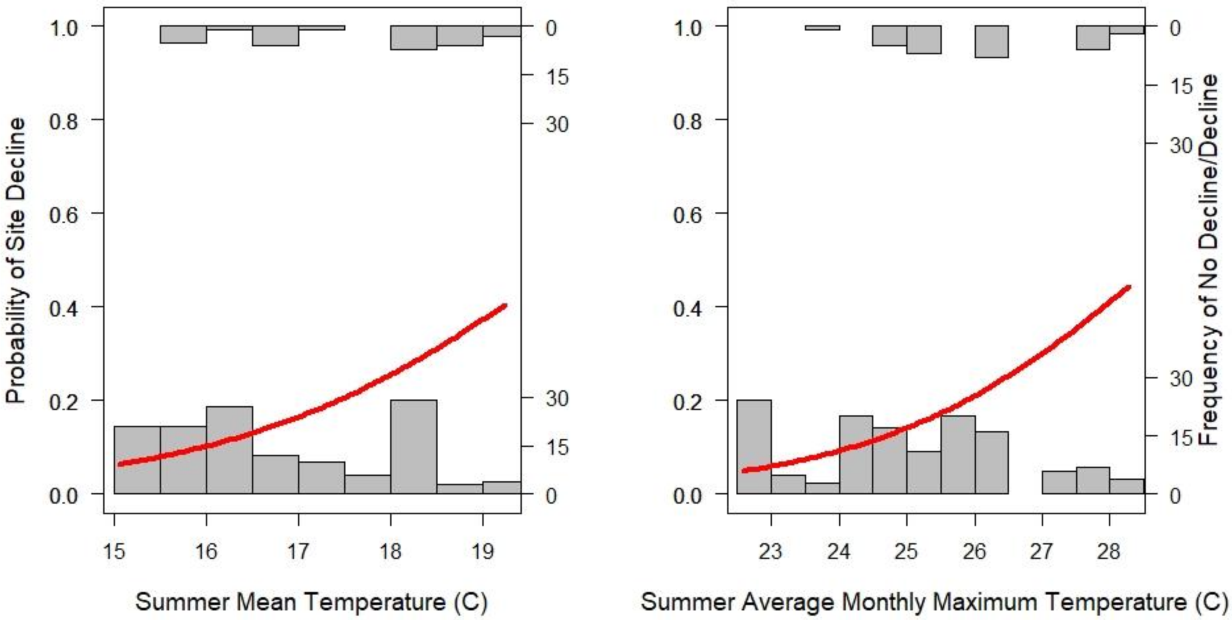


Fig. 2.5 Predicted probability of *A. macrophyllum* Site Declining (presence/absence) relative to 2015-17 summer mean temperatures and summer average temperatures. The predicted probabilities are represented by the red line, whereas the histograms represent the frequency of trees considered in decline or not.

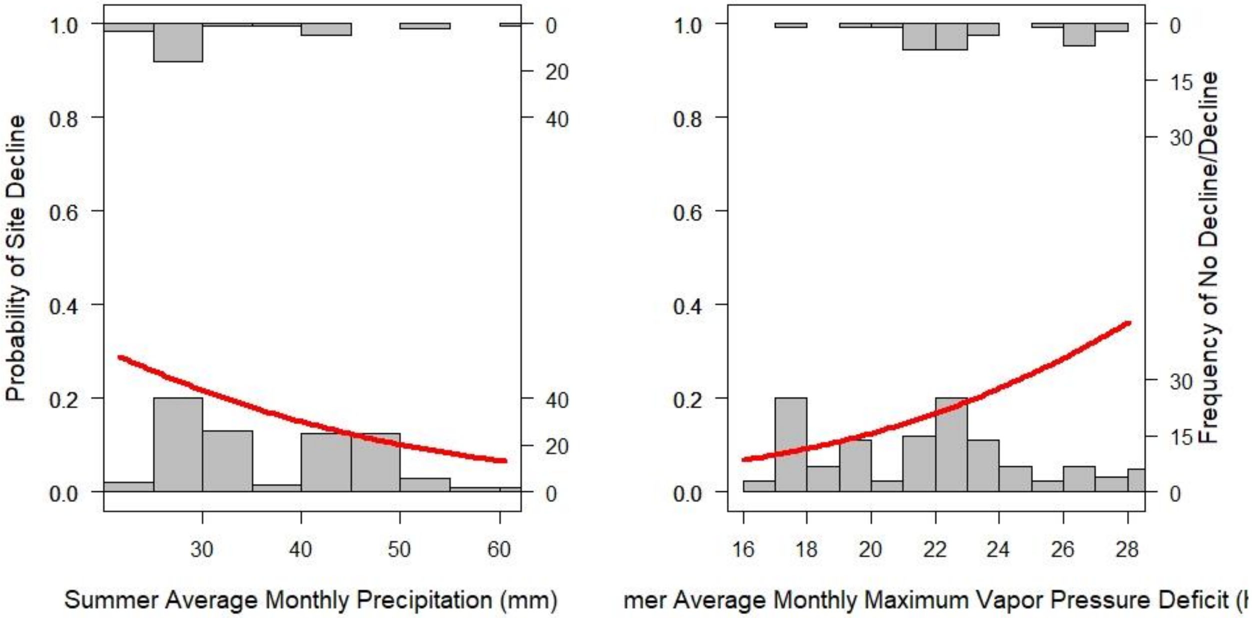


Fig. 2.6 Predicted probability of *A. macrophyllum* Site Declining (presence/absence) relative to 2015-17 summer precipitation and summer maximum vapor pressure deficit. The predicted probabilities are represented by the red line, whereas the histograms represent the frequency of trees considered in decline or not.

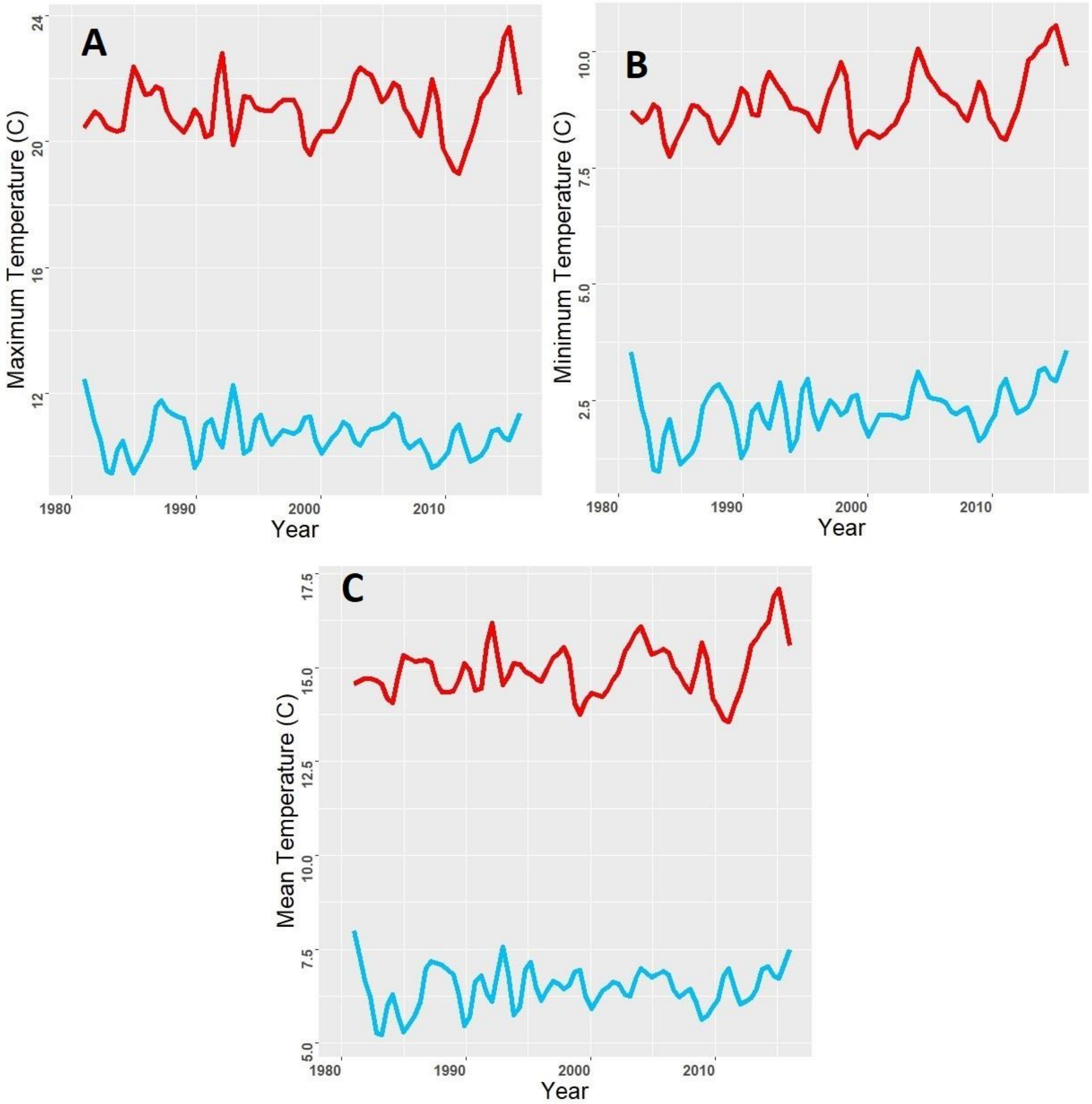


Fig. 2.7 Yearly average maximum (A), minimum (B), and mean temperatures (C) averaged across all sites, for the years 1981-2016. Red line represents May-August, blue line represents the preceding September-April.

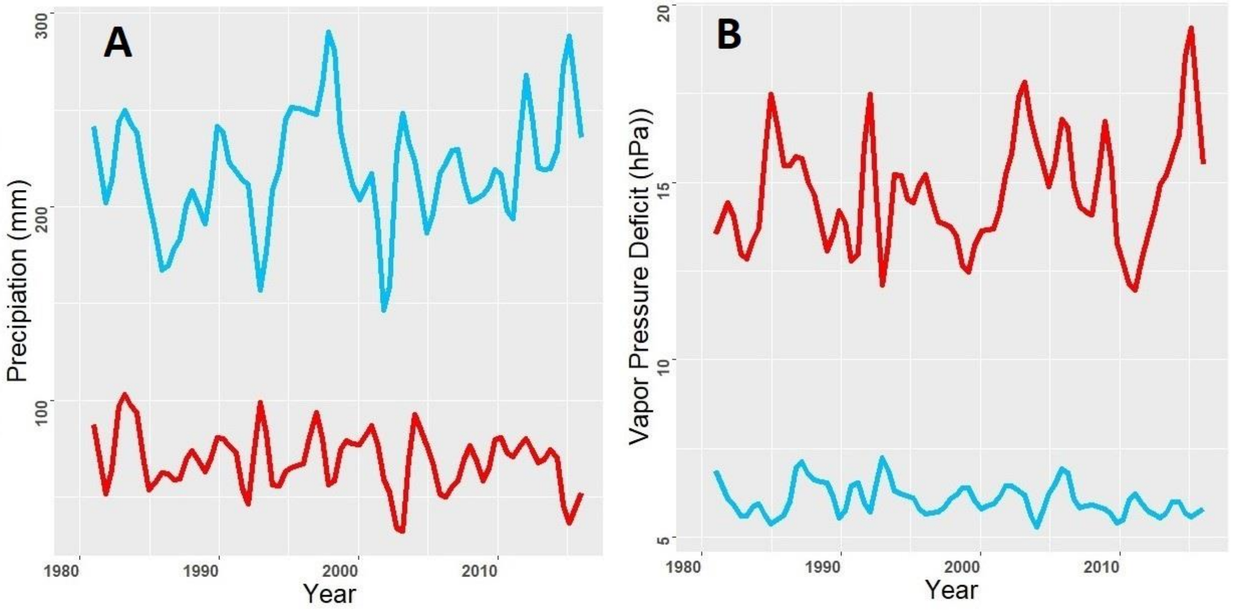


Fig. 2.8 Yearly average precipitation (A) and vapor pressure deficit (B) averaged across all sites, for the years 1981-2016. Red line represents May-August, blue line represents the preceding September-April.

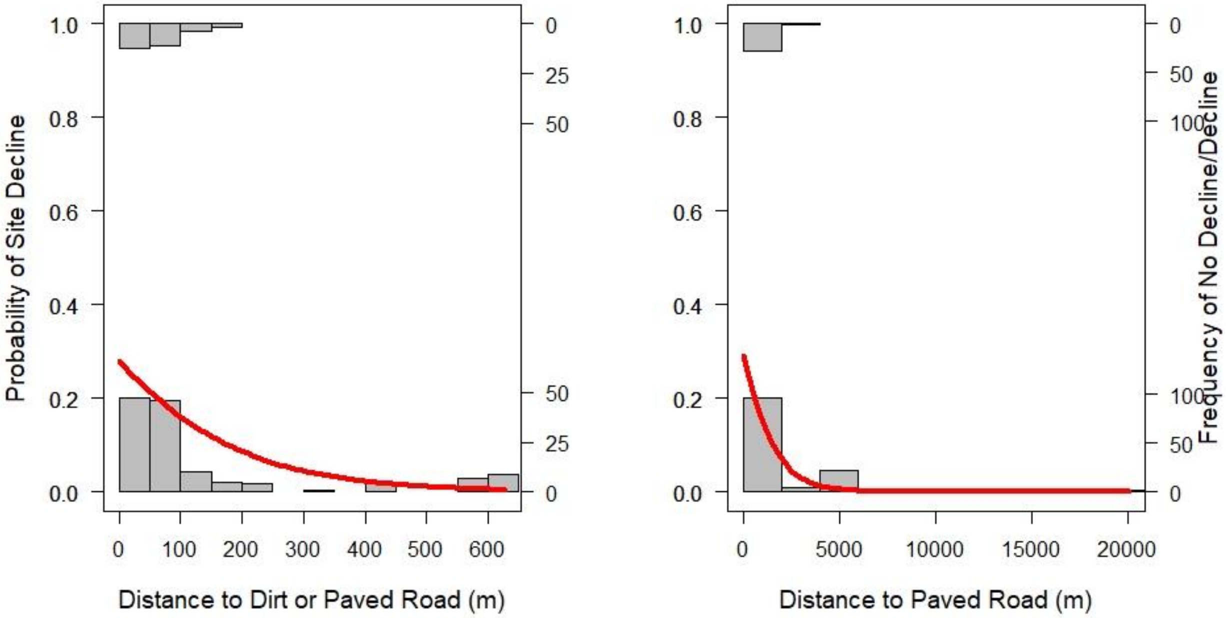


Fig. 2.9 Predicted probability of *A. macrophyllum* Site Declining (presence/absence) relative to distance to closest the dirt road or paved road and to the closest specifically-paved road. The predicted probabilities are represented by the red line, whereas the histograms represent the frequency of trees considered in decline or not.

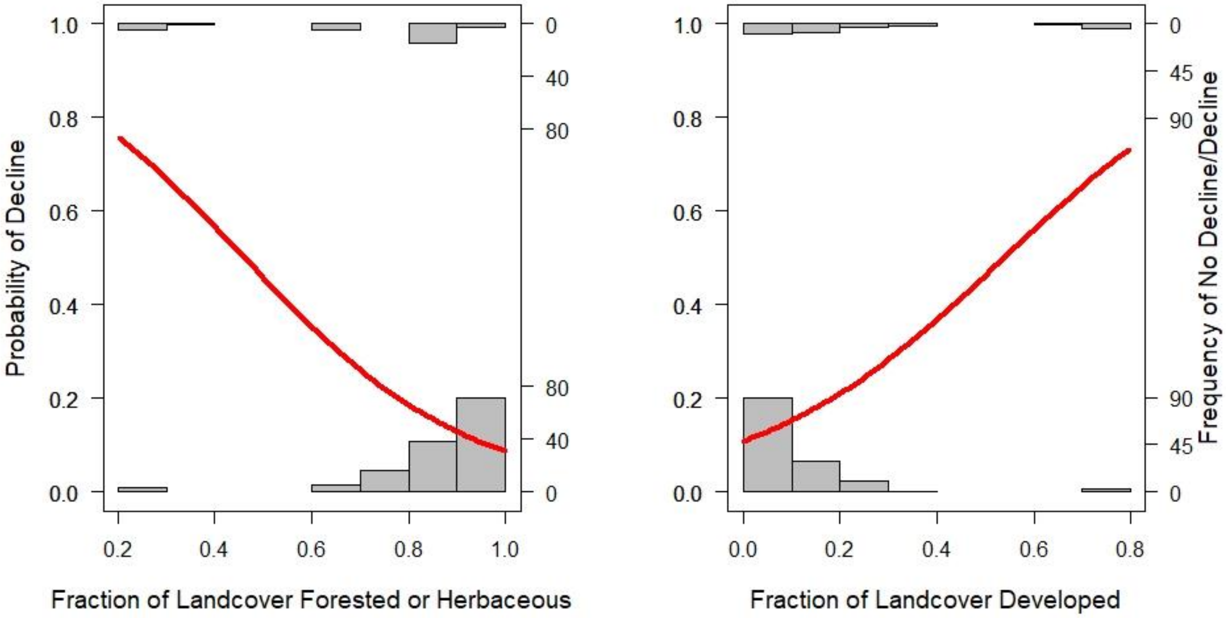


Fig. 2.10 Predicted probability of *A. macrophyllum* Site Declining (presence/absence) relative to the fraction of Developed land and of Forested/Herbaceous land, within a 100 ha square centered on the site. The predicted probabilities are represented by the red line, whereas the histograms represent the frequency of trees considered in decline or not.

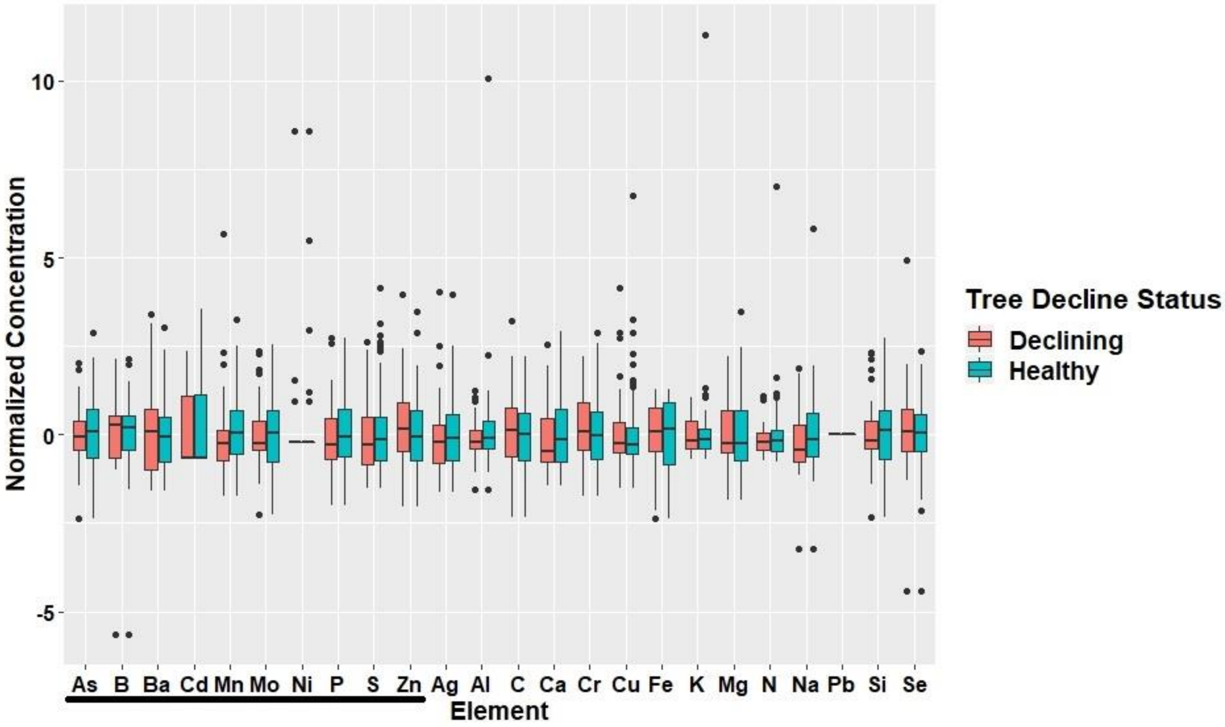


Fig. 2.11 Normalized soil concentrations for Declining and Healthy (no Site Decline) *A. macrophyllum* based on Random, DNR, and Landowner sites. Elements significantly associated with Tree Declining are underlined. Based on Site level concentrations.

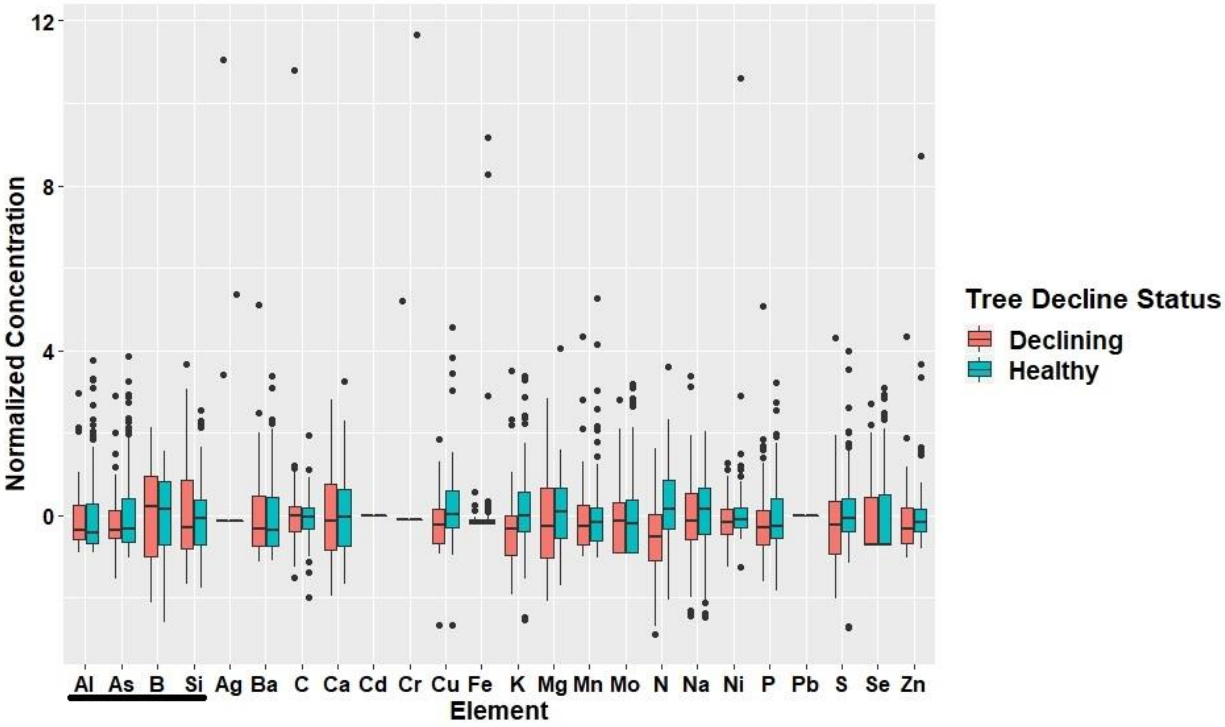


Fig. 2.12 Normalized foliar concentrations for Declining and Healthy (no Decline) *A. macrophyllum* based on Random, DNR, and Landowner sites. Elements significantly associated with Declining are underlined. Based on Tree level concentrations.

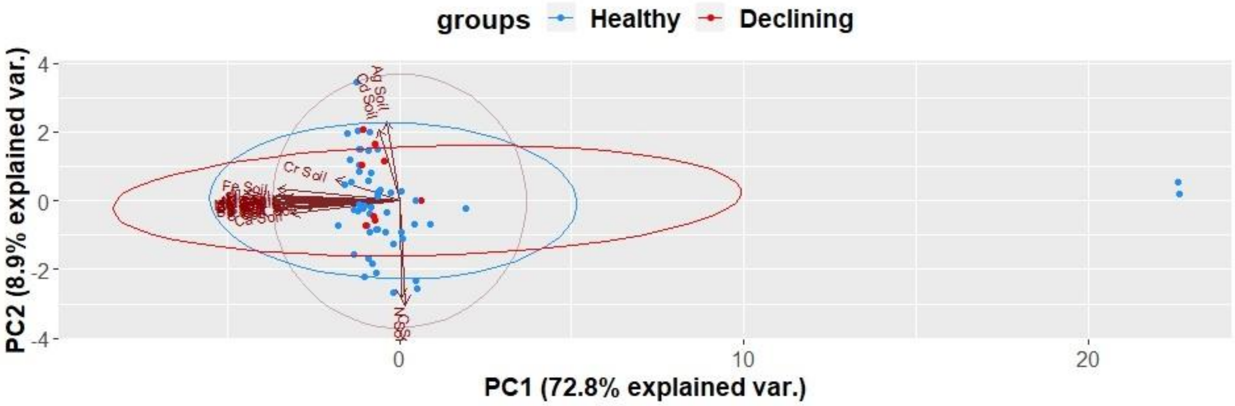


Fig. 2.13 Principal Components Analysis of all soil elemental concentrations of declining and healthy *A. macrophyllum* in Random sites, in relation to Tree Declining.

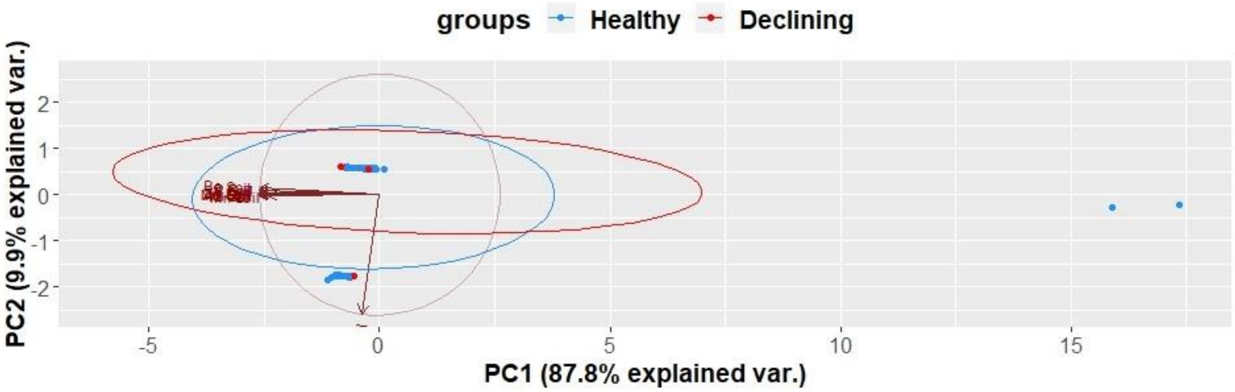


Fig. 2.14 Principal Components Analysis of all significant soil elemental concentrations of declining and healthy *A. macrophyllum* in Random sites, in relation to Tree Declining.

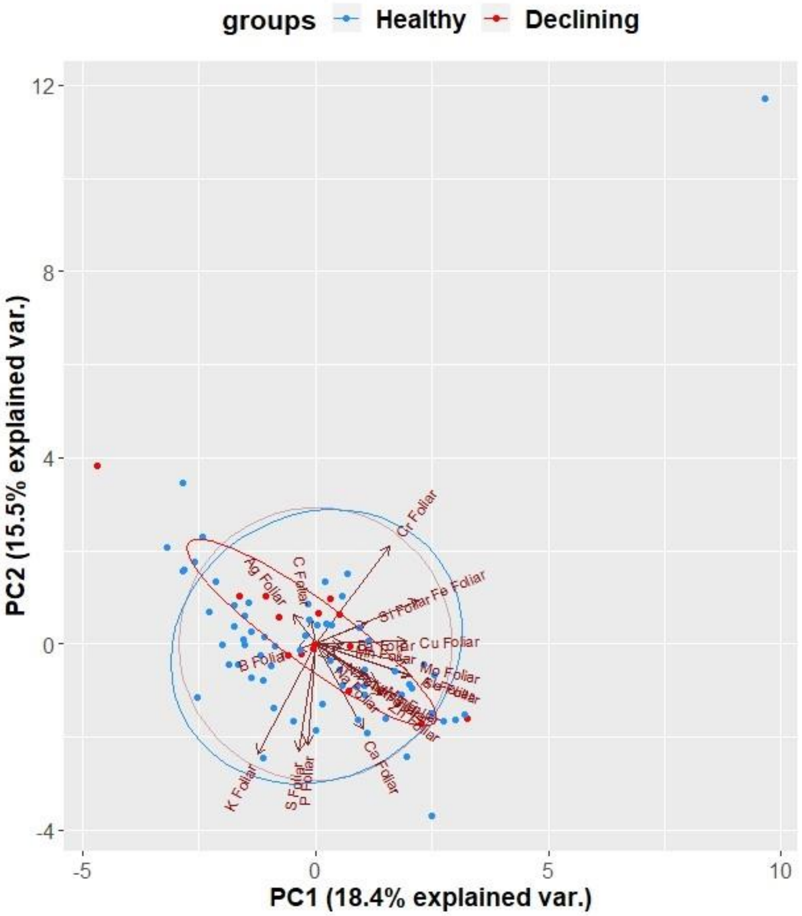


Fig. 2.15 Principal Components Analysis of all foliar elemental concentrations of declining and healthy *A. macrophyllum* in Random sites, in relation to Tree Declining.

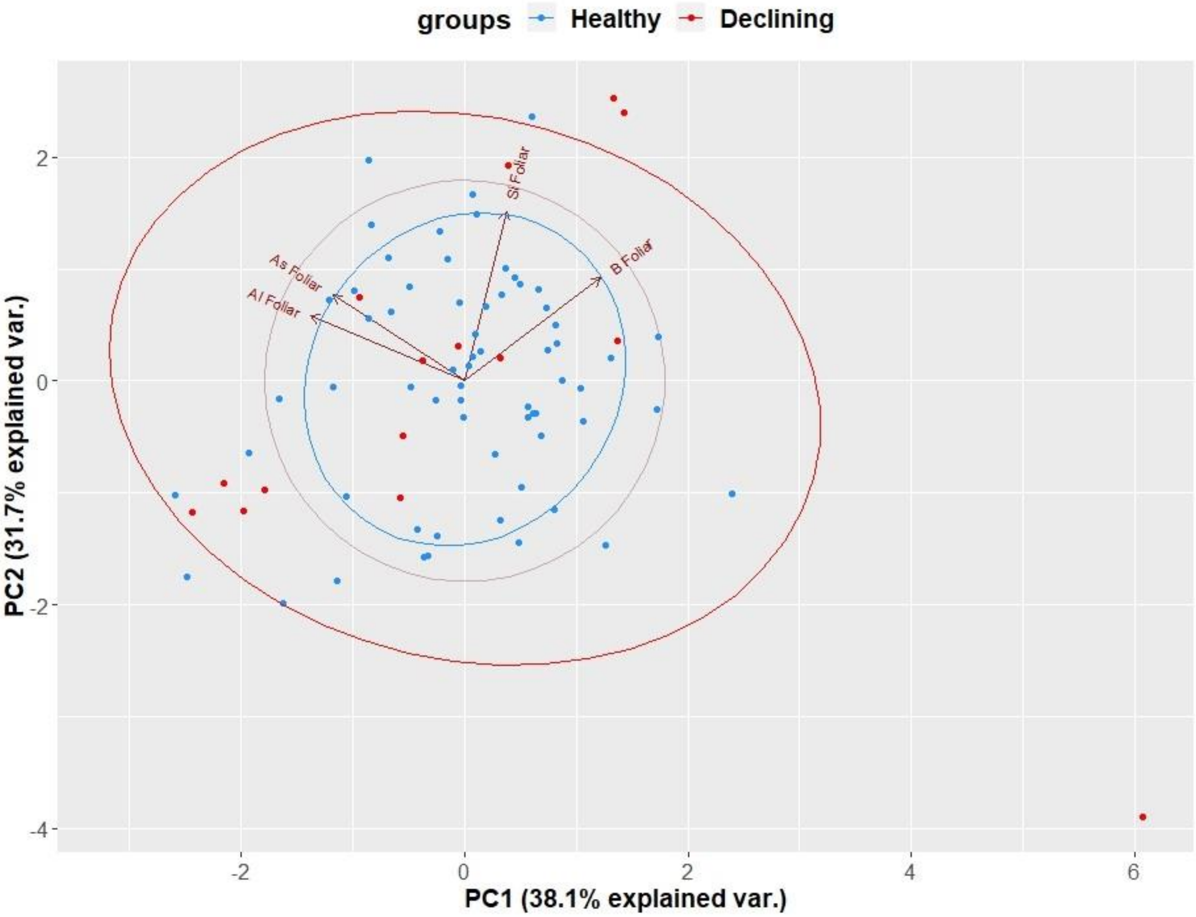


Fig. 2.16 Principal Components Analysis of all significant foliar elemental concentrations of declining and healthy *A. macrophyllum* in Random sites, in relation to Tree Declining.

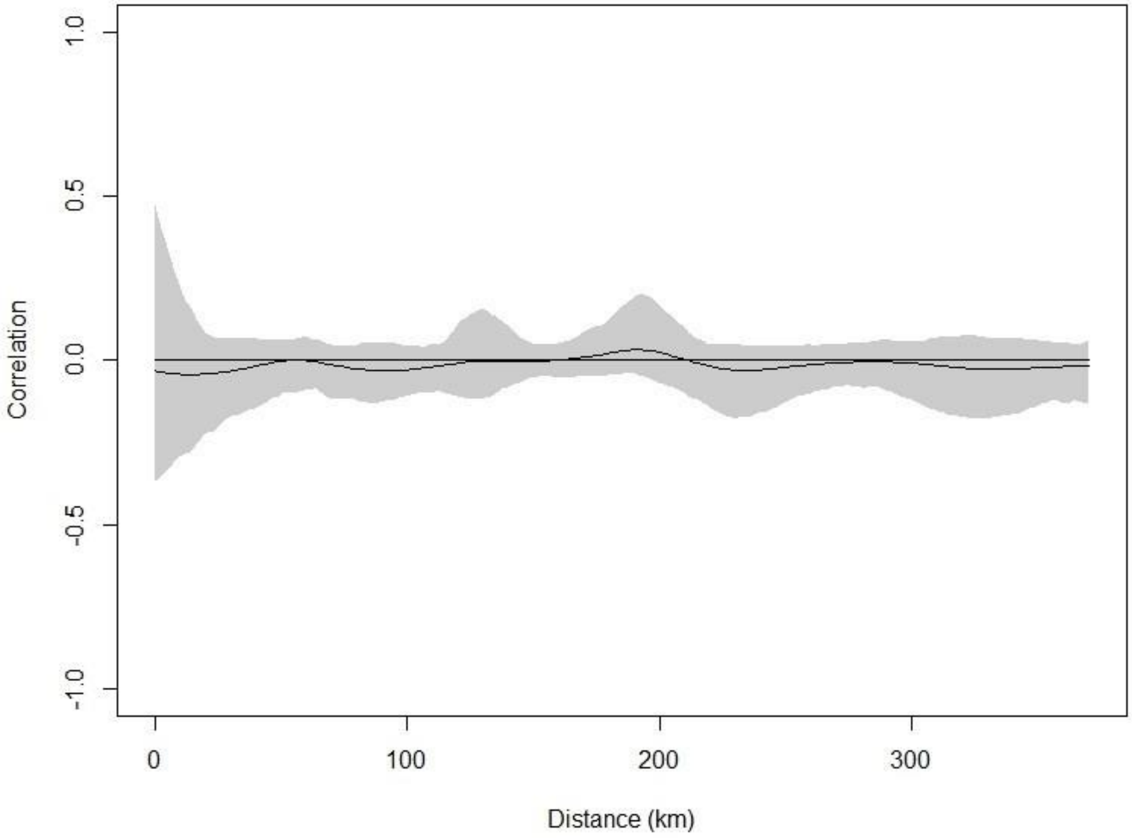


Fig. 2.17 Spatial autocorrelation of Site Severity (0-1) using data from Random and DNR sites. The grey shaded region represents the 95% confidence interval, which in this case does not reveal significant local spatial clustering of Site Severity.

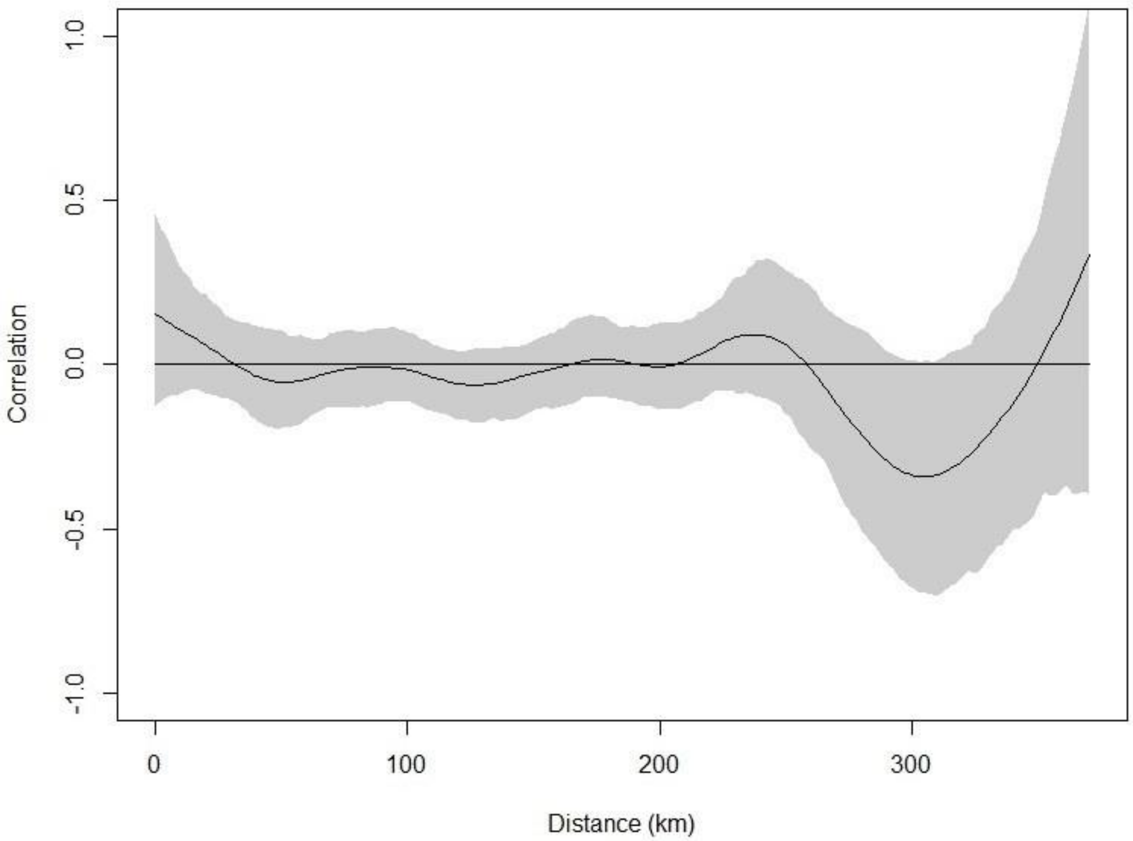
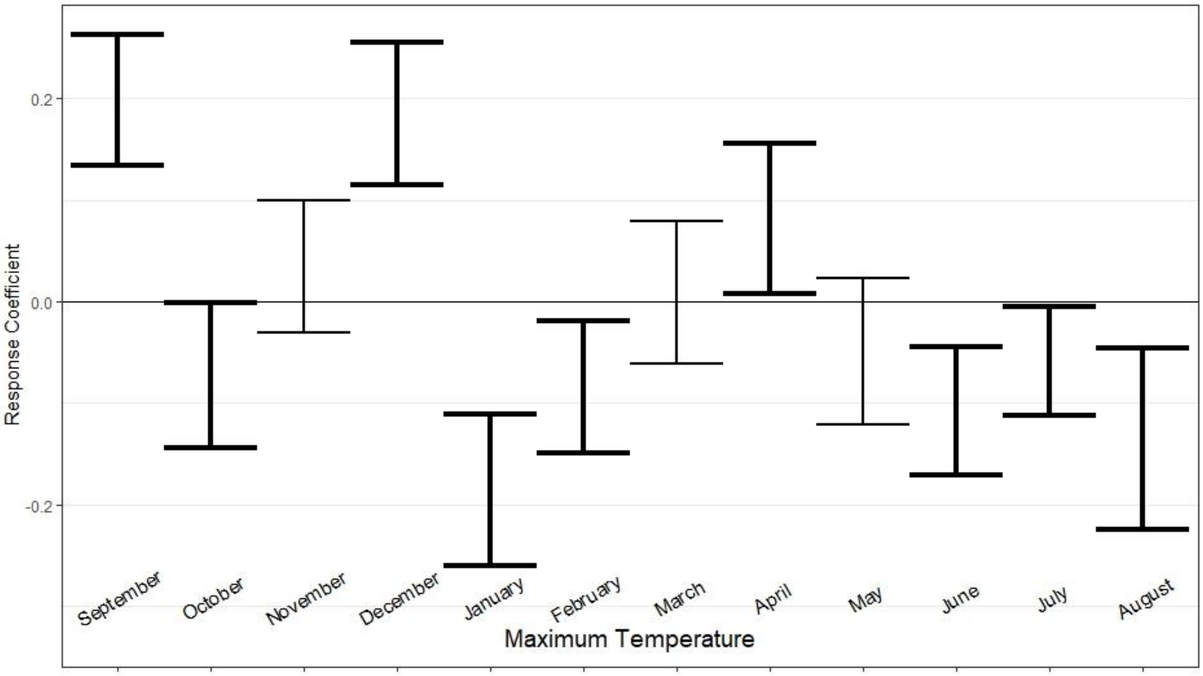


Fig. 2.18 Spatial autocorrelation of Site Declining (yes/no) using data from Random and DNR sites. The grey shaded region represents the 95% confidence interval, which in this case does not reveal significant local spatial clustering of Site Declining.



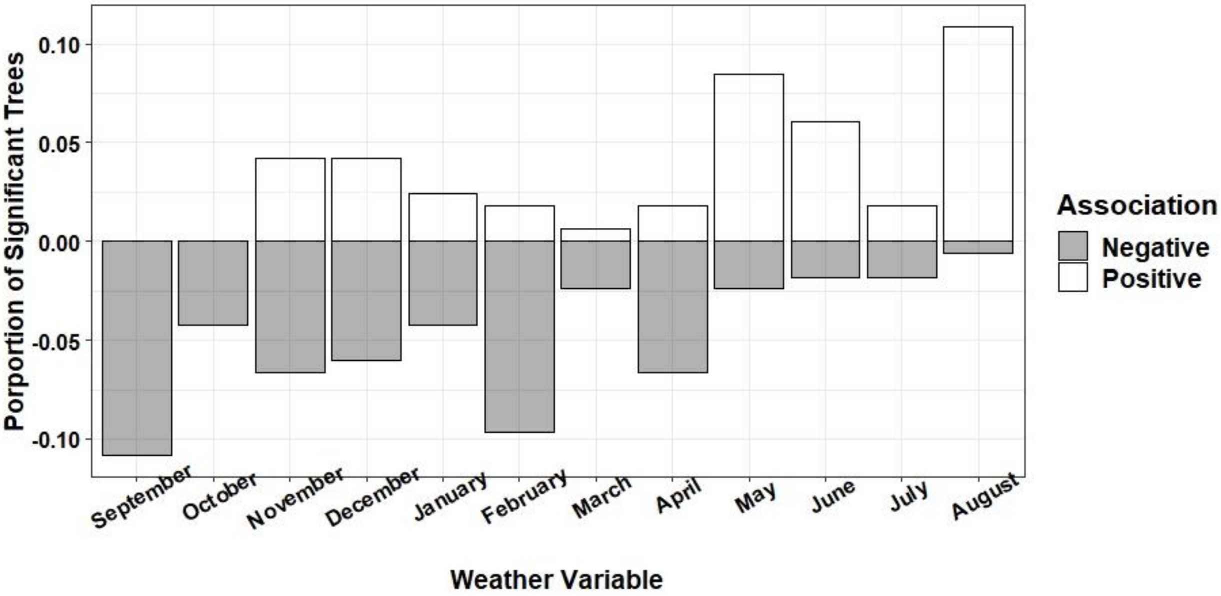


Fig. 3.1 Response coefficients for monthly average maximum daily temperature, as a predictor of ring widths of *A. macrophyllum*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, temperature was normalized by site.

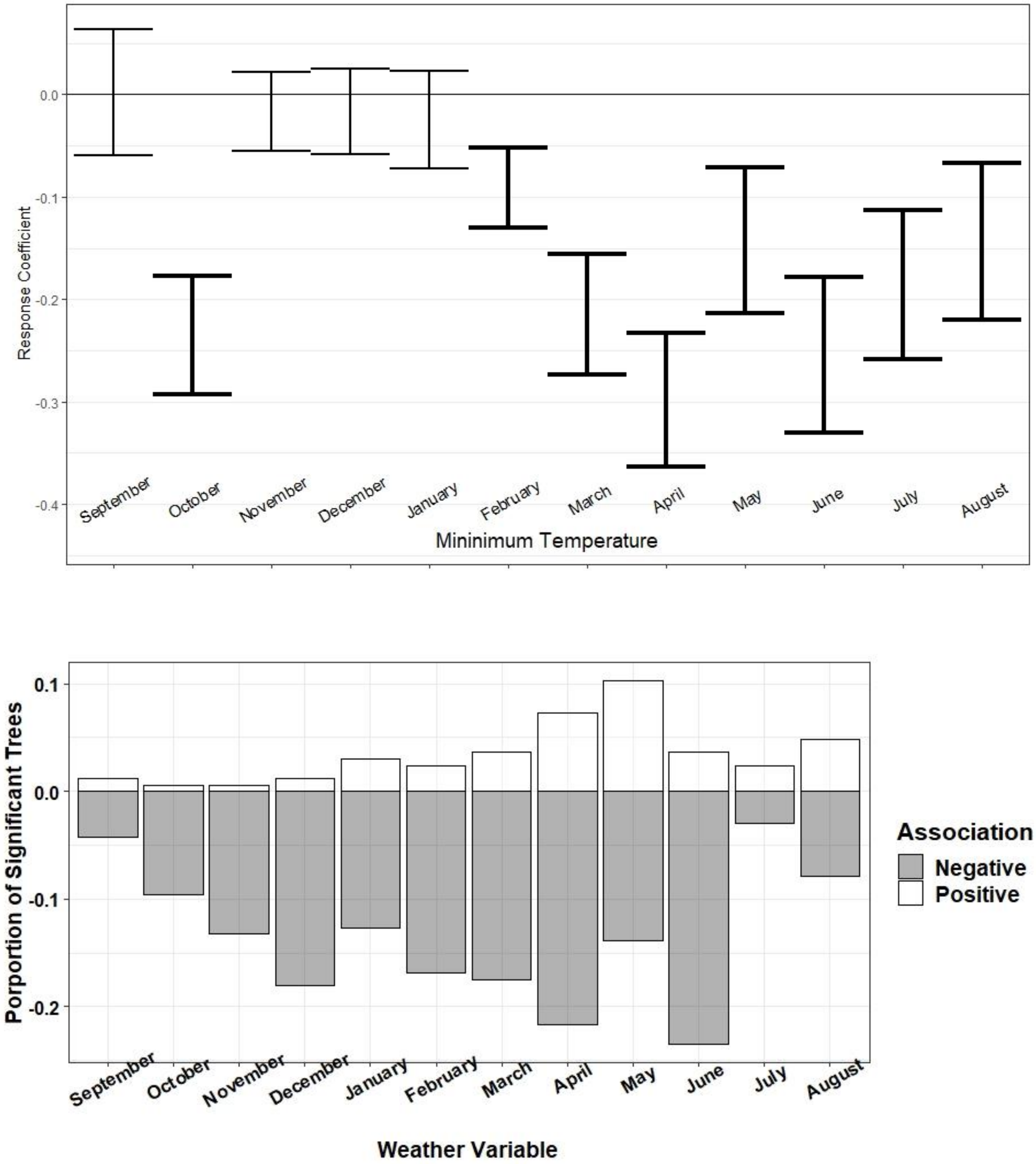


Fig. 3.2 Response coefficients for monthly average minimum daily temperature, as a predictor of ring widths of *A. macrophyllum*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, temperature was normalized by site.

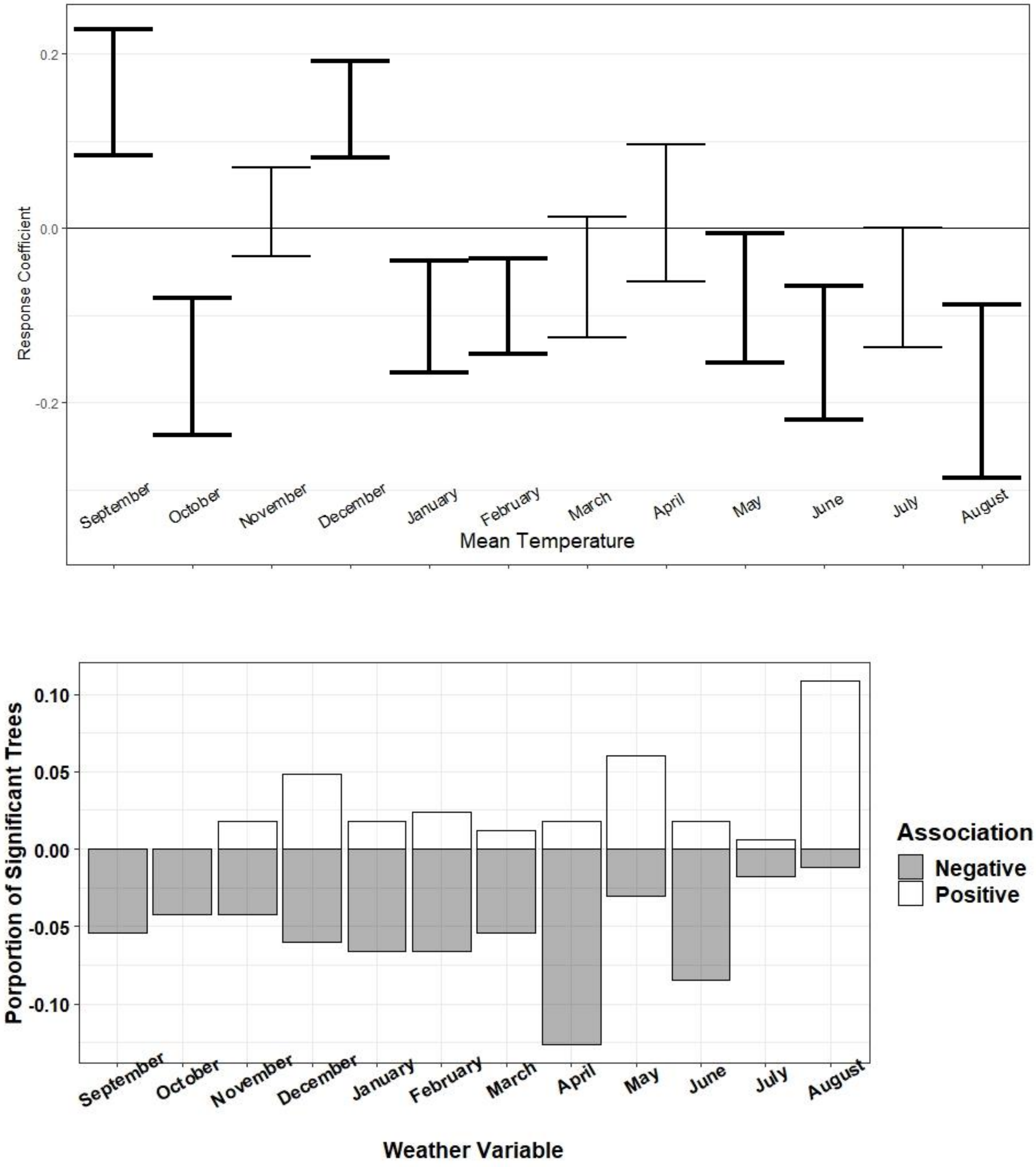


Fig. 3.3 Response coefficients for monthly average mean daily temperature, as a predictor of ring widths of *A. macrophyllum*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, temperature was normalized by site.

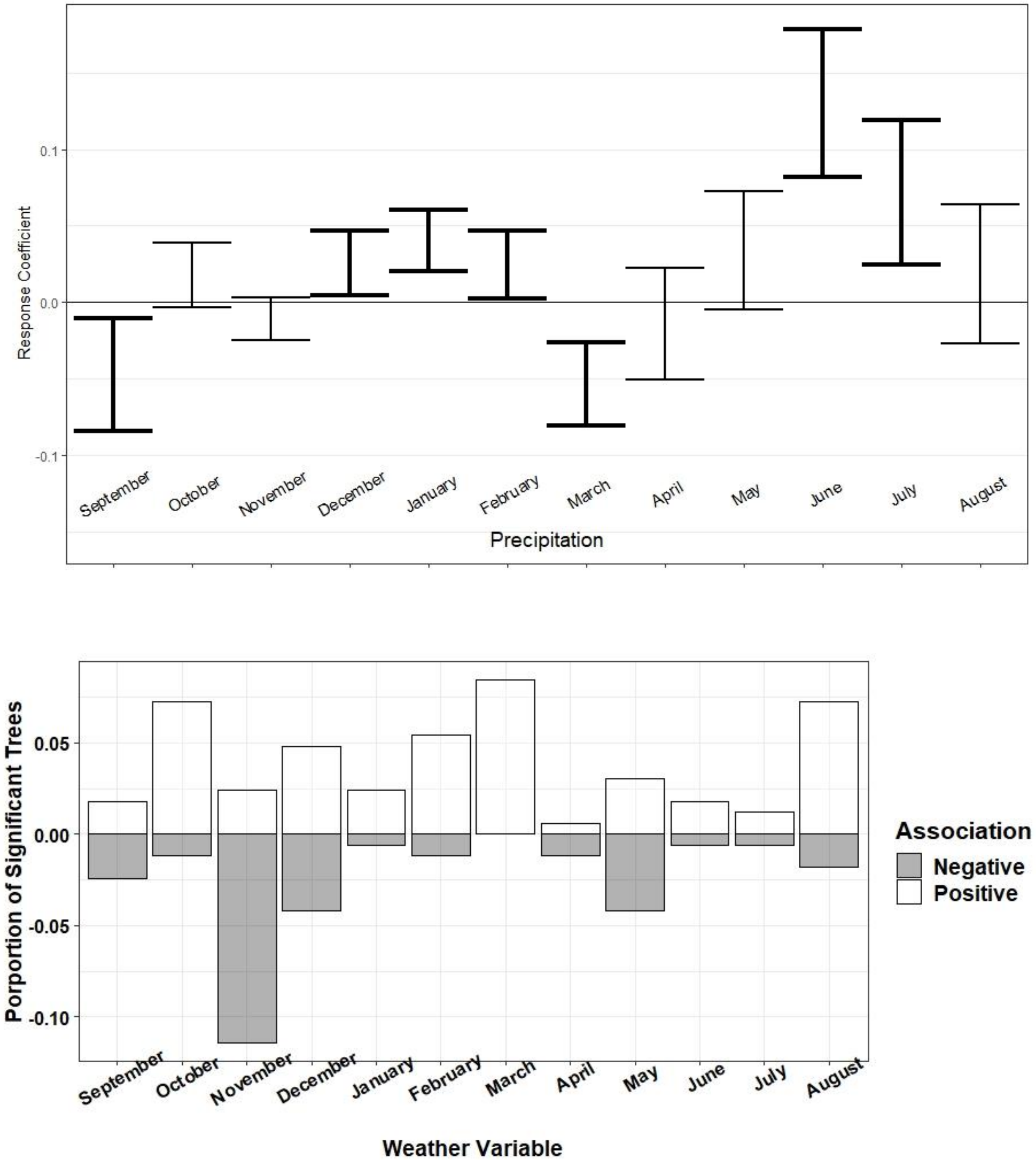


Fig. 3.4 Response coefficients for monthly average daily precipitation, as a predictor of ring widths of *A. macrophyllum*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, precipitation was normalized by site.

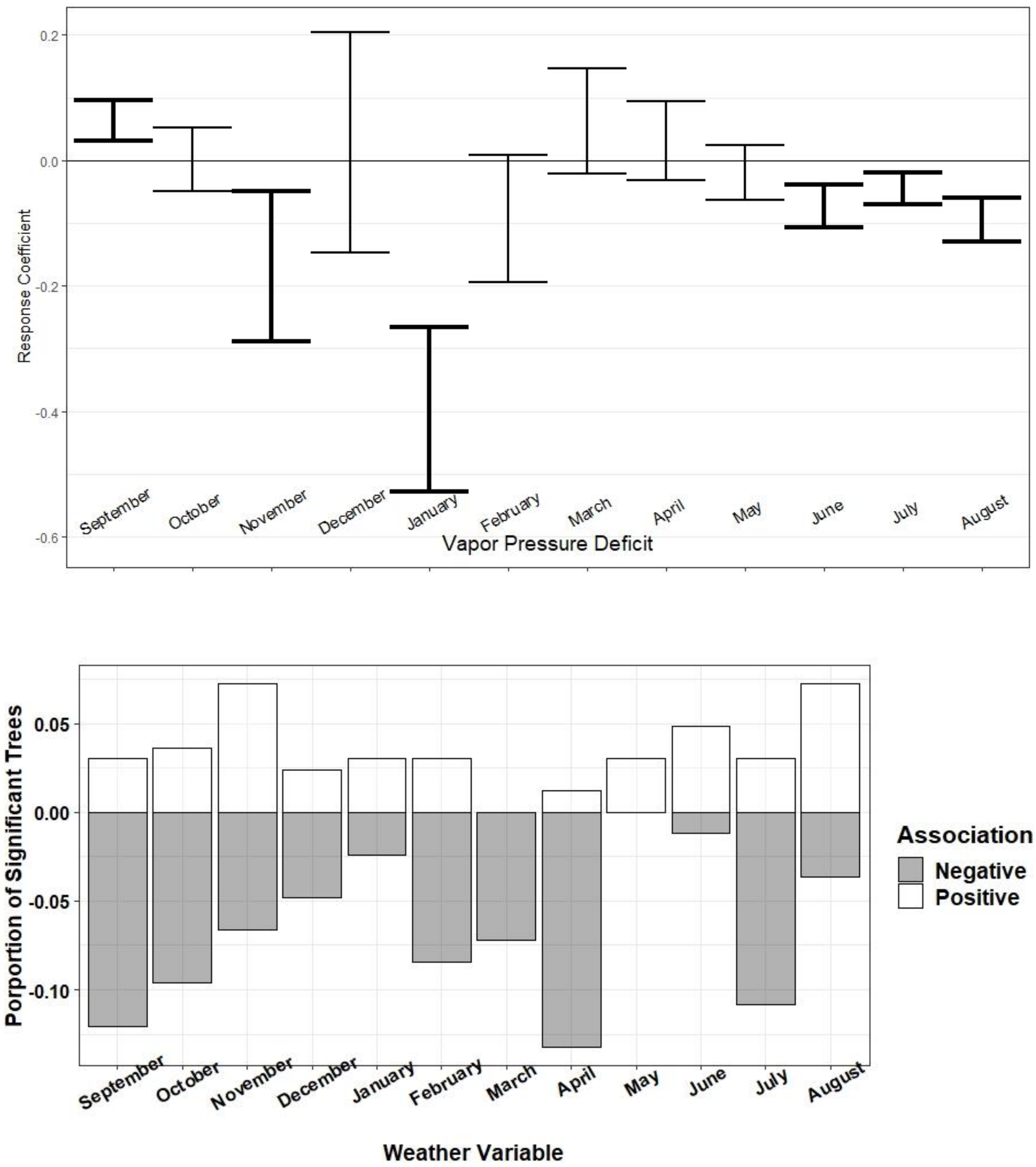


Fig. 3.5 Response coefficients for monthly average maximum daily vapor pressure deficit, as a predictor of ring widths of *A. macrophyllum*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, vapor pressure deficits were normalized by site.

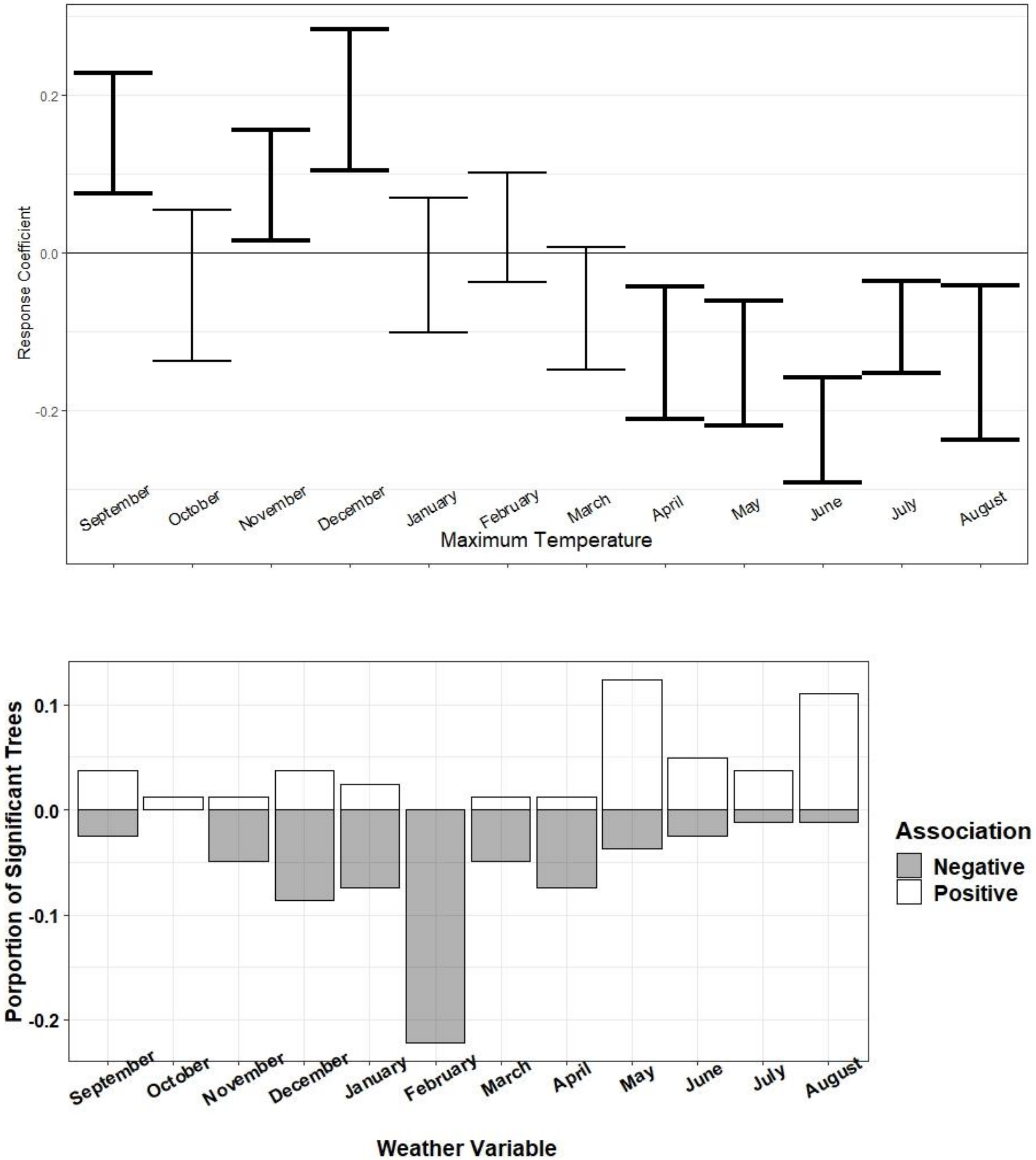
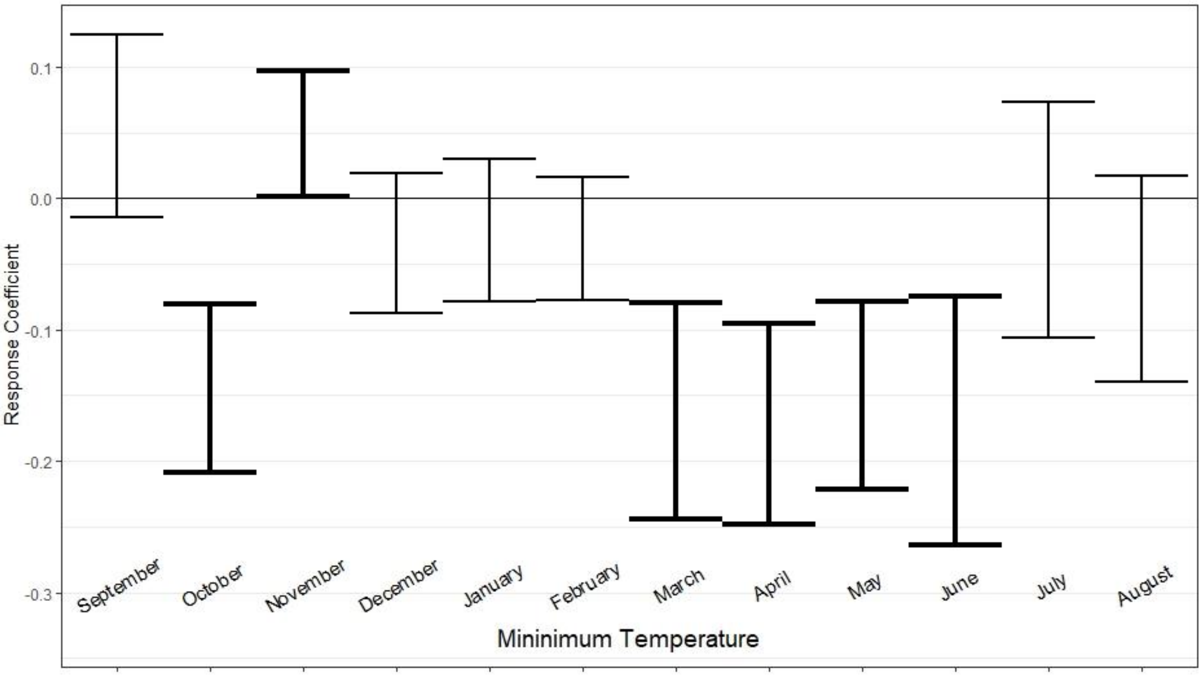


Fig. 3.6 Response coefficients for monthly average maximum daily temperature, as a predictor of ring widths of *P. menziesii*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, temperature was normalized by site.



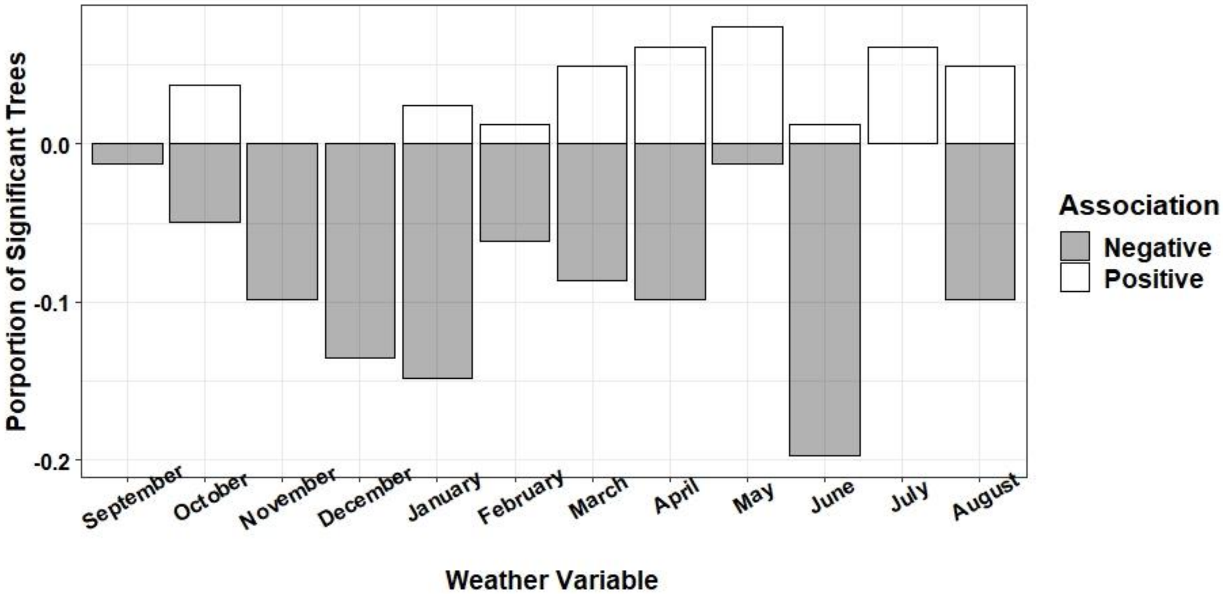
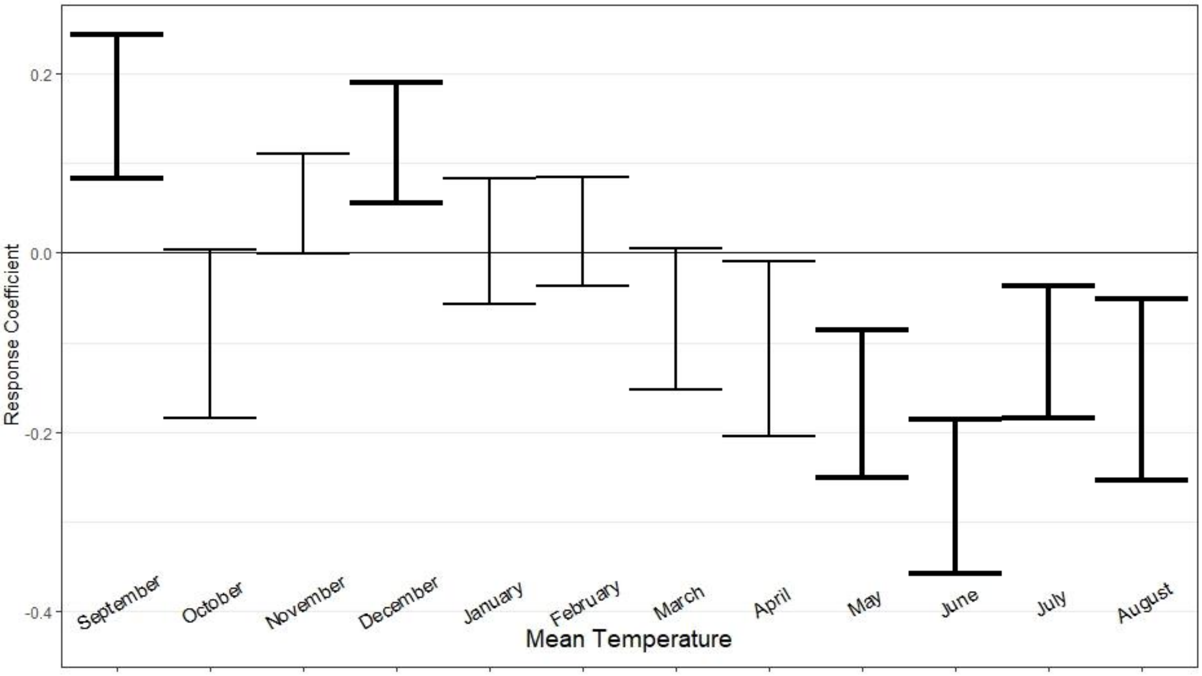


Fig. 3.7 Response coefficients for monthly average minimum daily temperature, as a predictor of ring widths of *P. menziesii*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, temperature was normalized by site.



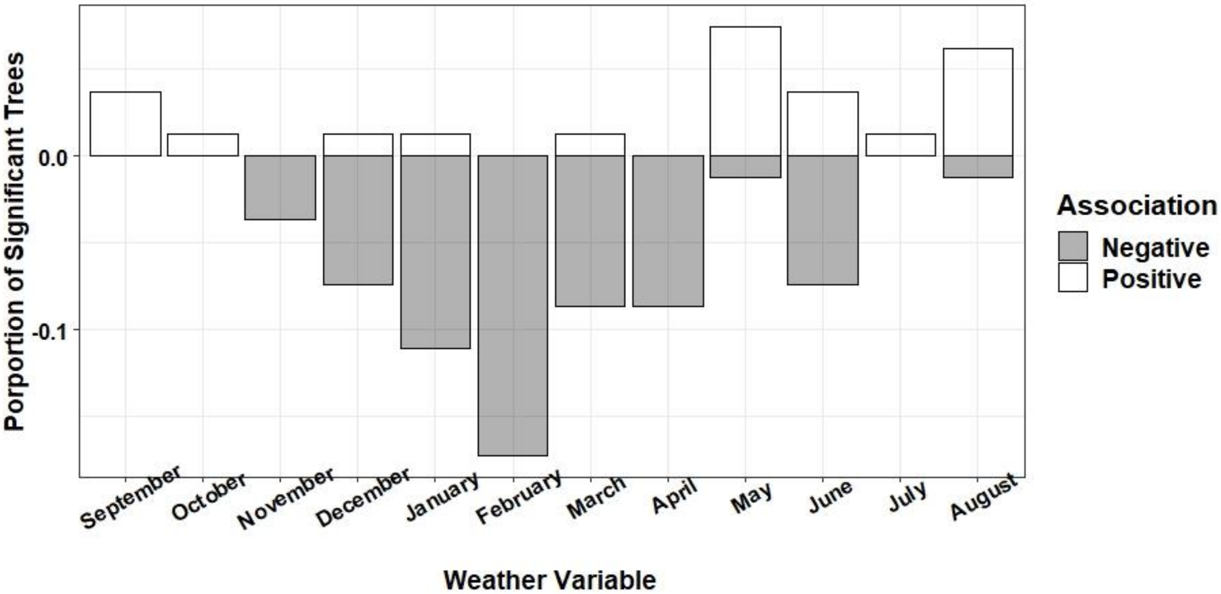


Fig. 3.8 Response coefficients for monthly average mean daily temperature, as a predictor of ring widths of *P. menziesii*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, temperature was normalized by site.

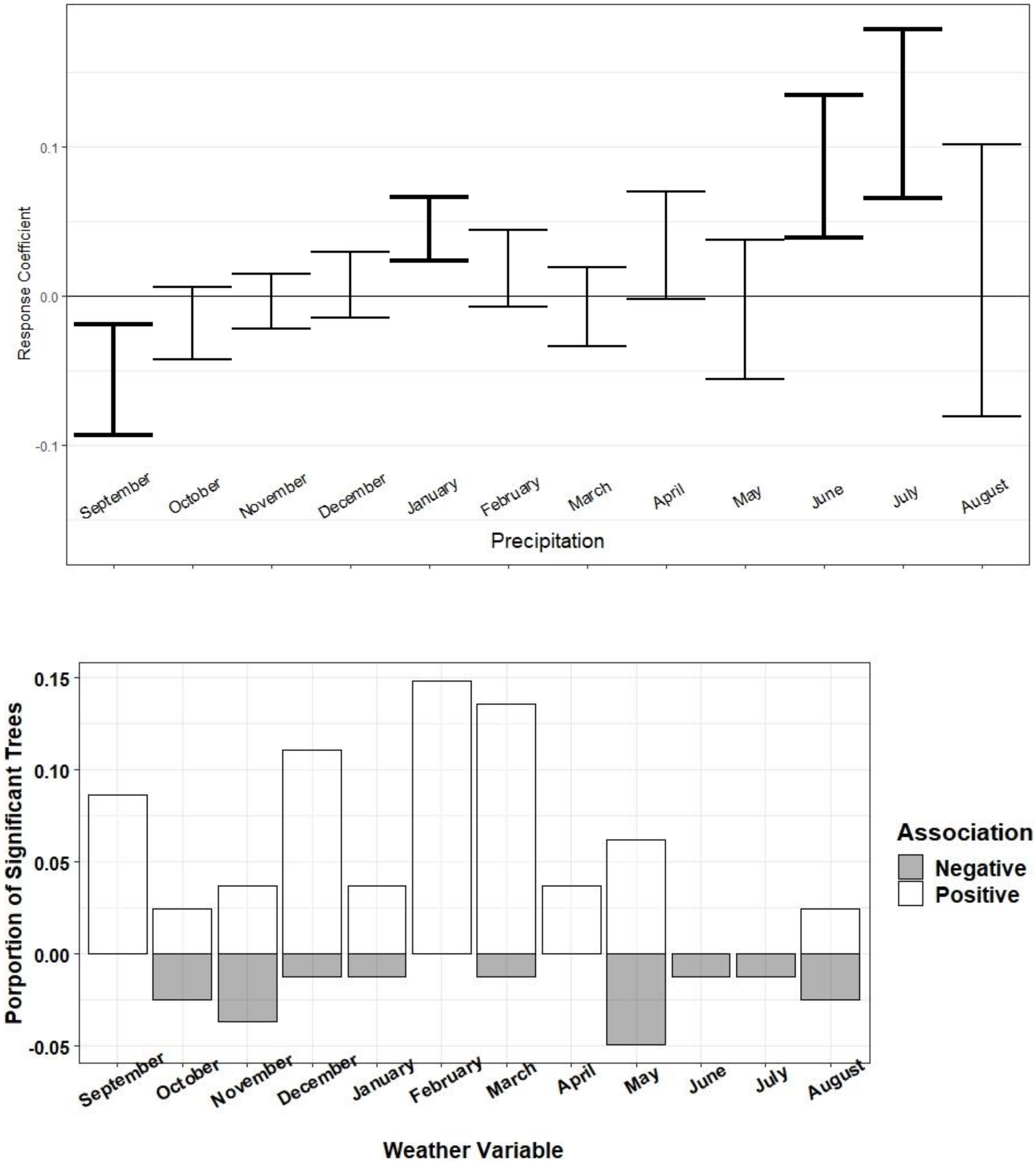


Fig. 3.9 Response coefficients for monthly average daily precipitation, as a predictor of ring widths of *P. menziesii*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, precipitation was normalized by site.

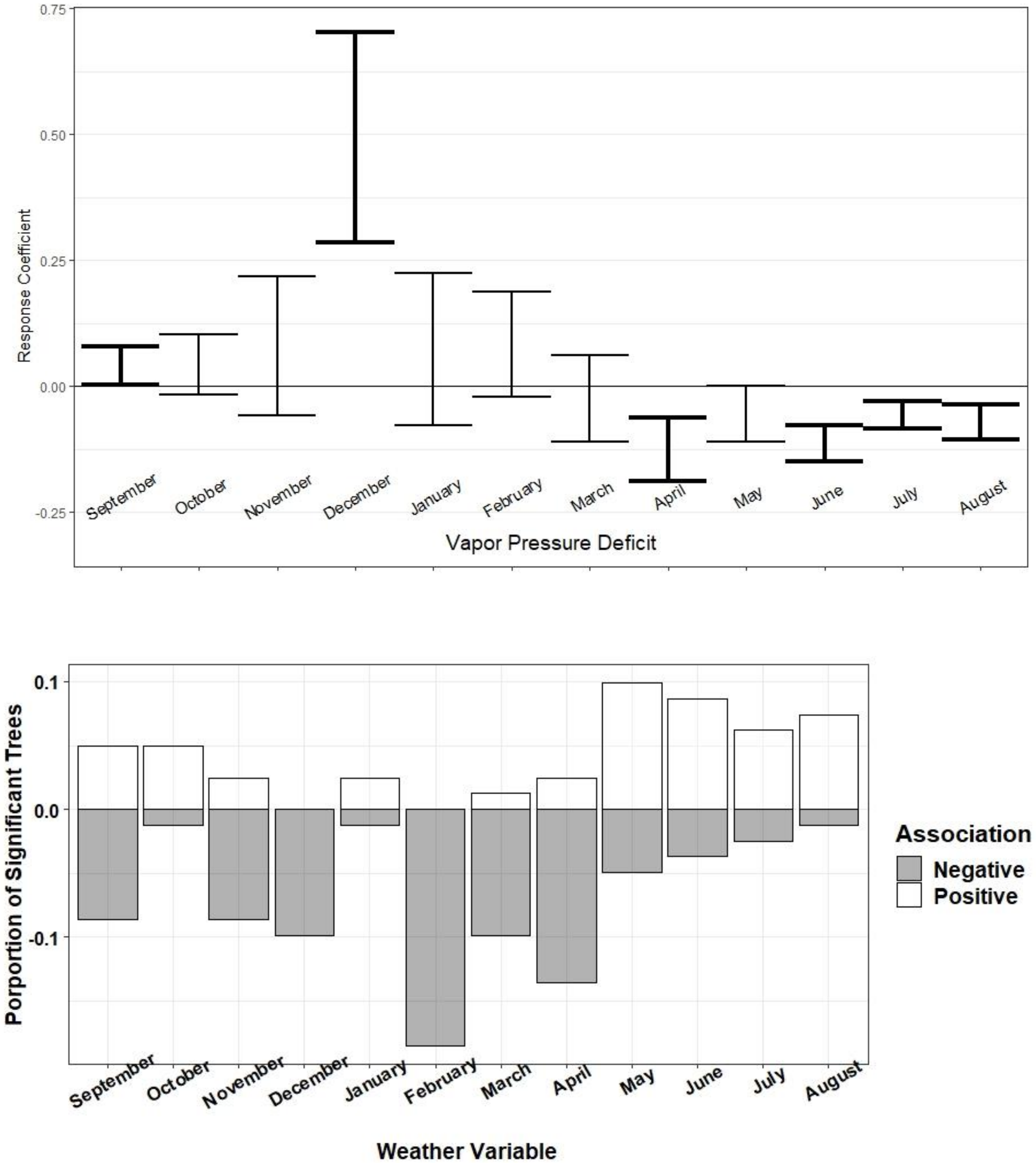


Fig. 3.10 Response coefficients for monthly average maximum daily vapor pressure deficit, as a predictor of ring widths of *P. menziesii*, with 95% confidence error bars shown (top), and number of positively and negatively significantly associated individuals as a proportion of the whole sample population (bottom). September-December are of the year preceding the growing season. Significant positive or negative associations with bolded error bars. Ring widths were detrended and normalized, vapor pressure deficits were normalized by site.

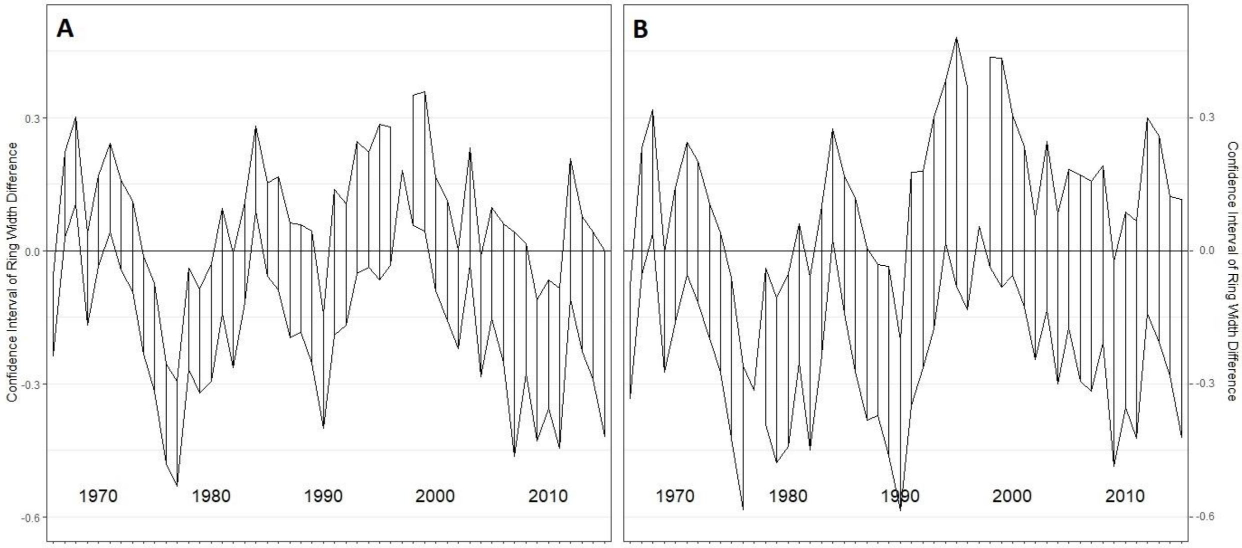


Fig. 3.11 Confidence intervals for the difference between detrended and normalized ring widths of *A. macrophyllum* and *P. menziesii*, from 1967 to 2016, for Random, DNR, and Landowner sites (A), and only Random sites (B). Confidence intervals below zero indicate *A. macrophyllum* with less detrended and normalized ring widths than *P. menziesii*.

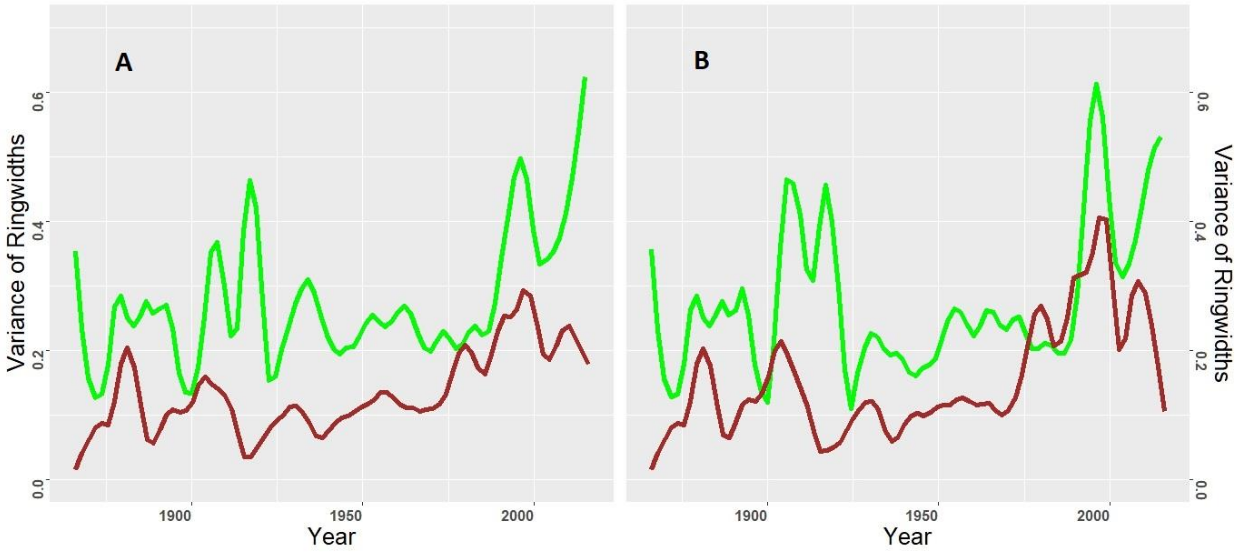


Fig. 3.12 Variance of detrended and normalized ring widths over time, for both *A. macrophyllym* (green) and *P. menziesii* (brown), from 1866 to 2016, using data from Random, DNR, and Landowner sites (A), and from only Random sites (B) . Both *A. macrophyllym* and *P. menziesii* have recent increases in variance, and variance in ring widths is consistently higher for *A. macrophyllym*, but recent years show a dramatic increase in variance of *A. macrophyllym* compared to *P. menziesii*.

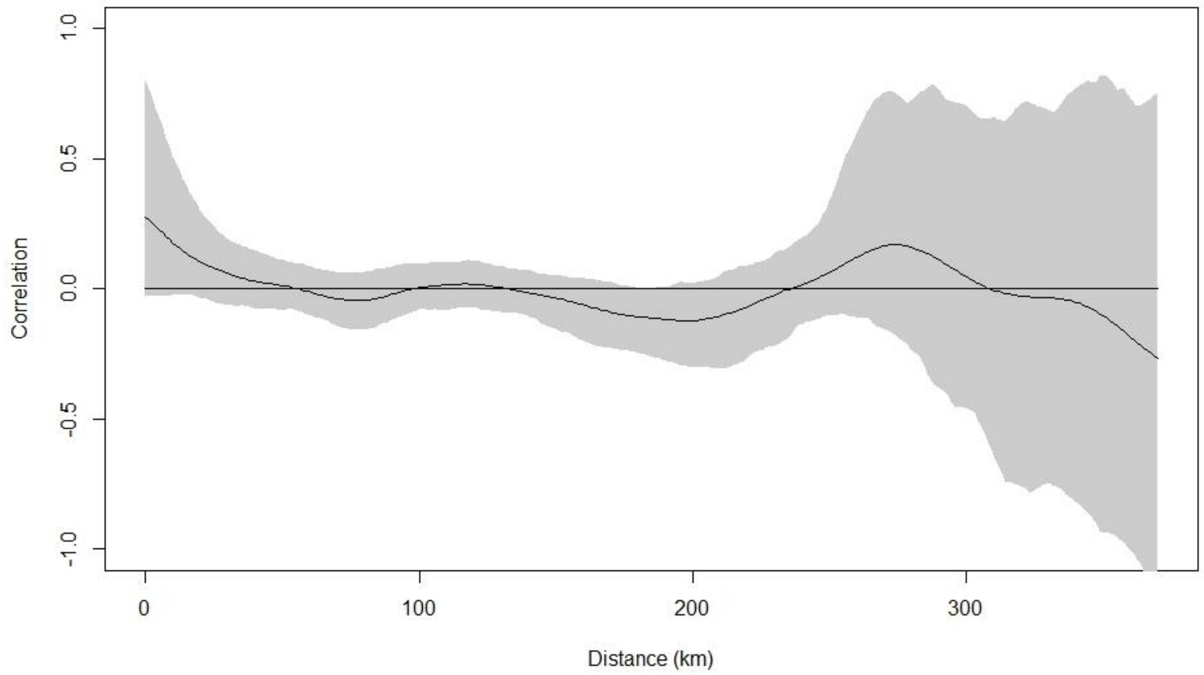


Fig. 3.13 Spatial autocorrelation of site average last year above average growth, for *A. macrophyllum*, using data from all site types. The grey shaded region represents the 95% confidence interval. There is potential local spatial clustering, but only at distances less than 50 km.

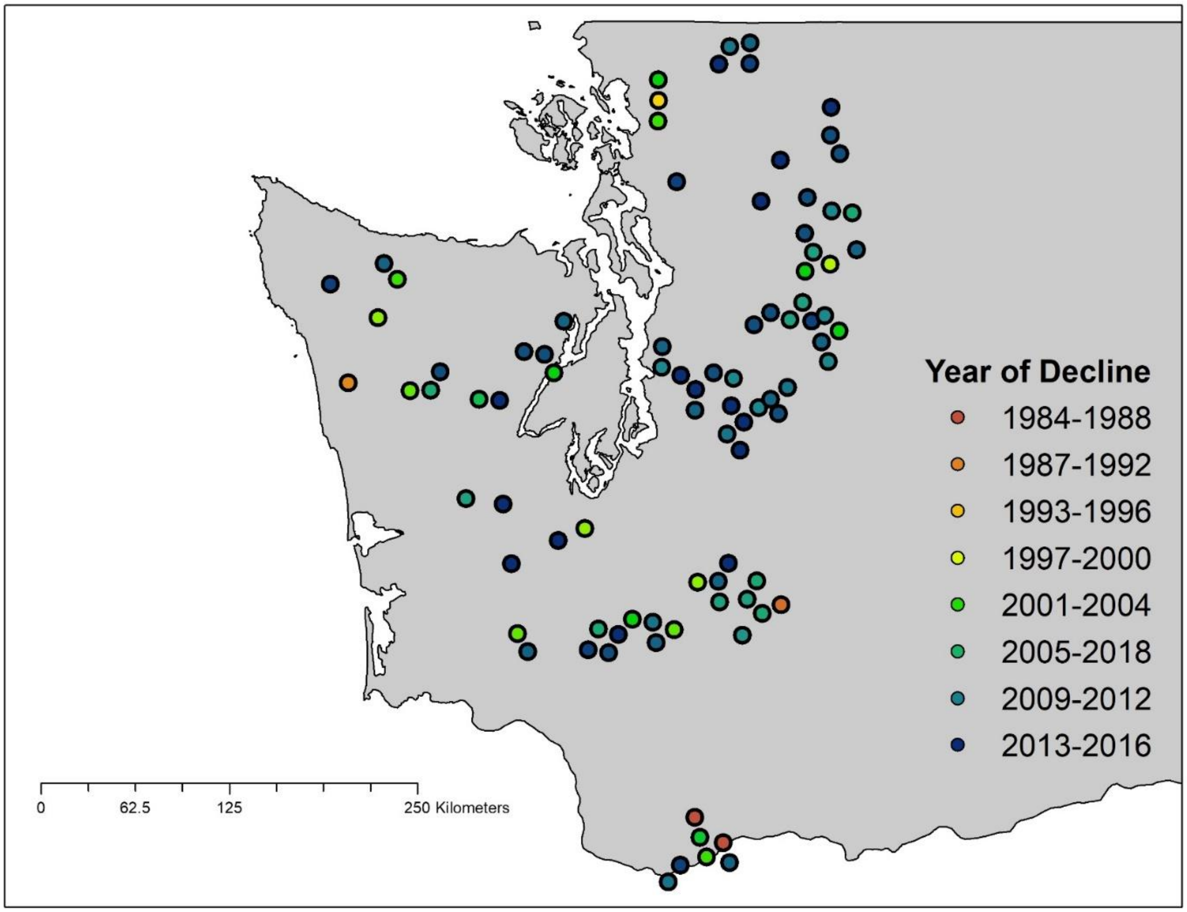


Fig. 3.14 The most recent year of above-average-growth for *A. macrophyllum*, calculated by determining the last year when growth exceeded the individual tree's negative exponential growth curve model, averaged by site, with all site types included. This was used as a proxy to compare beginning of decline initiation across sites. Visually, it appears there may be sub-50-kilometer clustering, but no pattern at larger spatial scales, suggesting a synchronous beginning of decline.