

Bigleaf maple, *Acer macrophyllum* Pursh, decline in western Washington, USA

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ABSTRACT

Acer macrophyllum is a prominent component of the western Washington landscape where it performs ecological, economic, and cultural functions. Reports of its decline and increased mortality in the Pacific Northwest were documented beginning in 2011. Symptoms of this decline include a systemic loss of vigor, loss of transpiration, and reduced photosynthesis due to leaf loss. We conducted a preliminary study of *A. macrophyllum* decline across western Washington in 2014–2015 and observed decline symptoms across the region, but we did not detect any specific biotic causative agents. We subsequently conducted a multi-approach study in 2017 to quantify the spatial and temporal patterns of *A. macrophyllum* decline in western Washington, and to examine biotic and abiotic associations with its decline. We sampled in urban and suburban areas, and in wildland forests, and collected site-specific data to test for associations with decline. We also measured elemental concentrations in foliar and soil samples to determine their association with decline. Lastly, we conducted a dendrochronological analysis to ascertain the spatial and temporal patterns of decline. We report that *A. macrophyllum* decline is a recent phenomenon, particularly since 2011, that was positively associated with sites closer to roads and with increased development, and with increases in summer temperatures. Site conditions, especially hotter urban sites, are predisposing *A. macrophyllum* to mortality. We did not detect a consistent biotic agent that could be implicated in *A. macrophyllum* decline. We contend that abiotic factors are either causing direct mortality to *A. macrophyllum*, or making them vulnerable to opportunistic biotic agents. The results of this study inform mitigating management strategies for *A. macrophyllum* in the forest of the Pacific Northwest.

1. Introduction

Tree mortality is an inherent component of forest ecosystem dynamics. However, in recent years, particularly in the forests of western North America, tree mortality rates are higher than historical conditions (Rehfeldt et al., 2009; van Mantgem et al., 2009; Cohen et al., 2016; Freeman et al., 2020). In some tree species, increased mortality can be a result of increases in insect outbreaks and epizootics of plant pathogens (Rizzo et al., 2002; Morin et al., 2007; Kurz et al., 2008; Stone et al., 2008; Cudmore et al., 2010). For example, decline in Pacific madrone, *Arbutus menziesii* Pursh (Elliott et al., 2002), white pines (Geils et al., 2010), and trembling aspen, *Populus tremuloides* Michx. (Ruess et al., 2021), have been linked to pathogens. Widespread mortality of lodgepole pine, *Pinus contorta* Douglas, has been linked to increased outbreak intensity of mountain pine beetle (Logan and Powell, 2001; Sambaraju

et al., 2012). In the case of the lodgepole pine mortality, warming temperatures, specifically warmer winter temperatures, led to decreased overwintering mortality in mountain pine beetle, resulting in higher population densities and greater mass attacks on host trees (Carroll et al., 2004; Aukema et al., 2008; de la Giroday et al., 2012). Climate change and other anthropogenically-derived sources of plant stress are perhaps pushing some species to the brink of their tolerance, resulting in either direct mortality or indirect mortality by opening a window of opportunity for biotic disturbance agents (Carnicer et al., 2011; Anderegg et al., 2013; Weed et al., 2013; Tobin et al., 2014; Allen et al., 2015). In this study, we investigated the spatial and temporal patterns, and potential abiotic and biotic factors, associated with the recent decline of bigleaf maple, *Acer macrophyllum* Pursh, in western Washington.

Acer macrophyllum is a deciduous, hardwood species native to

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western North America, from coastal California to British Columbia (Ruth and Muerle, 1958; Minore and Zasada, 1990). It is typically associated with colluvial and alluvial soils and is common on shallow rocky sites throughout its range (Franklin and Dyrness 1988). Its best growth occurs in areas with abundant soil moisture, such as river terraces, floodplains, and seepage sites on lower portions of slopes, and often occurs in patches within or on the streamside edges of conifer-dominated riparian communities (Peterson et al., 1999). *Acer macrophyllum* is limited by lack of moisture and cold temperatures at higher elevations, 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). Stems can re-sprout from the stump or root crown after fire, cutting, or herbicide application, and are adapted to rapid growth in canopy openings where stump sprouts compete with Douglas-fir in clear-cut stands (Dobkowski, 1995). Stump-sprouted *A. macrophyllum* stands are common after logging, and often form large dominant clumps where herbicides are not applied. It regenerates well from seed and is found in stands of all ages with the best survival and growth in openings, particularly in pole-sized forests; however, rodents often limit regeneration of *A. macrophyllum* through seed predation (Fried et al., 1988). Primary wildland forests with larger *A. macrophyllum*, and second and third growth managed forests with a mixture of *A. macrophyllum* and conifer species are common in Oregon and Washington.

In addition to its presence in wildland and managed forests, *A. macrophyllum* is a prominent deciduous component of urban and suburban forests in the Pacific Northwest (Hutyra et al., 2011; McLain et al., 2012), where it is one of the few tree species seemingly able to support the region's epiphytes, which are otherwise restricted on trees species growing in less populated areas and under lower levels of anthropogenic-derived pollution (Callahan et al., 2019). It is also one of the few commercially important deciduous species from Pacific coast forests (Minore and Zasada, 1990). Ecologically, it increases nutrient turnover rates (Fried et al., 1990), provides habitat for wildlife (Neitlich and McCune, 1997; Peterson et al., 1999), and is a species of cultural importance in the region (Fleisher, 1980).

Acer macrophyllum has been reported as declining in health and vigor throughout its entire range in western Washington since 2011. Symptoms of decline include deformed, wilted, and shrunken leaves with chlorotic margins and red to brown scorched tips, partial to entire crown dieback, and tree mortality (Ramsey, 2016; United States Forest Service, 2017; Betzen, 2018). Potential causes of a decline were initially hypothesized to be a plant pathogen, an anthropogenically-induced change in nutrient cycling or introduction of toxins, and/or shifts in climate beyond the limits of *A. macrophyllum* tolerance. These potential causes have been implicated in causing increased incidence of mortality and disease and reduced growth rates in forests (Woodman, 1987; Kurz et al., 1995; Hicke et al., 2012), as well as being the primary causative agent in the decline of several specific tree species (Kandler and Innes, 1995; Beier et al., 2008; Loo, 2009).

We conducted a multi-year, multi-approach study to quantify the spatial and temporal patterns of *A. macrophyllum* decline in western Washington, and to identify potential abiotic and biotic factors associated with decline. We sampled from forest sites in urban, suburban, and wildland forests of western Washington to document decline and collect a suite of site-specific data to test for associations with decline. Foliar and soil samples from sites were collected to measure elemental concentrations in each to investigate associations with decline. Samples from sites and trees in decline were bioassayed for the presence of plant pathogens. Lastly, we collected increment cores from healthy and declining stems and conducted a dendrochronological analysis to ascertain the spatial and temporal patterns of decline.

2. Materials and methods

2.1. Preliminary sampling

In 2014–2015, convenience sampling along roads was conducted around western Washington to provide an initial assessment of the spatial extent of decline (Fig. 1). A total of 63 *A. macrophyllum* stems that were noticeably declining were sampled, and diameter at standard height (dsh, ~1.4 m from the ground) was measured. In addition, foliar, branch, root, and decayed wood samples were taken from each of the 63 stems and soil milieu and analyzed for the presence of several plant pathogens including species of *Armillaria*, *Ganoderma*, *Phytophthora*, *Pythium*, *Nectria*, *Neonectria*, and *Verticillium*, and for *Verticillium albo-atrum*, *V. dahlia*, and *Xylella fastidiosa*. Samples were submitted to the Washington State University Plant and Insect Diagnostic Lab, Puyallup, WA, or to the Oregon State University Plant Disease Clinic, Corvallis, OR for screening using a variety of techniques including microscopic examination, soil baiting, direct isolation on selective media, PCR, and DNA sequencing.

2.2. Study sites

Full methodological details are available in Betzen (2018). Briefly, based upon findings from preliminary sampling efforts, we randomly selected 15 of the 63 sites from 2014 to 2015 for resampling in 2017; these resampled sites were selected within 10 regional subdivisions of western Washington (1 or 2 sites per regional subdivision). We also randomly selected 59 sites on public land from areas known to contain *A. macrophyllum* based on distributional data from the USDA Forest Service Forest Inventory Analysis (2017). Sites on public land included the Mount Baker-Snoqualmie National Forest (n = 17 sites), Gifford-Pinchot National Forest (n = 7), Olympic National Forest (n = 7), Olympic National Park (n = 6), North Cascades National Park (n = 1), Columbia River Gorge National Scenic Area (n = 3), King County I-90 corridor (n = 7), Washington Park Arboretum, and City of Seattle Cedar River Municipal Watershed (n = 8). In addition, 7 sites were located on private land (i.e., landowners who contacted the authors, generally in response to a declining *A. macrophyllum* on their property). Lastly, we sampled from 36 roadside sites *ad hoc*; these sites were selected based on the presence of decline. Locations of all sites are shown in Fig. 1, and 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 and Franklin, 1979).

At each of the 15 resampled sites, we installed one 40.47 m² plot centered on the *A. macrophyllum* sampled in 2014–2015; if the previously sampled tree could not be relocated, the largest diameter stem of *A. macrophyllum* within 30 m of the georeferenced location was selected. We also selected 1–2 additional 40.47 m² plots that were ~ 500 m away in opposite directions along the road to better ascertain the spatial extent of decline from previously-sampled sites that were known to contain declining *A. macrophyllum*. At each of the 59 randomized sites on public lands, we installed one 40.47 m² plot centered on a target tree. Target trees were chosen by selecting the largest diameter stem of *A. macrophyllum* within 30 m of a randomly generated spatial location chosen *a priori*. All randomly selected sites were within 200 m of a road or trail for ease-of-access purposes. At each of the 7 landowner plots, we installed one 40.47 m² plot centered on a *macrophyllum* with symptoms of decline. The center of all plots was georeferenced.

2.3. Measurement of abiotic and biotic variables

Within each 40.47 m² plot, we recorded the elevation, slope, and aspect, and measured soil pH. We also identified and measured the dsh of all stems ≥ 5 cm to quantify plot basal area. For every *A. macrophyllum* ≥ 5 cm in the plot, we also recorded the presence or absence of epicormic branching, visible signs of disease (e.g., heart-rot,

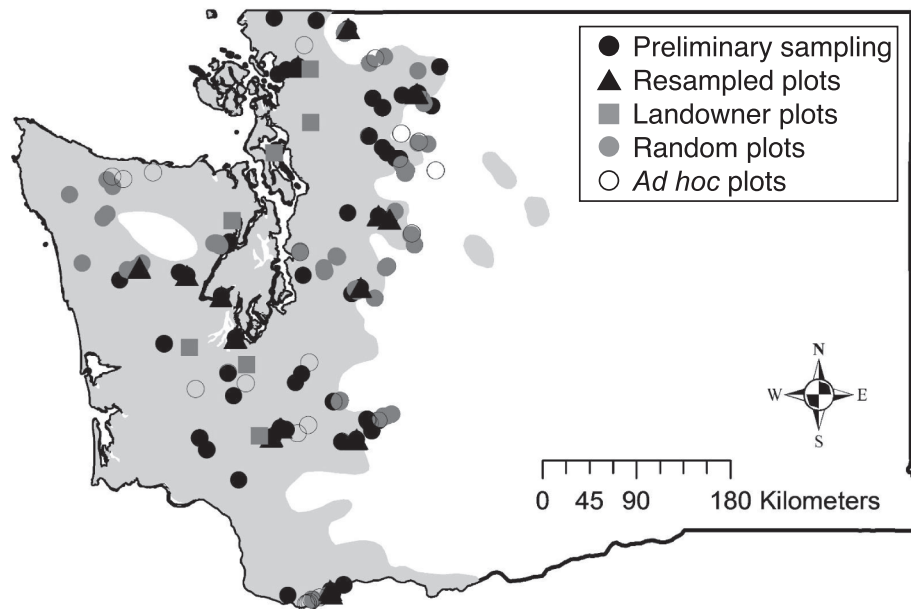


Fig. 1. Preliminary (2014–2015) and additional plots (2017) sampled for *A. macrophyllum* decline. The grey area indicates the native range of *A. macrophyllum* in western Washington (Minore and Zasada, 1990).

Armillaria spp.), and any visible signs of insect herbivory that could be detected from the ground. In addition, we selected up to three of the largest *A. macrophyllum* stems per plot for leaf sampling; the chosen stems were also used in subsequent dendrochronological and elemental analyses (see below). From each stem, we randomly collected leaves by hand or through the use of an extendable 10 m pole clipper. Samples consisted of compacted leaves, ~2 L in volume. Leaves were thoroughly examined for any herbivorous insects. The severity of *A. macrophyllum* decline was calculated based upon four metrics: crown dieback, thinning, discoloration, and reduced leaf size. Severity for each metric ranged from 0 (i.e., no visible signs of crown dieback) to 1 (i.e., 100% crown dieback). However, because severity calculations based on the four metrics were subsequently found to be bimodally distributed (i.e., the metric scores were either 0 or close to 1), we considered the presence or absence of *A. macrophyllum* decline as a binary response variable.

We used ArcGIS (Environmental Systems Research Institute, Redlands, CA) to measure the minimum distance between each plot and the nearest unpaved and paved road. We also overlaid a 1 × 1 km grid cell centered on each plot from which we estimated the proportion of the grid cell that was classified as forested/herbaceous, or developed, according to the National Land Cover Database (Homer et al., 2015). The land cover classes of deciduous forest, evergreen forest, mixed forest, grasslands/herbaceous, woody wetlands, and emergent herbaceous wetlands were used to denote forested/herbaceous, and the land cover classes of low intensity residential, high intensity residential, and commercial/industrial/transportation were used to denote developed land (Homer et al., 2015). We also compiled monthly records of precipitation, mean temperature, maximum temperature, minimum vapor pressure deficit, and maximum vapor pressure for June, July, and August for each year from 2015 to 2017; data were obtained from the PRISM Climate Group (2017). Data from June, July, and August in each year were averaged to represent recent summer conditions.

Using the presence or absence of *A. macrophyllum* decline in randomly-selected plots ($n = 59$ plots) as a binary response variable, we evaluated the main effects of weather variables, elevation, slope, aspect, soil pH, distances from paved or unpaved roads, proportion of forested/herbaceous land cover, proportion of developed land cover, and basal area using mixed stepwise logistic regression in R (R Core Team, 2018). Significance of parameter estimates were based on the likelihood ratio

chi-squared, G^2 . In this analysis, we only used data from the randomly-selected plots since the preliminary, landowner and *ad hoc* plots were chosen with bias as they were already known to contain declining *A. macrophyllum*.

Data from randomly-selected plots were used to examine the spatial pattern of decline. In this analysis, we considered the georeferenced location of individual *A. macrophyllum* stems that were rated as either in decline or not ($N = 246$ stems). We used a nonparametric spatial autocorrelation function in the *ncf* package (Bjørnstad and Falck, 2001; Bjørnstad, 2020) in R (R Core Team, 2018; Bjørnstad, 2020) to estimate spatial autocorrelation. Confidence intervals (95%) for the spatial autocorrelation function were estimated as the 0.025% and 0.975% quantiles of a bootstrapped distribution based on 250 replications (Bjørnstad, 2020).

2.4. Soil and foliar elemental analysis

We collected soil and foliar samples at each random-selected plot for use in elemental analyses to measure the association between elements and decline. Soil samples consisted of ~2 kg of soil collected using a 2.54 cm diameter by 30 cm deep soil core. Cores were extracted at 2, 4, 8, and 10 m from the center tree, located along the four cardinal directions (N, S, E, and W), and combined into one aggregate sample. Following collection, soil samples were weighed (wet weight) and then stored at ~4 °C until sieved at 2 mm, dried at ambient temperature, ground and homogenized using a ceramic mortar and pestle, and reweighed (dry weight). Foliar samples were collected from each *A. macrophyllum* selected for coring (up to three stems per plot). Leaves were collected by hand or through the use of an extendable 10 m pole clipper. Samples consisted of compacted leaves, ~2 L in volume. Foliar samples were dried at ambient temperature, then ground and homogenized by hand using a ceramic mortar and pestle. Elemental soil and foliar samples were analyzed using a CHN Analyzer 2400 (PerkinElmer, Inc., Waltham, MA) and a ICAP 61E (ThermoFisher Scientific, Jarrell-Ash, Waltham, MA) at the Analytical Service Center within the School of Environmental and Forest Sciences (University of Washington, Seattle, WA). Concentrations (ppm) 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.

Concentrations (ppm) of each element were transformed using $\log_{10}(y + 1)$ and tested for their association with the presence or absence of *A. macrophyllum* decline using mixed stepwise logistic regression in R (R Core Team, 2018). Significance of parameter estimates were based on the likelihood ratio chi-squared, G^2 . Separate analyses were conducted for soil and foliar samples. For soil samples, analyses were conducted at the level of the random plot, and whether or not the random plot contained a declining *A. macrophyllum* stem. For foliar samples, analyses were conducted at the level of the individual stem and whether or not the stem was recorded as declining; foliar samples from a total of 149 *A. macrophyllum* stems were used in the analysis from which 35 were recorded as declining.

2.5. Dendrochronological analyses

We cored up to three of the largest *A. macrophyllum* and *Pseudotsuga menziesii* (Mirbel) Franco stems in each plot using a 61 cm long by 5.15 mm wide, Hagl f increment borer (Forestry Suppliers, Jackson, MS). In trees with multiple stems, only the largest stem was cored. Marked *A. macrophyllum* from the preliminary survey, when located, were cored. Across all plots, a total of 232 *A. macrophyllum* stems, and 106 *P. menziesii* stems were initially cored. Each stem was cored twice, on opposite sides of the stem, both perpendicular to the direction of the slope. Cores extended to the pith of the tree, or up to 46 cm, whichever was shorter. After collection, cores were air dried at ambient 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).

Core measurements were crossdated visually with the aid of COFECHA (Holmes, 1983), with cores visually checked and edited to fix missing and duplicate rings. Analyses were limited to the most recent 50 years, and cores from trees < 50 years were omitted. Since two cores were extracted from each tree, the core with the least correlation to the series was discarded. Thus, a total of 177 *A. macrophyllum* (mean \pm SE dsh = 49.4 \pm 1.8 cm) and 82 *P. menziesii* (mean \pm SE dsh = 75.6 \pm 4.1 cm) were used in subsequent dendrochronological analyses. Ring measurements were detrended using a negative exponential model of biological growth according to:

$$y = a \exp(bt) + k \quad (1)$$

where y is radial increment, t is cambial age, and a , b , and k are fitted parameters (Fritts, 2001), using the dplR package (Bunn, 2008) in R (R Core Team 2018). Detrended ring widths were then normalized by subtracting the mean and dividing by the standard deviation, and converted into basal area increment, which is thought to be more representative of overall tree growth than ring width (Pedersen, 1998; Bigler and Bugmann, 2003). We used a Welch's t -test in R (R Core Team 2018) to determine if the detrended, normalized growth rates of *A. macrophyllum* were reduced compared to *P. menziesii* across all plots, and only from randomly-selected plots, for each year between 1965 and 2016.

We also used response function analysis (Briffa and Cook, 1990; Fritts 2001) to examine the relationship between growth responses of *A. macrophyllum* and mean monthly temperature, precipitation, and vapor pressure deficit. Climate data were obtained for each site and month between January 1981 and December 2016 (PRISM Climate Group 2017). Climate variables were normalized by subtracting the mean and dividing by the standard deviation. For each cored *A. macrophyllum*, detrended, normalized ring widths for each year within the timeframe (1981–2016) were compared with monthly values for each climate variable. We used a basic bootstrapping regression model with 1000 replications (Fritts et al. 1990) to construct 95% confidence intervals for the correlation coefficient between each

monthly climate variable and ring width. Correlation coefficients with confidence intervals that did not include 0 were considered as significantly positive or negative relationships.

Additionally, the most recent year of above-average-growth for each tree was recorded by determining the last year when growth exceeded the stem's negative exponential model. This most recent year of above-average-growth was then used as a proxy to estimate the year of decline in *A. macrophyllum*. We also estimated the spatial autocorrelation in the year of decline to determine whether the timing of *A. macrophyllum* decline followed a spatially clustered pattern (which could occur through biotic causes) or if the patterns of decline were across larger spatial scales (such as though regional abiotic causes). We used a nonparametric spatial autocorrelation function in the ncf package (Bj rnstad and Falck, 2001; Bj rnstad, 2020), and 95% confidence intervals for the spatial autocorrelation function were estimated as the 0.025% and 0.975% quantiles of a bootstrapped distribution based on 250 replications (Bj rnstad, 2020).

3. Results

3.1. Preliminary sampling

Signs of *A. macrophyllum* decline were observed across western Washington and did not initially reveal any spatial pattern other than declining trees were present across the entire extent of the preliminary sampling area (Fig. 2). Declining stems were found to be present across a range of *A. macrophyllum* age classes, as proxied by dsh (Fig. 2). Among all the leaf, branch, soil, root, and decayed wood samples collected from the 63 declining *A. macrophyllum* stems, no samples were positive for species of *Verticillium*. *Armillaria* spp. were detected in 11% of declining stems, and *Ganoderma* spp. were found in 3% of the declining stems, which suggests that neither root disease is the primary causal agent of *A. macrophyllum* decline in western Washington (Omdal and Ramsey-Kroll, 2011). *Pythium* species were present in most of the forest soils and roots sampled, although their role is not well understood and does not appear to be driving the decline (Abair et al. 2016). Other fungi isolated or identified, including *Kretzschmaria deusta*, were not found with enough consistency to attribute as causal agents. Species of *Neonectria* and *Nectria* were also not consistently detected. In samples collected in 2017, we found no evidence of *Xylella fastidiosa* or *Phytoplasma asteris*; however, two samples from the North Cascades were positive for *Verticillium* species (Ramsey, 2016; United States Forest Service, 2017). To date, no pathogen has been consistently detected in western Washington to explain the widespread occurrence of *A. macrophyllum* decline across the region, even in stems that were purposely sampled because they were noticeably in decline.

3.2. Abiotic and biotic variables associated with *A. Macrophyllum* decline

Within randomly-selected sites (59 sites, 245 stems), we observed 23.5% of *A. macrophyllum* stems with symptoms of decline (i.e., crown dieback, thinning, discoloration, and reduced leaf size). Across all sites previously sampled in preliminary efforts (40 sites, 243 stems), roadside *ad hoc* sites (37 sites, 76 stems), and in landowner plots (7 sites, 75 stems), which were non-randomly selected, we observed decline in 48.1% of *A. macrophyllum* stems. Across all sites, including non-random sites, signs of disease (e.g., heart-rot, *Armillaria* spp.) were detected in 5 stems without signs of decline, and 30 stems with signs of decline. Also, we detected signs of insect damage (leafhopper, leaf miner, and aphid damage) in 18 stems without signs of decline, and 15 stems with signs of decline; however, in both cases (i.e., stems with or without decline), populations of insects were detectable but were not at high enough densities to cause noticeable defoliation. Epicormic branching was more likely detected in stems with decline; 66.8% of declining stems had epicormic branching, while 34.9% of stems without signs of decline had epicormic branching. Collectively, all sites indicated that

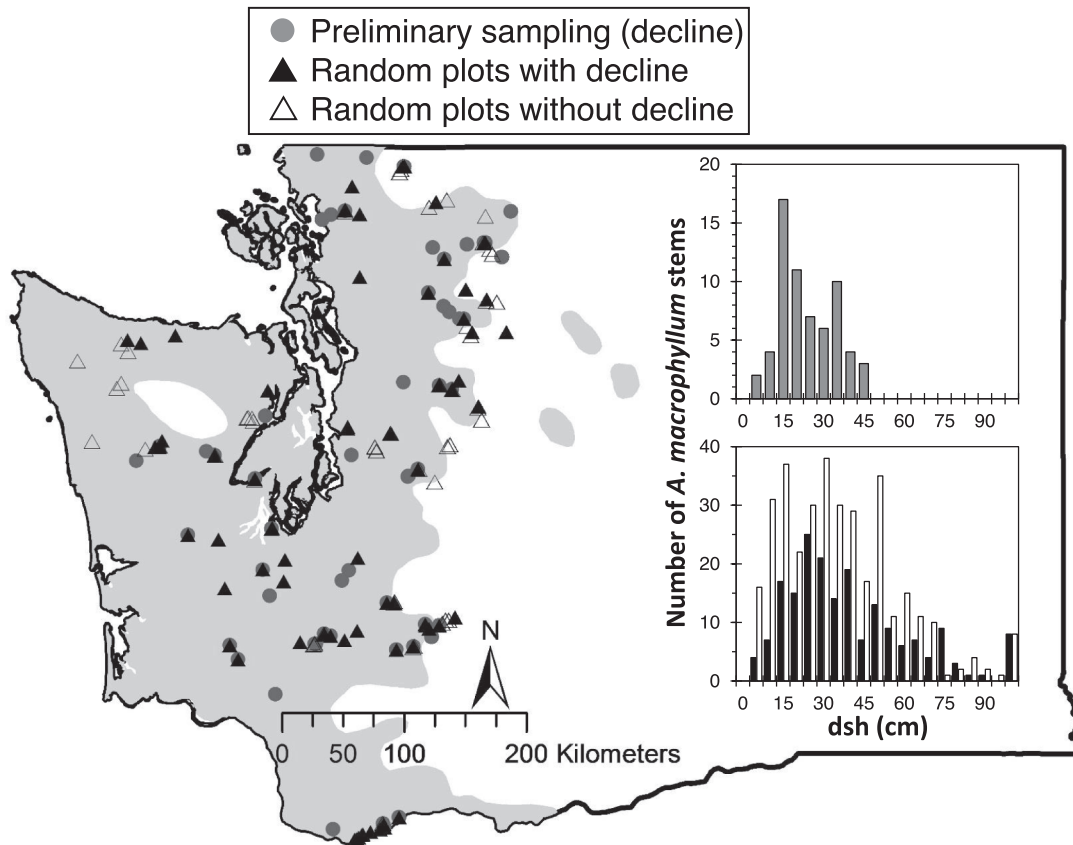


Fig. 2. Locations and histogram of the diameter at standard height (dsh) of declining *A. macrophyllum* from preliminary sampling efforts, and the presence or absence of declining *A. macrophyllum*, with the corresponding histogram of the respective dsh, from randomly-selected plots. In both cases, decline was observed across a range of *A. macrophyllum* age class.

A. macrophyllum decline was present throughout western Washington and across all *A. macrophyllum* age classes (Fig. 2); however, no specific insect species has been consistently detected in declining stems, and at high enough densities to cause detectable levels of defoliation or dieback.

Abiotic and biotic predictor variables that were significantly associated with the presence of *A. macrophyllum* decline in randomly-selected plots are listed in Table 1. Increases in mean summer temperature and mean maximum summer temperature were positively associated with the presence of *A. macrophyllum* decline. The probability of *A. macrophyllum* decline increased in areas located closer to a paved road, increased in sites with reduced forest and herbaceous cover, and increased in sites with more human development. The effect of mean summer precipitation, mean summer maximum vapor pressure deficit, elevation, slope, aspect, soil pH, distance from unpaved roads, and basal area were not significant (all $P > 0.05$). Collectively, the analyses suggest that sites that were more likely to contain declining *A. macrophyllum* stems were hotter areas closer to paved roads and other impervious

Table 1
Abiotic and biotic predictor variables significantly associated with the presence of *A. macrophyllum* decline from randomly-selected plots.

	Parameter estimate (±SE)	Z value	P-value
Mean summer temperature (°C)	0.762 (0.293)	2.603	0.009
Mean summer maximum temperature (°C)	0.695 (0.262)	2.652	0.008
Distance to paved road (m)	0.007 (0.003)	2.169	0.030
Proportion of forest/herbaceous cover	-8.276 (3.351)	-2.470	0.014
Proportion of area developed	9.202 (4.175)	2.204	0.028

surfaces. We did not observe significant spatial autocorrelation in decline, although there was a tendency for declining stems to be in close proximity to each other based on the estimate of the local spatial autocorrelation, or the estimate as the distance between sampling locations approaches 0 (local spatial autocorrelation estimate = 0.31; 95% CI = -0.04, 0.53; Fig. 3). Coupled with the lack of a consistent biotic

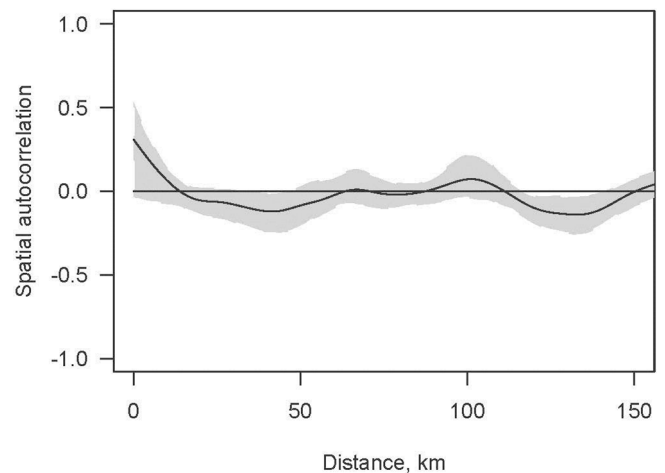


Fig. 3. Spatial autocorrelation in the presence of *A. macrophyllum* decline from randomly-selected plots (N = 246 stems). Although there was evidence of local spatial clustering (i.e., which is the estimate of spatial autocorrelation as the distance between sampling locations approaches 0), the estimate was not significant. The grey area represents the 95% confidence intervals of the estimate of spatial autocorrelation.

causative agent implicated in the decline of *A. macrophyllum*, the results suggest that current abiotic conditions are predisposing *A. macrophyllum* to decline.

3.3. Soil and foliar elemental analysis

In soil samples, Ca ($G^2 = 4.02, P = 0.045$), Cr ($G^2 = 9.12, P = 0.002$), Mn ($G^2 = 5.77, P = 0.016$), and P ($G^2 = 4.74, P = 0.029$) were significantly associated with *A. macrophyllum* decline at randomly-selected sites (Fig. 4A). All other elements were not significantly associated with *A. macrophyllum* decline (all $P > 0.05$). Increases in Ca, Mn, and P were associated with a decreased probability of *A. macrophyllum* decline, whereas an increase in Cr was associated with an increased probability of *A. macrophyllum* decline. Ca, Mn, and P are well documented to be important elements for plant growth and development (Pilon-Smits et al., 2009). In contrast, Cr can be toxic to plants and is a byproduct of several manufacturing operations (Shanker et al., 2005) that could be associated with sites with increased human development, which were linked to a higher probability of *A. macrophyllum* decline (Table 1).

In foliar samples, As ($G^2 = 17.96, P < 0.001$), B ($G^2 = 12.91, P < 0.001$), and Si ($G^2 = 17.95, P < 0.001$) were significantly associated with *A. macrophyllum* decline at randomly-selected sites (Fig. 4B). All other elements were not significantly associated with *A. macrophyllum* decline (all $P > 0.05$). Increases in B and Si were associated with a decreased probability of *A. macrophyllum* decline. B is an essential element in plant growth and development (Lehto et al., 2010), and although Si is not considered to be essential to plant growth, it is reported to enhance drought resistance in plants (Coskum et al., 2016). Increases in As, which is highly toxic to plants and has a long resident life (Zhao et al., 2009), were associated with an increased probability of *A. macrophyllum* decline.

3.4. Dendrochronological analyses

Annual mean and variance in the detrended, normalized ring widths for *A. macrophyllum* ($N = 177$) and *P. menziesii* ($N = 82$) in all plots and in randomly-selected sites are shown in Fig. 5. In both tree species, we detected reduced mean growth in the detrended, normalized ring widths between 2012 and 2016 (Fig. 5A, B). We also detected more variation in *A. macrophyllum* relative to *P. menziesii*, especially between 2008 and 2016 (Fig. 5C, D). There was also greater variation in *A. macrophyllum* growth between 1992 and 1999. In contrast, variation in annual growth for *P. menziesii* was fairly consistent between 1965 and 2016 (Fig. 5C, D). The high variation in growth rates in recent years for *A. macrophyllum* reflects its decline, especially given that decline was more likely to be present in hotter, more developed sites and less likely to be present in less developed sites (Table 1). In recent years, growth rates of *A. macrophyllum*, based upon detrended, normalized ring widths, were significantly less than those of *P. menziesii* between 2014 and 2016 (Fig. 5E, 5F). Interestingly, we also detected significantly reduced growth rates between 2000 and 2006 (Fig. 5E, 5F), which could reflect a period of decline following the period of high variation in *A. macrophyllum* growth rates between 1992 and 1999 (Fig. 5C, 5D).

The growth responses of *A. macrophyllum* to mean monthly temperature, precipitation, and vapor pressure deficit are shown in Fig. 6. Warmer and drier conditions were correlated with slow *A. macrophyllum* growth across most months. When considering climate between May and August, which generally reflects the *A. macrophyllum* growing season (Campbell and Franklin, 1979), we detected a significant negative correlation between mean monthly temperatures and ring width between the months of May and August, a significant positive correlation between mean monthly precipitation and ring width in June and July, and a significant negative correlation between mean vapor pressure deficit and ring width between the months of June and August (Fig. 6).

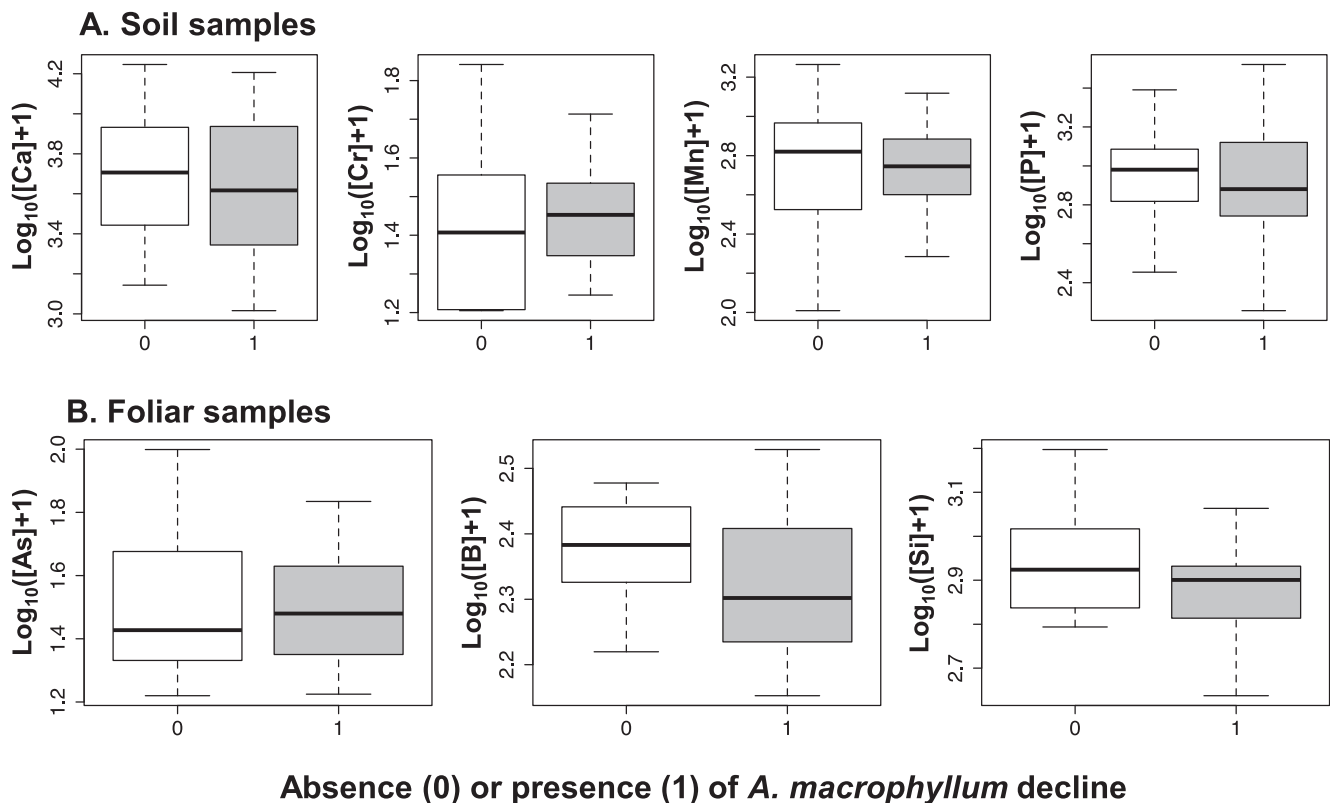


Fig. 4. Box plots of elemental concentrations (ppm, $\log_{10} + 1$) from soil (A) and foliar samples (B) based on the absence (0) or presence (1) of *A. macrophyllum* decline. A total of 24 elements were measured and tested for their association with *A. macrophyllum* decline; only elements with significant associations ($P < 0.05$) are shown.

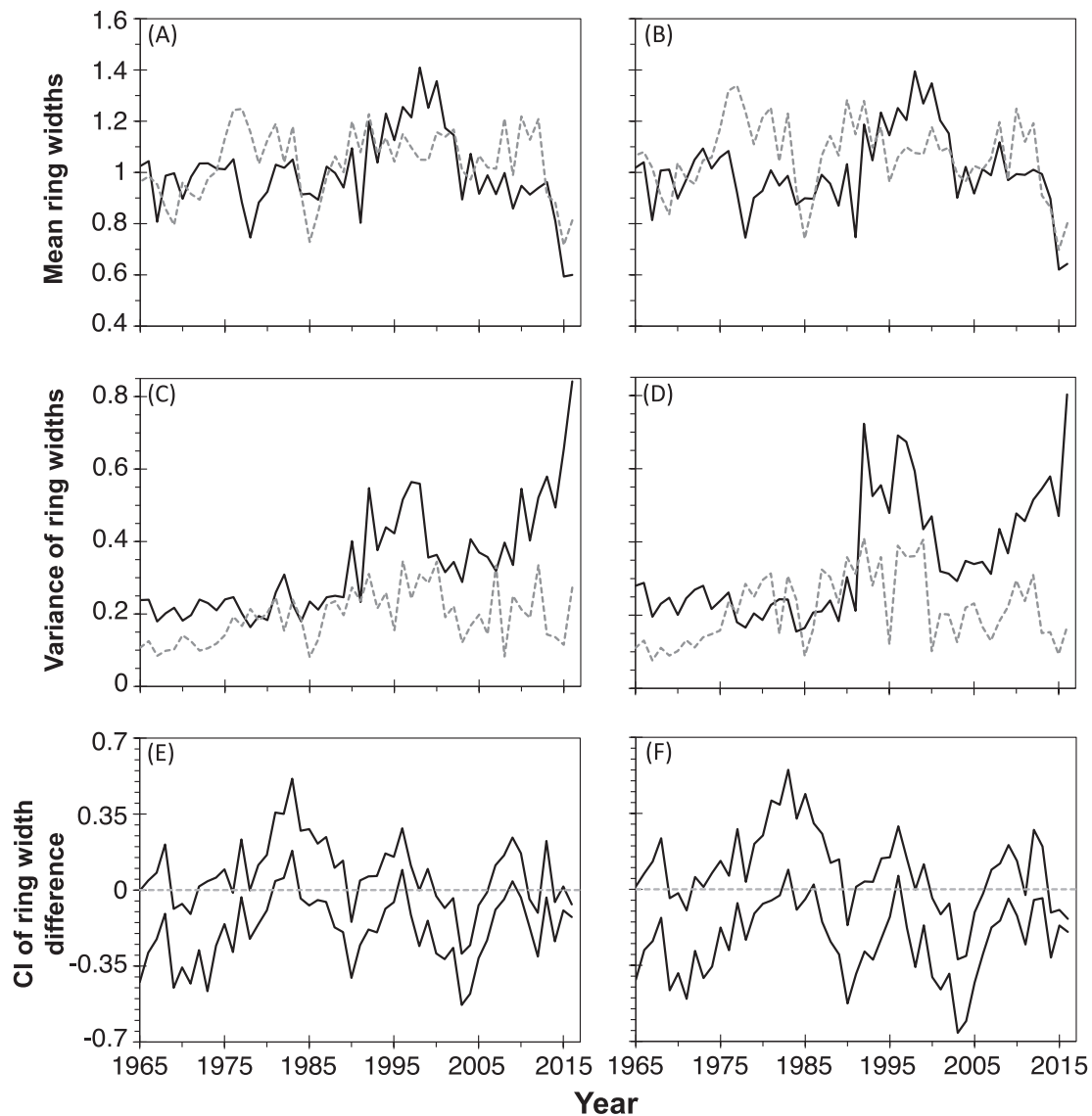


Fig. 5. Mean detrended, normalized ring widths for *A. macrophyllum* (solid black line) and *P. menziesii* (dashed grey line) from all plots (A) and from only randomly-selected plots (B), 1965–2016. Variance in detrended, normalized ring widths for *A. macrophyllum* (solid black line) and *P. menziesii* (dashed grey line) from all plots (C) and from only randomly-selected plots (D), 1965–2016. Confidence intervals in the Welch's *t*-test between detrended, normalized ring widths for *A. macrophyllum* and *P. menziesii* from all plots (E) and from only randomly-selected plots (F), 1965–2016; Confidence intervals below 0 indicate significantly less ring widths for *A. macrophyllum* relative to *P. menziesii*.

We also observed that September and December temperatures were positively correlated with growth, while September and March precipitation were negatively correlated with growth (Fig. 6), which could be related to the storing of carbohydrates for growth for the following year (Ettl and Peterson, 1995; Kusnierczyk and Ettl, 2002). Collectively, the analysis suggests that warmer months with less precipitation and increased vapor pressure deficit, particularly during summer months, were significantly associated with reduced *A. macrophyllum* growth (Fig. 6).

Across the study region, the estimated year of decline in *A. macrophyllum* in cored stems was mostly after 2011, which was observed in 64.6% of cored stems. Furthermore, 51.5% of stems were in decline between 2013 and 2016, and 18.8% from 2016 alone (Fig. 7). The dendrochronological analyses also confirmed that the decline of *A. macrophyllum* in recent years (2011–2016) occurred throughout the study region in western Washington, as opposed to being localized in one area of the study region (Fig. 7). The estimate of local spatial clustering in the year of decline was 0.41 (95% confidence interval: 0.05,

0.91) with a spatial range of 30 km (95% confidence interval: 19.4, 76.5 km; Fig. 7, insert). There was significant local spatial clustering, which suggests clustering of decline at a local site level, perhaps as a result of the sample design. However, there was no evidence of a spatial trend in the year of decline, and thus no evidence of declining *A. macrophyllum* spreading along a spatial gradient, which could be evidence of a spreading biotic agent. Collectively, the spatial analysis on the year of decline suggested a pattern of decline across a large spatial scale (Fig. 7).

4. Discussion

Decline in *A. macrophyllum* was detected across western Washington. The lack of a relationship between *dsh* and decline suggests that the decline is not specific to large, small, young, or old trees. The lack of a consistently identified biotic agent, such as a plant pathogen or insect, native or non-native, coupled with the occurrence of decline across the study region, suggests abiotic causes of decline. Indeed, the probability of decline increased in sites with higher mean and maximum summer

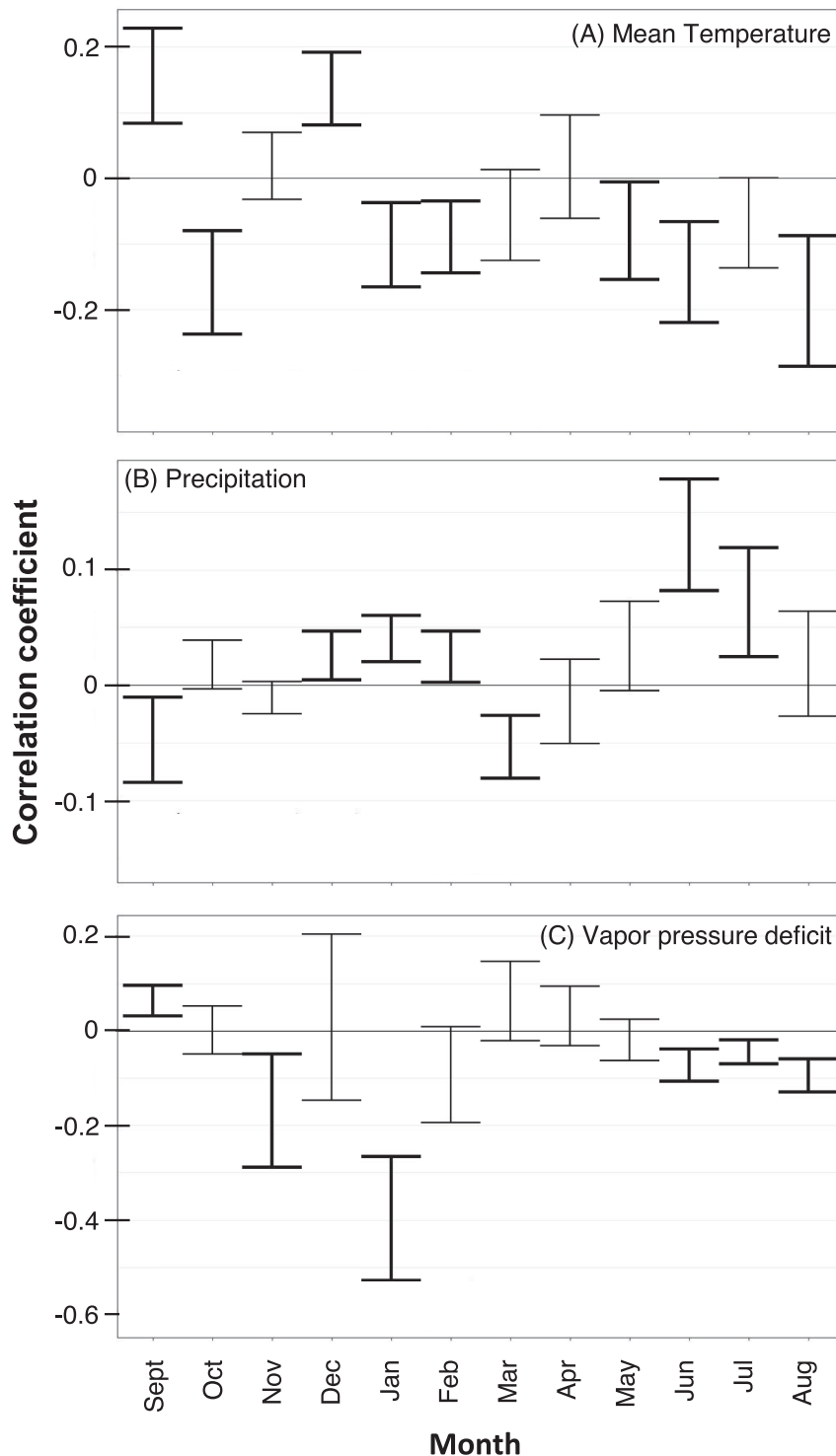


Fig. 6. Estimates of the 95% confidence interval of the correlation coefficient between yearly detrended, normalized ring widths of *A. macrophyllum* and monthly normalized mean temperature (A), precipitation (B), and vapor pressure deficit (C). Bolded monthly confidence intervals are significant as they do not include 0. The months of May to August generally corresponds to the *A. macrophyllum* growing season.

temperatures (Table 1). Recent summers in the Pacific Northwest region of North America have been marked by above average drought conditions and temperatures (Marlier et al., 2017; Watt et al., 2018). This study adds to others that have also reported on the links between increased temperatures and increased tree mortality (van Mantgem et al., 2009; Allen et al., 2010).

We also detected associations between certain site characteristics and the presence of *A. macrophyllum* decline. Increased probability of

decline was associated with sites that were closer to impervious surfaces with less forest cover and more human development (Table 1). The association between increased concentrations of Cr in soil samples, and increased concentrations of As in foliar samples, and increased probability of *A. macrophyllum* decline (Fig. 4) would also suggest the role of urbanized sites in predisposing *A. macrophyllum* to decline. Chromium can be harmful to biota, and is commonly associated with industry in urban environments (Byrne et al., 2017). Arsenic is an ubiquitous,

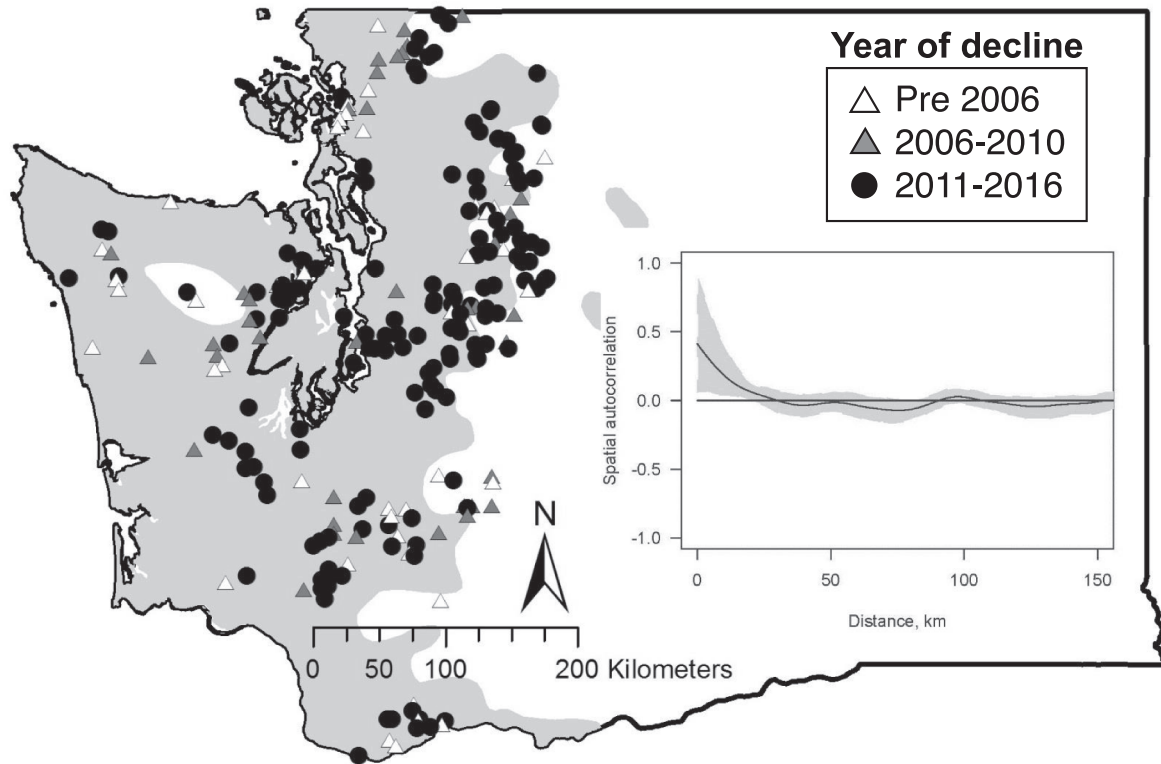


Fig. 7. Estimated year of decline in *A. macrophyllum* from dendrochronological analyses, which suggested that most stems had declined in recent years, and that decline was observed across the sampling area; plot locations were jittered for visual purposes. The insert graph depicts the spatial autocorrelation in the year of decline (95% confidence intervals in grey), which revealed local spatial clustering but no spatial trend across the sampling area.

highly toxic element, and higher concentrations of As have been associated with urbanized areas due to its association with industry (Defoe et al., 2014; Gawel et al., 2014). Although we did not directly measure the causative effect of Cr and As on *A. macrophyllum* decline, elevated concentrations of both would induce additional stress to *A. macrophyllum* that could further predispose stems to decline. Among the elements that were significantly associated with *A. macrophyllum* decline, a higher concentration of Si in non-declining stems (Fig. 4) was particularly interesting in the context of the role of abiotic stress in *A. macrophyllum* decline. Silicon has been shown to provide benefits to plants under drought conditions (Coskun et al. 2016), and has been suggested as an additive to mitigate plant stress in agricultural systems (Zargar et al., 2019). Future research should consider the causative relationship between the presence or absence of elements in soil and foliar tissues, and *A. macrophyllum* decline.

The use of dendroecology approaches to investigate tree decline has been useful in prior studies, including those that linked decline to introduced plant pathogens or insects (McEwan et al., 2006; Welsh et al., 2009; Siegert et al., 2014). For example, Leaphart and Stage (1971) used dendrochronological methods in *Pinus monticola* Douglas ex D. Don, and observed that drought conditions facilitated the development of pole blight disease in the western United States. Although we did not observe any evidence of a biotic agent causing *A. macrophyllum* decline in western Washington, our results suggest that variation in annual growth rates of *A. macrophyllum* has been particularly high in recent years (2011 and beyond; Fig. 5), with growth significantly lower than *P. menziesii* growing with *A. macrophyllum*, which corresponds to the first reports of *A. macrophyllum* decline in the state of Washington. Also, reduced annual growth of *A. macrophyllum* was significantly correlated with hotter, drier summer months (Fig. 6). The spatial analysis of decline supports the notion that *A. macrophyllum* decline is a spatially-

widespread phenomenon across its native range in Washington, and that locally spatial site conditions tend to be associated with the timing of decline (Fig. 7).

A prior study based exclusively on simulating future climate conditions and forecasting changes in species distributional ranges suggested that *A. macrophyllum* is not vulnerable to warming temperatures, in part due to its adaptive capacity (Case and Lawler, 2016). Although climate modeling studies are useful in understanding broad-scale consequences of climate change, they lack precision over smaller spatial scales. Indeed, the recent decline in *A. macrophyllum* reported here, as well as in other areas of its distributional range (Chadwick, 2015; Oregon State University, 2019), suggests that *A. macrophyllum* is more susceptible to higher temperatures, and perhaps drought conditions, than what is currently known. Also, although *A. macrophyllum* does have a latitudinally-broad geographical range, extending in coastal areas from southern California to northern British Columbia (Minore and Zasada 1990), individual trees and populations could be locally-adapted and consequently, more susceptible to recent trends in climate. This concept is supported by other studies that have found differing climate preferences among populations of the same species (Johnson et al., 2004; Mclachlan et al., 2007; Thomas et al., 2014).

5. Conclusion

Using a field-based study, we assessed the complexities of climate warming and its interconnectedness to local site characteristics to describe the widespread decline of *A. macrophyllum* in western Washington. We provide evidence that warm temperatures and local site conditions, particularly hotter urban sites that are associated with high concentrations of Cr and As, are predisposing *A. macrophyllum* to decline, even in the absence of a detectable biotic agent. Given the lack

of detected biotic agents, abiotic factors could be directly causing mortality to *A. macrophyllum*, and could also sufficiently weaken trees, making them vulnerable to opportunistic biotic agents that might otherwise not cause mortality to *A. macrophyllum*.

Credit authorship contribution statement

Jacob J. Betzen: Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Amy Ramsey:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – review & editing, Funding acquisition. **Daniel Omdal:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing – review & editing, Funding acquisition. **Gregory J. Ettl:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Funding acquisition. **Patrick C. Tobin:** Conceptualization, Methodology, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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