Modelling impacts to water quality in salmonid-bearing waterways following the introduction of Emerald Ash Borer in the Pacific Northwest, USA.

Dominic Maze
dominicmaze@gmail.com
City of Portland, Oregon, USA https://orcid.org/0009-0003-6785-0552
Julia Bond
City of Portland, Bureau of Environmental Services
Monte Mattsson
Clackamas Soil and Water Conservation District

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Abstract

Oregon ash (*Fraxinus latifolia* Benth.) wetlands and riparian forests are an important economic, cultural, and ecological resource in the Pacific Northwest, USA, and are threatened by the invasive insect, emerald ash borer (*Agrilus planipennis* Fairmmaire) (EAB). Following the discovery of EAB in Forest Grove, Oregon in June of 2022, concern has focused on EAB-induced ash mortality that has the potential to alter vegetation communities and modify wetland hydrology by elevating the water table. Of primary concern is an increase in solar loading of waterways and wetlands that are already degraded beyond meeting their beneficial uses for Endangered Species Act-listed salmonids and other cold-water species following canopy dieback of Oregon ash. Our study, begun before the first detection of EAB on the West Coast, models potential impacts of EAB-mediated Oregon ash canopy loss to temperature-related water quality on two waterways in the vicinity of Portland, Oregon. Our results indicate a significant increase in solar loading with likely negative impacts to aquatic Endangered Species Act-listed salmonids, other aquatic wildlife, and associated habitat. We forecast greater impacts to these resources outside our study scope and include management considerations and recommendations for entities with water quality-related regulatory obligations.

Introduction

Emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae), is the most destructive exotic forest insect in North American history (Herms and McCullough 2014, McCullough 2020). As of this writing, emerald ash borer (EAB) has reached 36 states in the U.S. and five Canadian provinces, leaving hundreds of millions of dead ash trees (McCullough 2020). EAB is an ecological specialist whose larvae and adults feed and congregate almost exclusively on ash species (*Fraxinus* spp., Oleaceae). In its native east-Asian range, EAB is a low-density pest of ash, while ash populations outside the insect's native range that lack evolved defense mechanisms are particularly sensitive to infestation and mortality (Haack et al. 2015). Following detection of an established EAB population in Forest Grove, Oregon in June 2022, Oregon ash (*Fraxinus latifolia*) became the most recent North American ash species to be observed infested in its native range, resulting from an unidentified dispersal event of EAB to northwestern Oregon. Widespread infestation of Oregon ash is imminent: the sole publication examining potential impacts to Oregon ash found Oregon ash to be highly susceptible to EAB (Wagner and Todd 2015). Current field surveys of EAB in northwest Oregon indicate that EAB is well-established in the discovery locale and that EAB readily infests and damages Oregon ash, in situ (Maze, personal observation). Given the high mortality rates of other, evolutionarily naive *Fraxinus* species following EAB establishment, this suggests a high probability for functional extinction of Oregon ash in its native range (Ward et al. 2021).

Oregon ash is native to the West Coast, ranging from the southern coast of British Columbia through western Washington and Oregon, and ultimately extending to southern California where it is mostly introgressed with the native velvet ash (*F. velutina)* (Baldwin et al. 2012). In the Pacific Northwest, Oregon ash typically grows in moist, bottomland habitats reaching heights of 16 to 25 meters as a late-successional climax species in Oregon's Willamette Valley and Washington's Puget Trough (Arno and

Hammerly 1977). Oregon ash also becomes a co-dominant to dominant overstory species in early to mid-successional habitat types such as riparian corridors along tributaries of the Willamette River, Oregon and lower Columbia River where it provides shade, bank stabilization, and filtration of pollutants and excess nutrients—ecological services that maintain stream conditions favorable to salmonids and other native aquatic species (Prive 2017). Oregon ash mortality and subsequent canopy loss induced by EAB is expected to lead to significant physical and chemical changes at the landscape-level, directly impacting water quality and altering native plant and animal community composition and successional trajectories (Bartemucci et al. 2006, Prive 2017, Klooster et al. 2018). Research on the direct and indirect impacts of EAB to North American ash populations have, up to now, focused on both urban forests and ex-urban native *Fraxinus* spp. populations as far west as Colorado, with no known published research on potential impacts involving endemic Oregon ash.

A primary concern following EAB-induced Oregon ash canopy loss is the expected increase in local, incoming solar radiation and thereby stream temperatures (Malcolm et al. 2004). Water temperatures above 16°C are particularly problematic for salmonids due to reduced dissolved oxygen levels (Bjornn and Reiser 1991). Macroinvertebrate prey species that juvenile salmon depend upon also suffer reduced fitness when streams warm (Allan 2004). Additionally, salmonid disease outbreaks and mistimed migrations are positively correlated with increasing water temperature, leading to further declines in salmonid fitness and population size (Bjornn and Reiser 1991). Oregon ash is unique among local overstory tree species in its ability to tolerate soils inundated with water for extended periods (Frenkel and Heinitz 1987, Prive 2017). The lack of native replacement tree species filling this prospective functional void suggests exotic species are likely to fill gaps and could provide inferior levels of stream shading and other ecosystem services such as bank stabilization, wildlife habitat, and native invertebrate forage currently provided by Oregon ash (Davis et al. 2017, Prive 2017, Engelken et al., 2020).

Stream temperatures in the Pacific Northwest are frequently above the state water quality standards designed to protect sensitive aquatic species, including Endangered Species Act (ESA)-listed salmon and trout. In Oregon and in response, Oregon's Department of Environmental Quality (DEQ) develops pollution reduction plans designed to reduce the thermal inputs to the streams. A key driver of increased stream temperatures in the Willamette Basin is loss of streamside shading and concomitant solar loading (DEQ 2006). System potential shade – the maximum proportion of solar radiation that is attenuated or scattered before reaching the stream— is achieved when the riparian plant community has reached its mature, undisturbed condition in which vegetation heights are at or near their expected potential, resulting in the maximum effective shade for the stream. For streams in the lower Willamette Basin where our study is situated, DEQ identifies restoration and protection of riparian vegetation as the primary methods for increasing stream shading and mitigating increased stream temperatures and bases the nonpoint source load allocations (i.e., the allowable amount of a pollutant, in this case heat) on achieving system potential shade conditions.

Currently, no models or data exist for predicting landscape level impacts following widespread mortality of Oregon ash. Here, we integrate (1) LiDAR-based canopy cover data with (2) field survey data estimating canopy contribution of Oregon ash specifically, and (3) modeled solar loading impacts to salmonid-bearing waterbodies in the Portland, Oregon metropolitan area before and after EAB-induced functional extinction of Oregon ash.

Methods

Study Sites

The present study involves two salmonid-bearing waterways in the metropolitan area of Portland, Oregon: (1) Johnson Creek begins in an agricultural region east of Portland, receiving multiple tributaries and draining 138 km^2 while flowing westward for 42 km through agricultural, natural, suburban, urban, and industrial habitats before emptying into the Willamette River near Milwaukie, Oregon (Lee and Snyder 2009). (2) The Columbia Slough is a slow-moving, tidally-influenced, and heavily leveed water body running parallel to the Columbia River and draining 132 km^2 while flowing 33 km westward from Fairview Lake in Troutdale, OR to the confluence of the Willamette and Columbia Rivers (Columbia Slough Watershed Council 2023) through mostly industrial and natural areas. The riparian areas of both waterways support Oregon ash and both waterbodies have been identified by the State of Oregon as impaired due to high water temperatures (DEQ 2022). Each of these streams can be approximately bisected at their midpoints into a western reach that is dominated by urban landscape features and an eastern reach dominated by exurban and rural landscape features (Fig. 1). As such, we separately analyzed these west and east reaches.

To randomize geographic sampling, we used ArcGIS 10.7.1 software (ESRI 2019) to subdivide our study's streams into 30 m lengths and assign a unique ID to each segment. These IDs were assigned random numbers using the 'random()' function in Microsoft Excel, and sequentially sorted by random number. The first 5% of rows (quadrats) for each stream reach were selected as sample sites. We wanted to evenly split our sample sites between north bank and south banks and so used the same randomization procedure to evenly assign sample sites to these banks. Finally, these sampling sites were exported back to ArcGIS, and geoprocessing functions allowed us to create 10 m x 30 m bands adjacent to these stream reaches/segments (quadrat design is further explained in the next section and illustrated in Fig. 2).

Modeling Scenarios

We modeled three scenarios as part of this effort to compare conditions on the landscape and concomitant effects on solar loading:

1. *Current Conditions*: an assessment of riparian shade as represented in 2019 LiDAR data, before the functional extinction of Oregon ash due to EAB.
2. *System Potential*: a hypothetical future condition representing the maximum potential riparian shade. All existing canopy vegetation from 2019 is assumed to have reached full-grown heights and

all areas with currently no canopy vegetation are assumed to have full-grown trees. This scenario represents the maximum possible effective shade in each stream.

3. *Ash Loss*: modeled riparian shade based on 2019 conditions, but assuming complete removal of Oregon ash from the landscape due to EAB.

To simulate the impact of the complete loss of Oregon ash, we modified the “Current Conditions” scenario described above by removing portions of the existing riparian canopy based on the ash abundance estimated by the field surveys. In ArcGIS we subdivided the three 10 m x 30 m bands every 10 m to create areas that are approximately 10 m x 10 m. The areas were designed to approximate the canopy extent of a fully grown Oregon ash tree. We then randomly selected a subset of these 10 m x 10 m areas. The number of selected areas were modeled as having no trees present to simulate the loss of ash trees. We generated and modeled 100 scenarios to evaluate the loss of riparian canopy by EAB.

Field Surveys to Estimate Canopy Contribution of Oregon ash:

Field surveys served two objectives: (1) to quantify the proportional contribution of Oregon ash to the riparian canopy to forecast the impacts of canopy loss, and (2) provide precise counts of Oregon ash boles while characterizing the distribution of all co-dominant and dominant riparian shrubs and trees. Our survey focused on 30 m-wide riparian zones directly above ordinary high-water of both river-right and river-left along the full length of the streams—a total potential survey area of 2.59 km^2 and 2.05 km^2 for Johnson Creek and the Columbia Slough, respectively. We sampled the total riparian area by surveying the randomly assigned 30 m^2 quadrats described in the previous section (Fig. 2). We further subdivided each quadrat into three 10 m x 30 m bands running parallel to the stream to provide greater resolution for two reasons: (1) vegetation growing near the water’s edge typically provides more shade than plants growing further from the stream, and (2) fine scale habitat characteristics such as soil nutrient and moisture content can vary close to streams and may influence species distributions (Giller and Malmqvist 1998). Thus, these “bands” are our sampling units. We surveyed 429 bands from 143 quadrats along Johnson Creek, and 348 bands from 116 quadrats along the Columbia Slough, representing 5.2% and 5.3% of the total defined riparian areas, respectively.

Field surveys were conducted when leaves were present, between July and October 2020 (and prior to detection of EAB in the Pacific Northwest). Procedures varied among four scenarios:

Scenario 1: Desktop analysis We first employed recent aerial satellite photographs (Oregon Metro 2020) to visually identify sampling quadrats where Oregon ash would be excluded from field surveys due to structural or other land-use factors such as parking lots and roads (34 quadrats identified for this category). These sites nonetheless provided canopy cover data for the model, included as 0% canopy.

Scenarios 2–4: Field surveys

In the field, vegetation was functionally categorized in each band into overstory (tallest tree cohort within band), understory (trees > 2.0 meters but distinctly below overstory species), and shrub (≤ 2.0 meters). When the same species occupied two or more functional layers it was separately recorded within each category.

Scenario 2: No Oregon ash

When no Oregon ash was present, we conducted a rapid vegetation assessment to inform future mitigation and restoration efforts by recording up to five of the most abundant species within overstory, understory, and shrub functional layers.

Scenario 3: Overstory exclusively Oregon ash

For field surveys where Oregon ash was the only overstory species within a given band, we recorded numbers of Oregon ash boles, and measured their height ranges within each band using a laser rangefinder. As in *Scenario 2*, we documented up to five co-dominant species within the understory and shrub layers.

Scenario 4: Co-dominant overstory

When Oregon ash was co-dominant with other species in the overstory, we recorded numbers of Oregon ash boles, measured their height ranges, and estimated percent canopy contribution as the average of two independent visual estimates. Up to five co-dominant species within the understory and shrub layers were recorded.

Canopy Composition Analysis

To quantify the overall canopy cover within randomly-selected stream-lengths, we used first-return LiDAR data collected in 2019 to generate a riparian canopy model, from which we quantified canopy heights, distribution, and the total canopy cover. The quadrat-specific zonal canopy cover results were combined with the associated field surveys to estimate the total area of each band composed of Oregon ash. From this we were able to calculate the relative proportion of the riparian canopy that was composed of Oregon ash.

Effective shade, thermal loading models

To assess the potential impacts of riparian canopy loss along Johnson Creek and the Columbia Slough, we modeled solar loading and effective shade using remote sensing data. Effective shade is the proportion of solar radiation that is attenuated or scattered before reaching the stream by the cumulative biotic and abiotic landscape features (Fig. 3). To calculate effective shade, we used the shade module of Heat Source version 26 (Michie et al. 2021), a computer model used and maintained by Oregon DEQ

(Boyd and Kasper 2003). We modeled effective shade for both waterways from July 1 to August 31 at a 15-minute timestep. We summarized these results as the July–August mean at each modeling node: the summertime period when stream temperatures in the Portland area tend to be greatest.

The model relies on GIS inputs to characterize the surrounding topography and land cover features (including vegetation canopy cover) that affect the amount of solar radiation reaching the stream surface. For modeling effective shade of Johnson Creek and the Columbia Slough, these GIS inputs were compiled using TTools version 9.0 (Michie 2021), a GIS tool that assembles stream channel and land cover geospatial data for input into the Heat Source model.

For both waterbodies we modeled the effective shade every 25 m along the center of the channel. For each modeling node, we sampled the surrounding topography and land cover within 75 m of the center of the stream, in 3 m increments (Fig. 2).

Table 1

Inputs used to model solar loading, including the datasets used to characterize land cover surrounding the modeled streams and the Heat Source modeling parameters. See the References section for links to complete GIS metadata

Feature	Purpose	Input/Value
Topography	Streambank and nearby topography used to calculate topographic shade.	2019 bare earth LiDAR (City of Portland, 2021)
Riparian Vegetation	Tree canopy height and tree type (coniferous or deciduous) used to characterize the riparian vegetation. Tree heights and canopy density attenuate solar loading.	2019 first return LiDAR (City of Portland, 2021) ; Canopy Classification (Oregon Metro, 2016)
Impervious Features	Identified buildings, roads, and parking lots used to construct land cover codes to characterize adjacent land use. Buildings assumed to provide shade.	Impervious Areas (City of Portland, 2017)
Model Time Period	Range of dates for which incoming solar loading is calculated	July 1 to August 31
Model Time Step	Modeling time increment for each modeled day	15 minutes
Model Node Spacing	Distance between points along the stream line where solar loading is calculated	25 meters
Landcover Sampling Transects	Number of transects per steam node where adjacent landcover characteristics are sampled (e.g., tree heights).	8 transects
Landcover Transect Sample Spacing	Distance between landcover sampling along each transect at each stream node.	3 meters

Model Calibration

Riparian vegetation attenuates less than 100% of light; to account for this the Heat Source model includes a canopy density parameter that represents the proportion of incoming solar radiation that is blocked by vegetation. The canopy density values used in the initial model runs were based on the vegetation characteristics described in the Lower Willamette temperature TMDL (DEQ, 2006) and included a 75% density value for deciduous vegetation and an 80% density value for coniferous vegetation.

We refined the canopy density parameter using riparian canopy cover measurements recorded as part of the City of Portland's watershed monitoring program (Portland Area Watershed Monitoring and Assessment Program; City of Portland 2023a) and the Bureau of Environmental Service's Restoration Monitoring Program (City of Portland 2023b). Densiometer readings were collected and converted to canopy cover using the methods of Lemmon (1957). We found that the field measured canopy cover values were typically substantially higher than the TMDL canopy density values; particularly in riparian areas dominated by conifers. For the purposes of this assessment, we used the 25th percentile canopy cover values to better reflect measured field conditions. As a result, both density values were increased, with the density value for deciduous canopy of 78% and a density for coniferous canopy of 90%.

Results

Our models indicate that EAB-induced loss of Oregon ash in the riparian canopy would increase solar loading to Johnson Creek and the Columbia Slough (Fig. 4) with the magnitude of increase based on the current extent of ash in the canopy, which in turn correlates to land use. The eastern, exurban, and rural portion of Johnson Creek would see the greatest increase in solar loading during the summer (mean increase of 23.7%, Table 2). A smaller increase in solar loading of 13.1% would be expected along the western, urban portion of Johnson Creek (Table 2).

In the Columbia Slough, the Lower Slough (western portion) would experience a 1.8% increase in summer solar loading, while the eastern half of the Columbia Slough would see a slightly greater increase of 2.7% (Table 2).

Table 2
Modeled increase in solar loading compared to current (2019) conditions due to the loss of Oregon ash from EAB across the 100 model runs

Increase in Solar Loading (%)								
Waterbody	**Location**	**n**	**Min**	**10th Percentile**	**Mean**	**90th Percentile**	**Max**	**Std Dev**
Johnson Creek	East	100	22.2	22.8	23.7	24.5	26.0	0.71
	West	100	11.6	12.5	13.1	13.9	14.9	0.56
Columbia Slough	East	100	2.3	2.5	2.7	3.0	3.2	0.20
	West	100	1.7	1.7	1.8	1.9	2.0	0.08

The field surveys revealed spatial variation in the abundance of Oregon ash along the two surveyed waterbodies, both longitudinally and laterally (distance from stream edge). Within the riparian area of the Columbia Slough, we found that there was a greater abundance of Oregon ash along the western portion of the waterbody with the 10 m band closest to the channel having the highest proportion of Oregon ash (Fig. 6). Conversely, we found the eastern portion had a considerably lower abundance of Oregon ash. The 10 m bands closest to the channel had 3–4 times less canopy composed of Oregon ash when compared to the western portion of the Columbia Slough.

We observed a similar pattern along Johnson Creek: a greater abundance of Oregon ash in the 10 m bands closest to the stream channel. In contrast to the Columbia Slough, we found that Oregon ash composed a greater proportion of the riparian canopy along the eastern portion—the upper half—of Johnson Creek (Fig. 7).

Discussion

Our results suggest the decrease in canopy cover in riparian corridors and the resultant increase in thermal loading due to the EAB-induced loss of Oregon ash will have significant impacts to water quality and aquatic habitat, with implications for federal and state regulators and entities seeking regulatory compliance. Loss of Oregon ash canopy within the Willamette River basin and elsewhere is forecasted to result in increased thermal loading of waters, putting municipalities and other entities responsible for meeting Clean Water Act water quality standards at risk of non-compliance, in addition to threatening ESA-listed salmonid populations. Given the abundance and distribution of Oregon ash and its susceptibility to EAB, it is expected that low elevation riparian and wetland habitat and water quality in the Willamette Valley and Puget Trough will be rapidly degraded following establishment of EAB. Ash mortality will result in increased water temperatures (Broadmeadow et al. 2011, Engleken and McCullough 2020), affecting an array of aquatic organisms at multiple trophic levels. EAB in the Pacific Northwest, west of the Cascade Mountain range, presents a forest pest worst-case scenario: the loss of a dominant and largely functionally irreplaceable riparian and wetland tree species that provides critical habitat for both ESA-listed and non-listed species and water quality ecosystem services.

Our findings highlight that the water quality impacts of Oregon ash loss will depend not only the abundance of Oregon ash along the stream, but also on the characteristics of the waterbody and, unsurprisingly, the location of the ash canopy. The western portion of the Columbia Slough is relatively wide (mean channel width of 50 m), making it difficult to fully shade—even with a mature riparian canopy along both stream banks, the greatest possible effective shade would be less than 25% (Fig. 5). Despite the abundance of Oregon ash along this portion of the Columbia Slough, the increase in solar loading due to the loss of riparian canopy would be relatively small (1.8%; Fig. 5). Conversely, the eastern portion of the Columbia Slough is substantially narrower (mean channel width of 16 m), but with a lower abundance of Oregon ash, particularly in the bands closest to the channel. The potential loss of riparian canopy along this portion of the Columbia Slough would result in a somewhat greater increase in solar loading (2.7%, Fig. 5).

Our field surveys indicate that the riparian canopy along Johnson Creek is composed of less Oregon ash than the Columbia Slough (Fig. 6 and Fig. 7); however, the anticipated impacts of canopy loss due to EAB is substantially greater. Both waterbodies have an east-west orientation, but Johnson Creek has a narrower channel (mean channel width of 7 m), allowing for more shading of the stream channel (Fig. 5). Despite the lower abundance of Oregon ash, the loss of this riparian canopy would result in a greater increase in solar loading to Johnson Creek.

While we focused our study on riparian corridors, Oregon ash provides a similar shading function in many forested wetlands in the Willamette basin. The magnitude of ecological impacts in both habitats will largely be determined by what plant associations establish post-invasion (Van Driesch and Reardon 2014). Oregon ash is unique, regionally, as an early-seral to climax species and in its ability to form pure stands and maintain a forested state in wetlands and floodplains as the dominant species at all stages of stand development (Prive 2017), although with reduced germination on scoured, more mineral soils and moderate shade tolerance, Oregon ash is often a late-seral species (Fierke and Kauffman 2005, Prive 2017). Successional dynamics among tree species is less clear, however, in wetlands and riparian areas that rarely experience high-intensity flood events, including the bulk of the Willamette River basin and Puget Trough that were hydrologically modified due to large-scale water-control efforts beginning in the 1930s (Griffith 1983). On wet sites with less scour and with a higher organic soil component, Oregon ash is often a colonizing tree species, and is one of few tree species, locally, that can develop into a closed canopy forest in these conditions (Prive 2017). Other local tree species, such as Oregon white oak (*Quercus garryana*), black cottonwood (*Populus trichocarpa*), and alders (*Alnus rubra* and *A. rhombifolia)* are shade intolerant, and currently unlikely to persist in later seral stages in some settings (Prive 2017), although the future absence of Oregon ash on the landscape makes this uncertain.

The loss of Oregon ash in riparian corridors and wetlands where it is the dominant or co-dominant plant species may have broad hydrologic impacts, as well. In other North American wetlands where ash co-dominates, such as black ash (*F. nigra*) wetlands in the upper Midwest, research suggests that large-scale dieback caused by EAB would result in higher water tables and a conversion to graminoid to shrub dominated systems (Pavik et al. 2012, Slesak et al., 2014, Looney et al., 2015) with significant changes to food webs and habitat structure (Youngquist et al. 2017) and potential for altered nitrogen cycling (Toczydlowski et al. 2020). In the wetlands and floodplains in the Willamette Valley, especially those with the longest inundation periods and highest water tables, we expect to see a broad disruption of successional dynamics and a conversion to open, shrub dominated systems (Pavik et al. 2012) or to wetlands invaded by exotic reed canary grass (*Phalaris aundinacea*) (Fierke and Kauffman 2006, Prive 2017) along with occasional slough sedge-dominated (*Carex obnupta*) wetlands, especially where Oregon white oak canopy remains.

While the results of our study in and adjacent to Portland, Oregon indicate a significant local impact to water quality from the EAB-induced loss of Oregon ash in riparian habitat, our study systems are relatively depauperate of Oregon ash compared to many other low-elevation forested wetlands and local tributaries of the Willamette River and lower Columbia River where Oregon ash is, or is almost, the sole tree species, suggesting impacts post-EAB establishment will be significantly greater in many areas and across basin-scale watersheds than our results indicate. For our study waterways, compensatory growth of other tree species is expected to eventually mitigate some EAB-induced increase in solar loading, however, this compensatory growth is expected to be uneven given the distribution of Oregon ash, recruitment of exotic species in mortality gaps, and habitat requirements of other native tree species that may reduce their ability to fill niches left open by Oregon ash.

Although the modeled increases in solar loading may seem modest, it is important to note that both waterbodies in our study regularly exceed Oregon's water quality criteria for temperature throughout the summer (City of Portland 2022). Current daily maximum water temperatures of both waterbodies are often warmer than what is optimal or tolerated by salmon and steelhead trout. Any increase in solar loading would contribute to increased water temperatures that are less hospitable to these endangered and threatened aquatic species. Additionally, impacts to these systems are not limited to the stream themselves. Both waterbodies serve as off-channel refuge along the Willamette and Columbia rivers to migrating salmon and steelhead. Even though both waterbodies may seasonably be warmer than what is optimal or tolerated by salmonids, they are still cooler than the Willamette River. Given Portland's location at the confluence of the Willamette and Columbia rivers, all salmon and steelhead that spawn within the Willamette and Columbia Basins pass through or adjacent to Portland. As such, the Columbia Slough and Johnson Creek provide valuable habitats for all migrating salmon and steelhead, not only those that rear or spawn in these two waterbodies.

Since the discovery of the first known, established West Coast EAB population in Forest Grove, Oregon by the first author of this paper in June of 2022, local governments and organizations, and state and federal agencies and departments, have sought to predict the impacts of EAB and mitigate impacts on the West Coast. While initial risk assessments focused on potential impacts to urban street trees and property values, we continue to emphasize that efforts must be directed toward characterization of the risk and consequences to water quality and habitat caused by establishment of EAB in western Oregon and Washington. Surveys and early detection must be prioritized so that nascent EAB population growth is slowed, and the rate and severity of impacts are reduced. The lessons learned from impacts of EAB in natural areas east of the Continental Divide should be applied in both natural and rural areas and urban forests. Efforts should be made by local agencies, watershed councils, and soil and water conservation districts to augment restoration and natural area enhancement planting palettes with alternate species best approximating mature Oregon ash structure, however, as noted above, options are limited. In contrast to primarily deciduous forests in the interior, mid-latitudes of North America and the Eastern Seaboard, Pacific Northwest low-elevation deciduous-dominated forests have relatively low native tree diversity. It is unlikely that any native tree species will replace Oregon ash in many settings and that most plants that are able to recruit and persist in gaps formed by Oregon ash mortality will be shorter-statured, exotic species such as exotic *Rubus* spp. and exotic trees with less dense canopies (Prive 2017). Interplanting Oregon white oak, black cottonwood, white alder, and Pacific willow (*Salix lasiandra*) into forested wetlands and riparian areas with high Oregon ash abundance should be a primary effort for mitigating some of the expected shade loss, even though these species may not persist and/or effectively recruit on the most poorly drained riparian areas and forested wetlands (Frenkel and Heinitz 1987, Prive 2017). Smaller-statured, native willows (*Salix* spp.) should be considered for planting on 1st order streams and may be unlikely to recruit given they are already a relatively uncommon component of lower-elevation, Willamette Basin riparian corridors (Prive 2017). Retaining widespread exotic tree species such as bird cherry (*Prunus avium*) (in more mesic settings), sycamore maple (*Acer pseudoplatanus*), and the regionally, less-common silver maple (*Acer saccharinum*), should be considered where they can replace functions such as shade and allochthonous leaf inputs. Effective early management of woody invasive plant species, such as exotic hawthorns (*Crataegus monogyna* and *C. heterophylla*) and wild pears (*Pyrus* spp.), should be prioritized to limit these species dominating where EAB-induced Oregon ash mortality has occurred or is expected.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception, design, and manuscript development. Data collection and material preparation coordinated by Monte Mattsson and Dominic Maze. Julia Bond performed the modelling analysis and sequestered remote sensing data. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

All data and code supporting the findings of this study are available at the following URL: https://efiles.portlandoregon.gov/record/16345433

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Figures

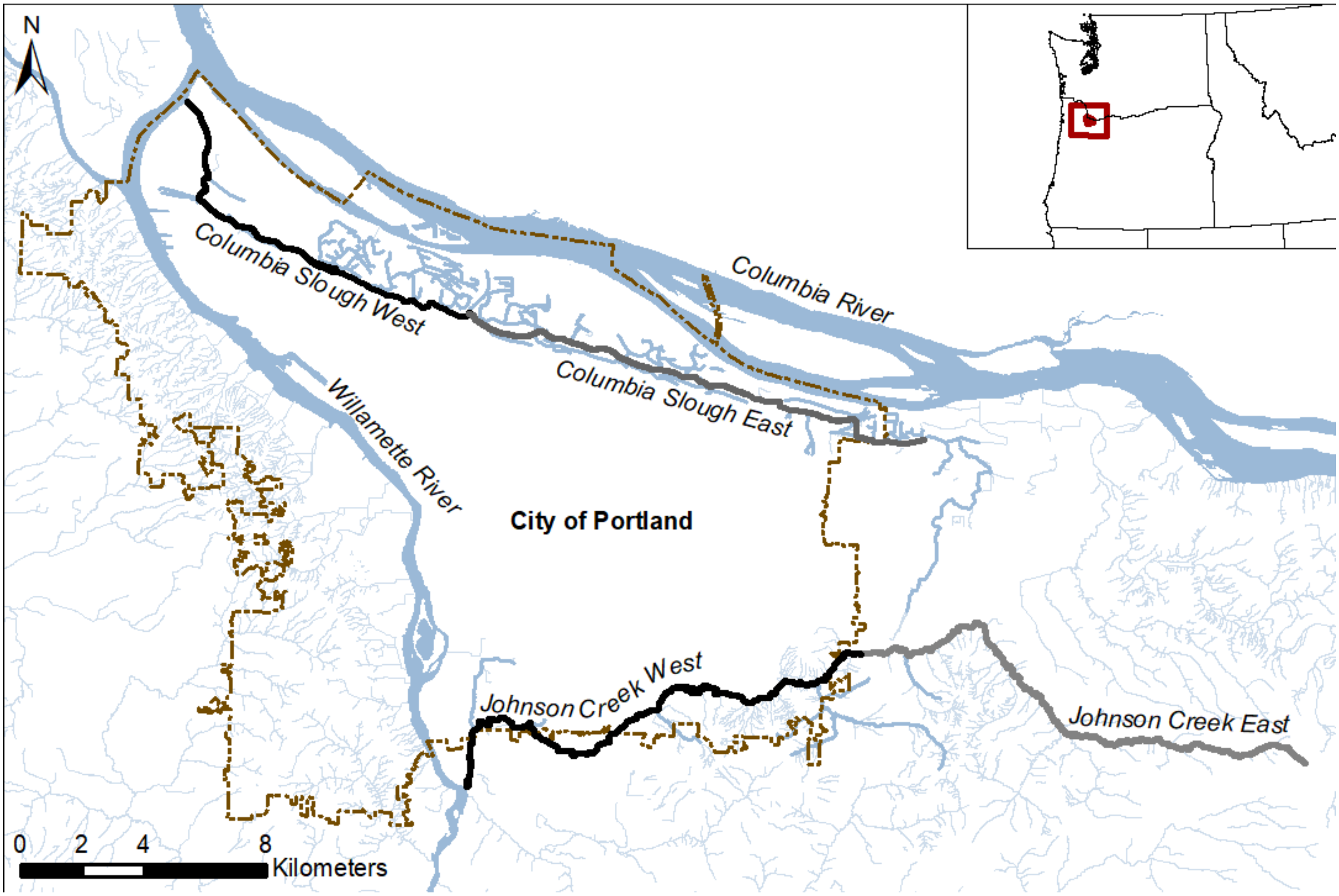

Figure 1

Black lines highlight the western reaches and the gray lines highlight the eastern reaches of the modeled waterbodies, Columbia Slough and Johnson Creek, located in the Portland, OR metro area

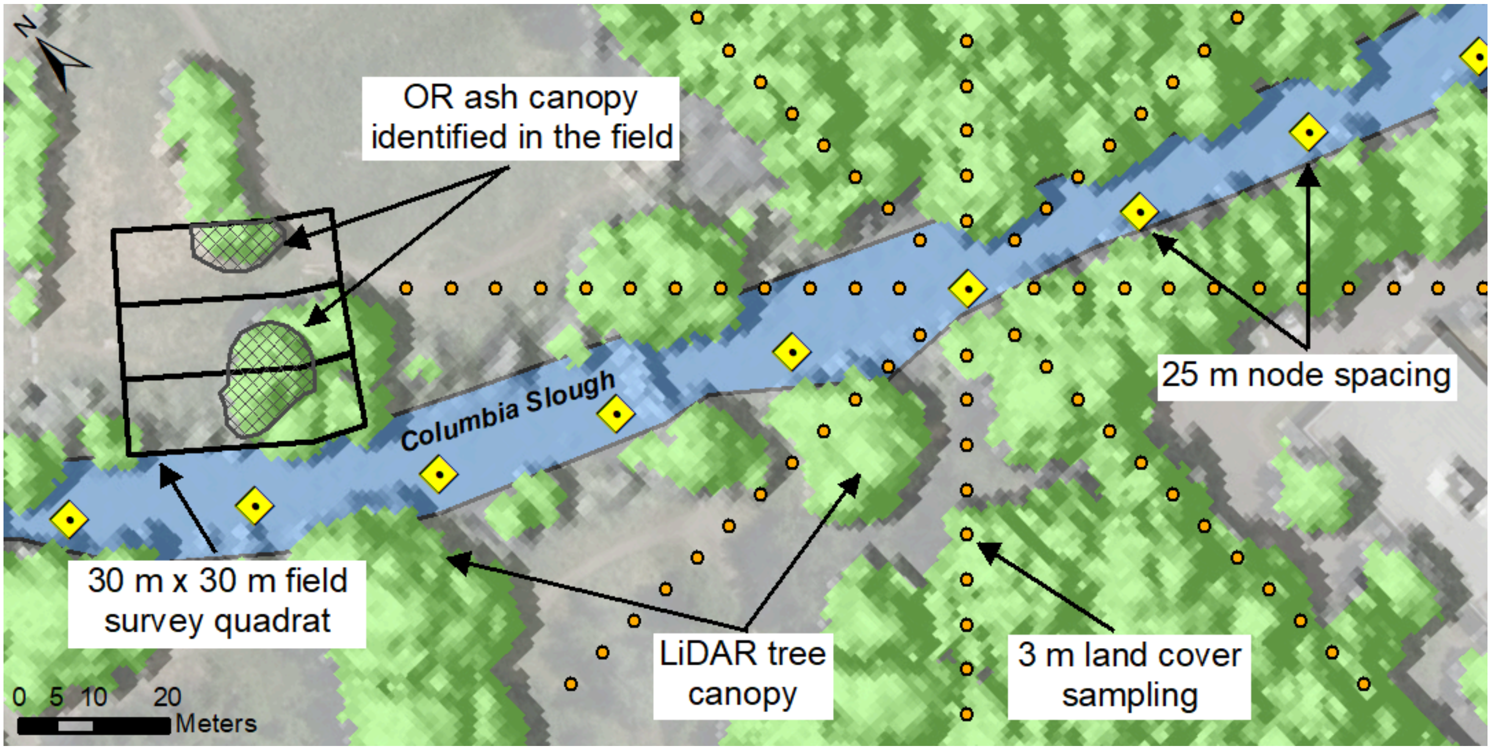

Figure 2

Illustration showing the 30 m quadrats and the 10 m bands used in the field surveys, the LiDAR derived tree canopy, and shade modeling nodes

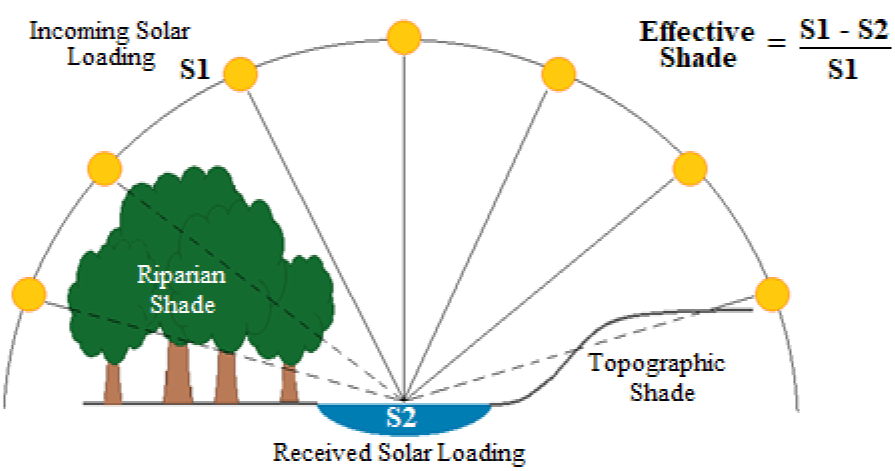

Figure 3

Illustration of effective shade. S1 is the incoming solar loading based on the day of the year, position of the sun, and elevation of the site. S2 represents the solar load that reaches the surface of the stream, accounting for any attenuation due to riparian or topographic shade

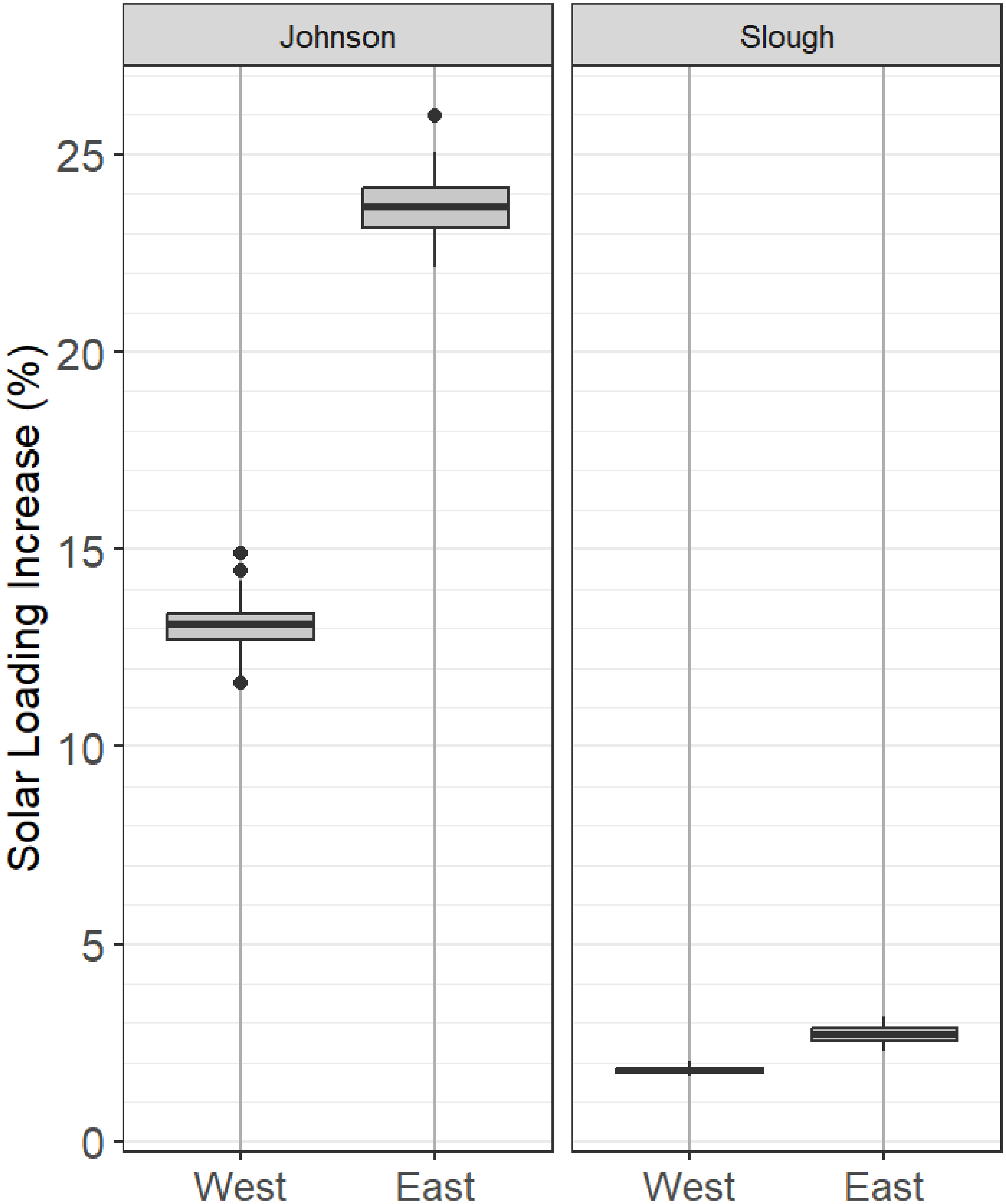

Figure 4

Increase in the July-August solar loading compared to current (2019) conditions due to the loss of Oregon ash from EAB across the 100 model runs

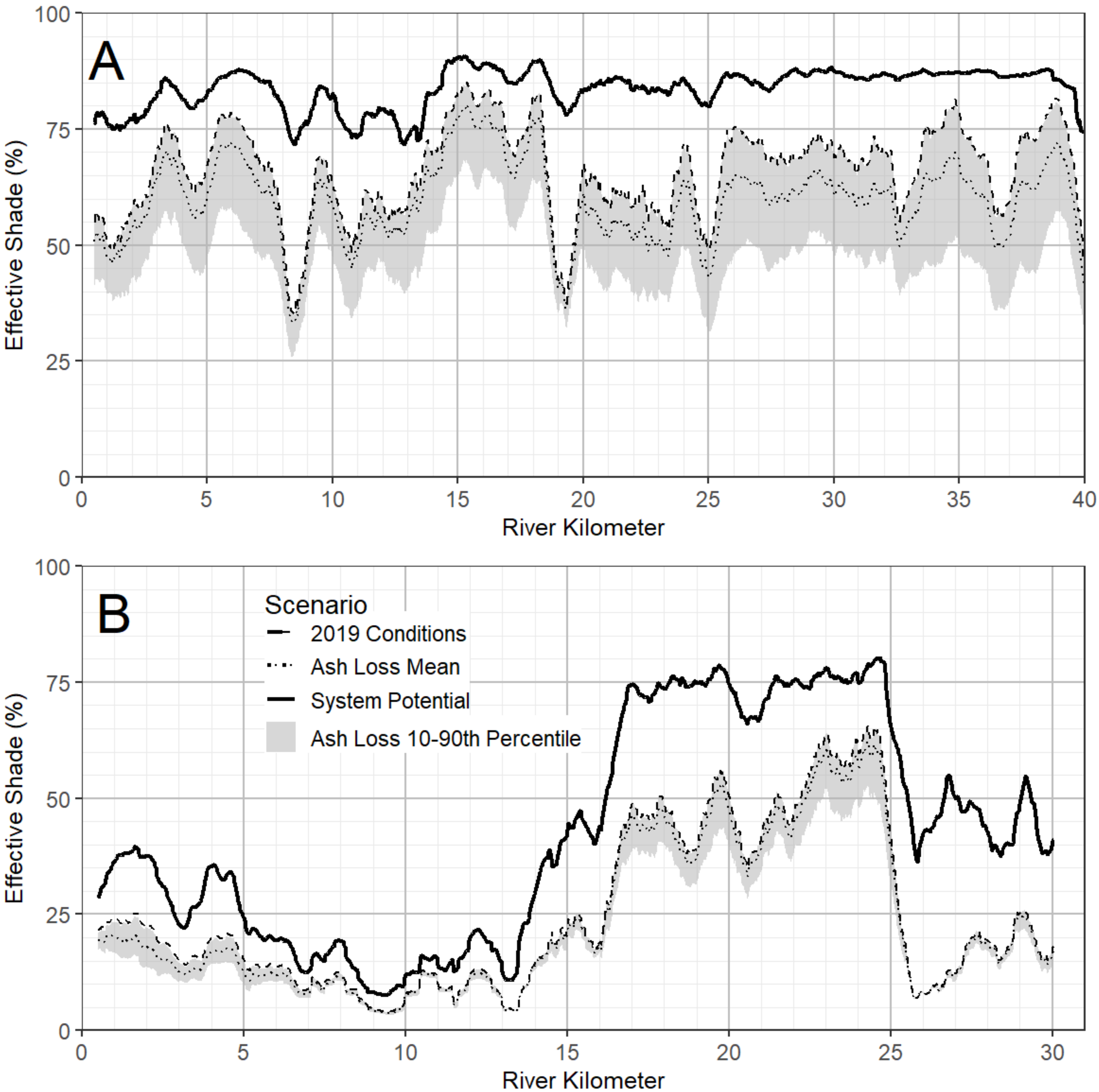

Figure 5

Effective shade scenarios for (A) Johnson Creek and (B) Columbia Slough. Results along the length of each river (500 meter rolling averages) from its mouth (river kilometer 0)

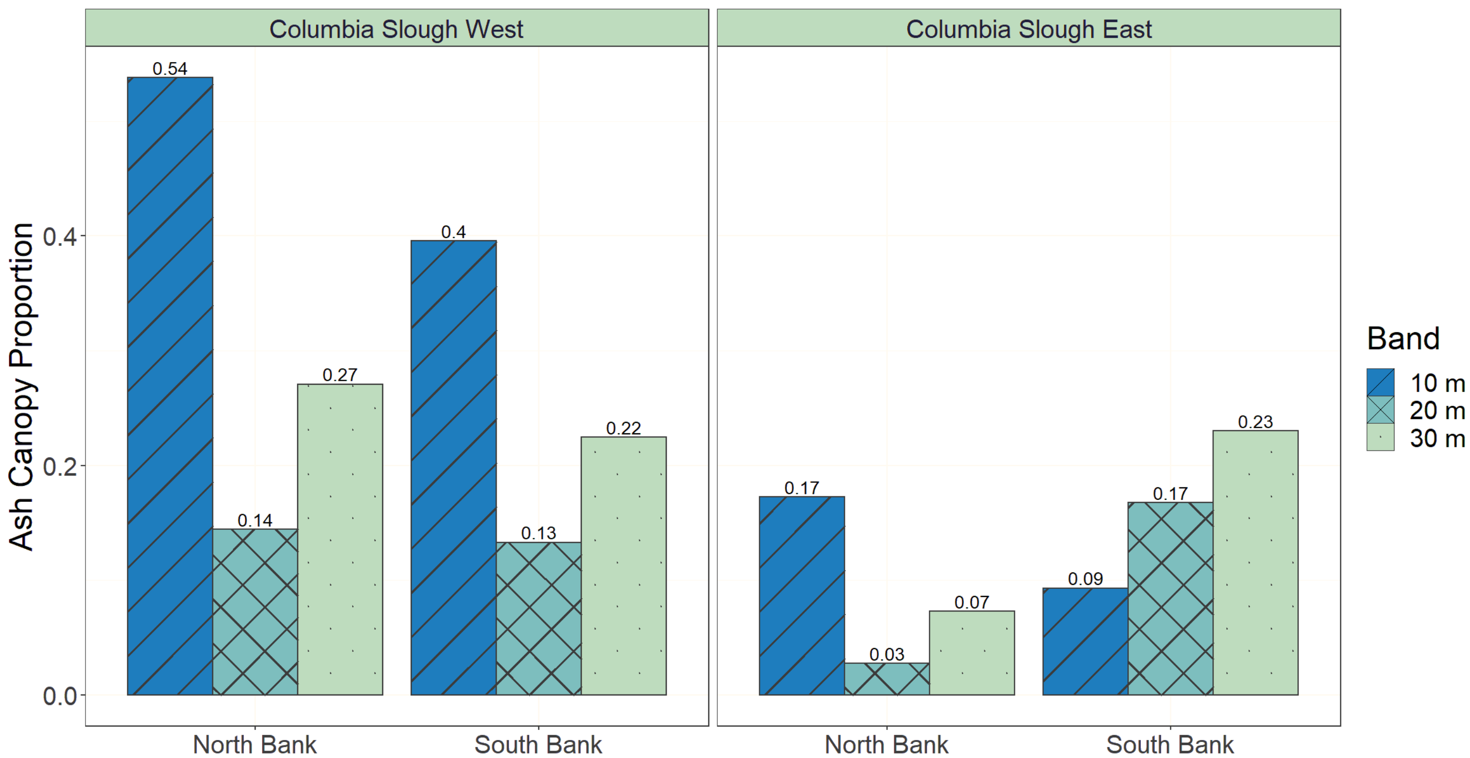

Figure 6

Proportion of the riparian canopy composed of Oregon ash along the Columbia Slough.

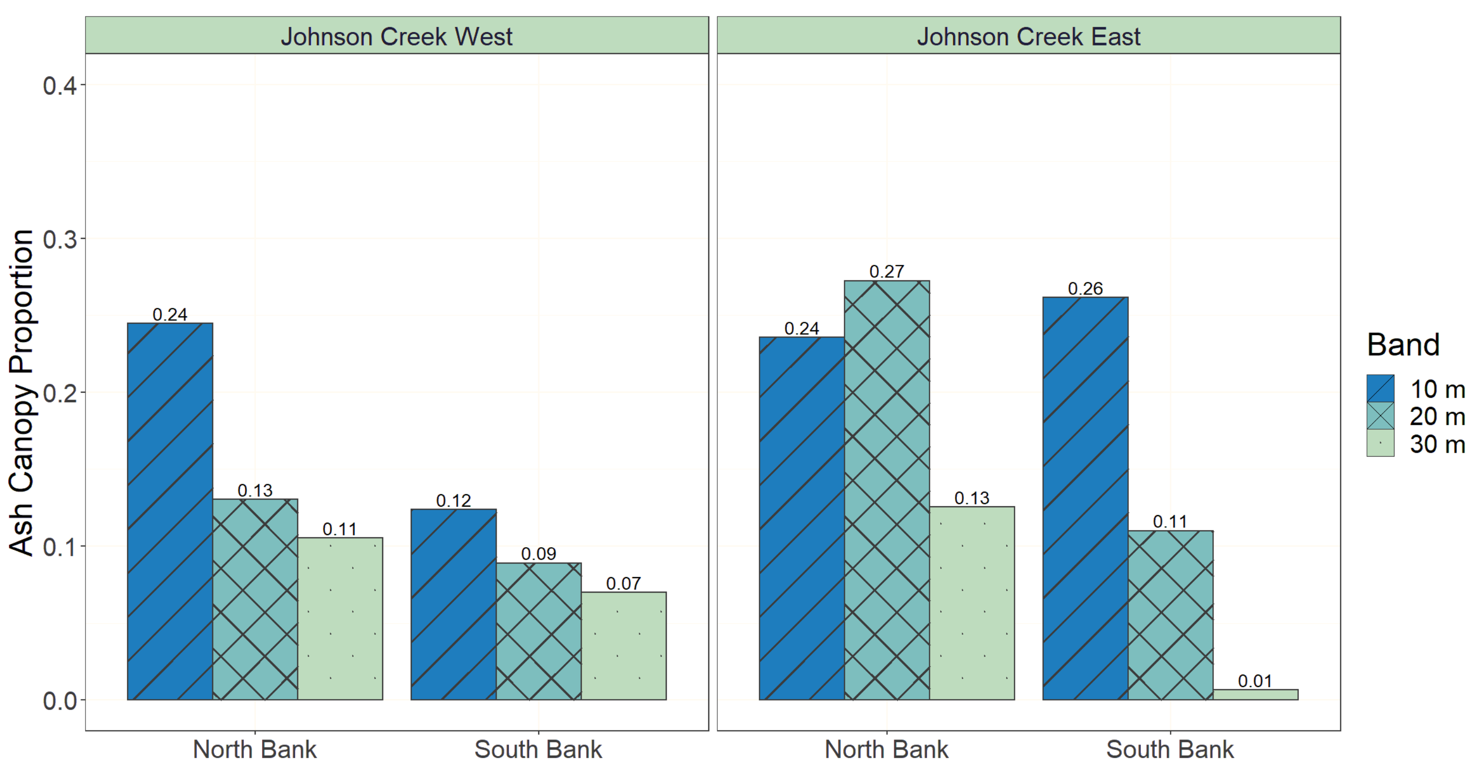

Figure 7

Proportion of riparian canopy composed of Oregon ash along Johnson Creek