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Effects of wildfire on streambed sediment size in the Cascades and Klamath regions of the Pacific Northwest

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Abstract

Background Wildfire can influence erosion regimes and alter sediment delivery to river systems, which can change the sediment size composition of rivers. Understanding how wildfire impacts streambed grain size distributions is essential in understanding broader wildfire impacts on aquatic habitat and downstream water resources. In Western Washington, Oregon, and Northern California, the Aquatic and Riparian Effectiveness Monitoring Program (AREMP) has been collecting ongoing monitoring data since 2002. Since the beginning of the monitoring program, approximately 37% of AREMP monitored sites have experienced one or more wildfire within their contributing watersheds. In this study, we used machine learning models to analyze AREMP sites within the Cascades and Klamath regions to assess (1) how the presence and severity of wildfire explain streambed sediment size in western Pacific Northwest (PNW) watersheds and (2) how watershed characteristics influence the effects of wildfire on streambed sediment across two distinct regions in the PNW.

Results We found distinct patterns in how fire may be influencing instream sediment size in the Cascades compared to the Klamath, which could in part be explained by differences in fire regime and land management legacies between the two regions. In the Cascades, post-fire canopy cover and instream large wood seem to be driving differences in observed post-fire stream sediment compared to expected unburned conditions, while soil and lithology characteristics are the main drivers of difference in the Klamath region. Overall, we found that how streams respond to wildfire in the Cascades might be controlled by factors that influence sediment transport dynamics, while watershed response to fire in the Klamath may be controlled by hillslope sediment production.

Conclusions Our findings offer insight into which landscape controls influence whether aquatic habitat might be vulnerable to or resilient to change post-fire, across different regions in the PNW.

Keywords Wildfire, Streambed sediment, Pacific Northwest, Aquatic habitat

Resumen

Antecedentes Los fuegos de vegetación pueden influenciar los regímenes de erosión y alterar el transporte de sedimentos hacia los sistemas de ríos, lo cual puede cambiar el tamaño en la composición de esos sedimentos. El entender como los incendios impactan la distribución del tamaño de sedimentos en los cauces de los ríos es esencial para entender los amplios impactos sobre el hábitat acuático y los recursos acuícolas río abajo. En el oeste de

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Washington, Oregón, y el norte de California, el Programa de Efectividad en el Monitoreo de Áreas Acuáticas y Ribereñas (AREMP), ha venido colectando datos de monitoreo desde 2002. Desde sus inicios, el 37% de los sitios monitoreados por el AREMP han experimentado uno o más incendios dentro de sus cuencas tributarias. En este estudio, utilizamos Modelos de Aprendizaje Automático (*Machine Learning Models*), para analizar sitios del Programa AREMP dentro de las regiones de *Cascades* y *Klamath*, para determinar: (1) cómo la presencia y severidad de los incendios explican el tamaño de los sedimentos en los cauces de las cuencas hidrográficas de la región del Noroeste del Pacífico (*Pacific Northwest* o PNW de ahora en más), y (2) cómo las características de estas cuencas hidrográficas influyen los efectos de los incendios sobre los sedimentos de estos cauces en estas dos regiones diferentes del PNW.

Resultados Encontramos patrones distintos sobre cómo los incendios pueden estar influenciando el tamaño de los sedimentos en los cauces de las *Cascades* comparados con los de la región de *Klamath*, los cuales pueden ser explicados, en parte, por los legados que dejan el régimen de fuegos y el manejo de la tierra en ambas regiones. En las *Cascades*, la cobertura del dosel en el post fuego y grandes troncos en los cauces parecen ser las causas de las diferencias en la cantidad de sedimentos observados en el post fuego, comparado con una situación de no quemado, mientras que las características del suelo y su litología parecen ser las causantes de esas diferencias en la región de *Klamath*. En general, encontramos que la manera en que los arroyos y ríos responden a los incendios en las *Cascades* parecen ser controlados por factores que influyen la dinámica del transporte de los sedimentos, mientras que esa respuesta en las cuencas hidrográficas de *Klamath* podrían ser controladas por la producción de sedimentos provenientes de laderas.

Conclusiones Nuestros resultados proveen de conocimientos sobre cuál es el tipo de paisaje que controla la influencia sobre el hábitat acuático, y si éste puede ser vulnerable o resiliente a cambios en el post fuego, en diferentes regiones del PNW.

Background

The bed material of a river is controlled by nonlinear and episodic processes that drive sediment delivery, transport, and storage (Wohl et al. 2015). Wildfire can alter sediment regimes in rivers by influencing upslope erosion and subsequent sediment delivery and in-channel hydrologic processes (Benda et al. 2003; Kang et al. 2024; Moody and Martin 2009; Santi and Rengers 2022). The incineration of vegetation from wildfire can lead to a release of stored sediment into channels as dry ravel (DiBiase and Lamb 2020; Jackson and Roering 2009; Roering and Gerber 2005) or can be transported after a storm event as runoff erosion (Hammer 2022; Moody and Martin 2001; Wondzell and King 2003) and debris flows (McGuire et al. 2024; Selander et al. 2025; Wall et al. 2020). Wildfire can also affect the particle size fraction of soils and hillslope sediment, potentially altering the grain size distributions of the sediment supplied to rivers (Santi and Rengers 2022). Post-fire episodic inputs of sediment into river networks can alter bed grain size distributions, which can degrade or enhance aquatic habitat and impact water quality and downstream drinking water infrastructure (Bixby et al. 2015; Hohner et al. 2019, 2016; Murphy et al. 2019; Rieman et al. 2012). For example, increased inputs of fine sediment can reduce water quality and bury gravels necessary for fish spawning habitat (Brown et al. 2001; Hohner et al. 2019; Rieman et al. 2012), while the deposition of coarse material can enhance channel complexity and improve aquatic habitat (Bisson et al. 2003;

Sedell et al. 2015). Wildfires can also increase streamflow for multiple years post-fire (Hallema et al. 2018; Loiselle et al. 2020; Long and Chang 2023; Wampler et al. 2024; Pirani and Coulibaly 2025; Wall et al. 2026). Higher flows can, in turn, winnow away fine sediment from river beds and result in a coarsening of the bed material over time (Brogan et al. 2019; Busby and Wilcox 2024; Chin et al. 2019; Short et al. 2015).

Many studies have investigated post-fire changes to instream sediment within the first 3 years of fire (Busby and Wilcox 2024; Chin et al. 2019; Coble et al. 2023; Sestrich et al. 2011), but the longer-term implications are not well understood. Post-fire hillslope erosion regimes can change over time. For example, hillslope vulnerability to runoff-generated erosion can decline after the first-year post-fire (McGuire et al. 2021). In contrast, delayed mortality in forested environments can lead to increased risk of shallow-landsliding over 5 years post-fire (Reilly et al. 2023; Wondzell and King 2003). Changes in hillslope post-fire geomorphic processes in conjunction with sustained higher streamflows post-fire, make it essential to examine longer-term trends in wildfire's influence on instream sediment.

Most empirical investigations into stream sediment changes from wildfire are localized to the impacts of a single fire event or an individual watershed (Benda et al. 2003; Brogan 2018; Chin et al. 2019; Zelt and Wohl 2004) and until very recently, few studies had investigated post-fire response within the western Pacific Northwest (PNW),

which is the region of Washington, Oregon, and Northern California to the west of the Cascades Crest (Busby and Wilcox 2024; Coble et al. 2023). Landscape characteristics such as climate, soils, topography, land cover, management history and fire regime all influence how post-fire geomorphic processes manifest (Santi and Rengers 2022; McGuire et al. 2024). While there are an abundance of investigations into wildfire impacts on aquatic habitat (Dunham et al. 2003; Rieman et al. 2012; Wagenbrenner and Robichaud 2014), majority of these studies have been done in the interior PNW (Benda et al. 2003; Roper et al. 2023; Armstrong et al. 2026), Rocky Mountain Region (Sestrich et al. 2011; Brogan et al. 2019; Chin et al. 2019; Sedell et al. 2015), and southern California (Spina and Tormey 2000; DiBiase and Lamb 2020). Therefore, findings from these studies conducted in drier climates may not apply to rivers in the wet, temperate climate of the western PNW.

Over the last decade, forests in the western Pacific Northwest have begun to experience larger, higher severity wildfires due to increasing drought and lengthening fire seasons (Halofsky et al. 2020; Reilly et al. 2022; Westerling et al. 2006). The 2020 wildfire season in the Cascade Mountains of Oregon motivated an increase of research into how wildfires impact watersheds in the moist-forest environments of the western PNW (Busby and Wilcox 2024; Coble et al. 2023; Kang et al. 2024; Selander et al. 2025; Wampler et al. 2024). Busby and Wilcox (2024) measured instream sediment size after the 2020 fires in the western Cascades and found an influx of fine sediment in the first winter post-fire, and then an ultimate coarsening of the bed material in the second-year post-fire. This contrasts with Coble et al. (2023), who observed no significant changes to the amount of fine sediment in their western Cascades study reaches within the first year following fire. Thus, more research is needed to understand how wildfire influences instream sediment and at longer timescales in this understudied region.

The Aquatic Riparian Effectiveness Monitoring Program (AREMP), which began collecting watershed condition data in the western PNW in 2002, is well positioned to answer questions regarding the long-term impacts of wildfire on river systems across the western PNW (Fig. 1; Dunham et al. 2023). Over the course of the monitoring program, many AREMP monitored watersheds have experienced wildfire. Two of the regions that have experienced fire over the last two decades within the scope of AREMP are the Cascades and the Klamath regions, which are distinct from each other geologically and climatically, and are dominated by different fire regimes. In this study, we use the AREMP dataset to investigate (1) how the presence and severity of wildfire explain streambed sediment size in the Cascades and Klamath regions and (2) how watershed characteristics influence the effects of

wildfire on streambed sediment across the two distinct regions of the Cascades and Klamath in the PNW.

To address these objectives, we developed machine learning models to investigate the key drivers of streambed sediment size in both the absence and presence of wildfire, by using a combination of field, geospatial, and statistical methods. We chose to specifically examine both the percent fines and median grain size (D50) of the study reaches. It is important to understand post-fire changes in percent fines because higher amounts of fines in a system can represent degraded aquatic habitat and water quality (Bisson et al. 2003; Bixby et al. 2015; Hohner et al. 2019). In addition, investigating D50 illuminates broader trends in the full grain size distribution and is an important element in understanding the sediment transport dynamics of a system (Czuba 2018; Murphy et al. 2019). This study provides a novel long-term and region-wide approach to understanding the impacts of wildfire on instream sediment in the western PNW.

Methods

To address our research objectives, we conducted the following analyses in watersheds of the Cascades and Klamath regions of the PNW: (1) identified which landscape controls are driving streambed sediment size in the absence of wildfire by constructing machine learning models to predict the percent fines and D50 of unburned AREMP subwatersheds, (2) evaluated whether or not the drivers explaining sediment size in the absence of fire continue driving streambed sediment size post-fire by applying the models in step 1 to the dataset of post-fire percent fines and D50 measurements, and (3) identified which landscape characteristics explain the differences between streambed sediment size in burned and unburned watersheds by modeling the difference between the unburned model predictions and the post-fire observations (Fig. 2). The goal of this analysis is to investigate the relationship between wildfire, instream sediment size distributions, and the broader landscape context. The models we construct are not to be used as predictive or forecasting tools but can illuminate general relationships between wildfire and aquatic habitat to inform future investigations.

Study sites

Aquatic and riparian effectiveness monitoring and the northwest forest plan

AREMP assesses the effectiveness of the Northwest Forest Plan (NWFP) by tracking watershed conditions and trends through time. The NWFP encompasses 9.7 million ha of federal lands in western Washington, western Oregon, and northwestern California, spanning the range

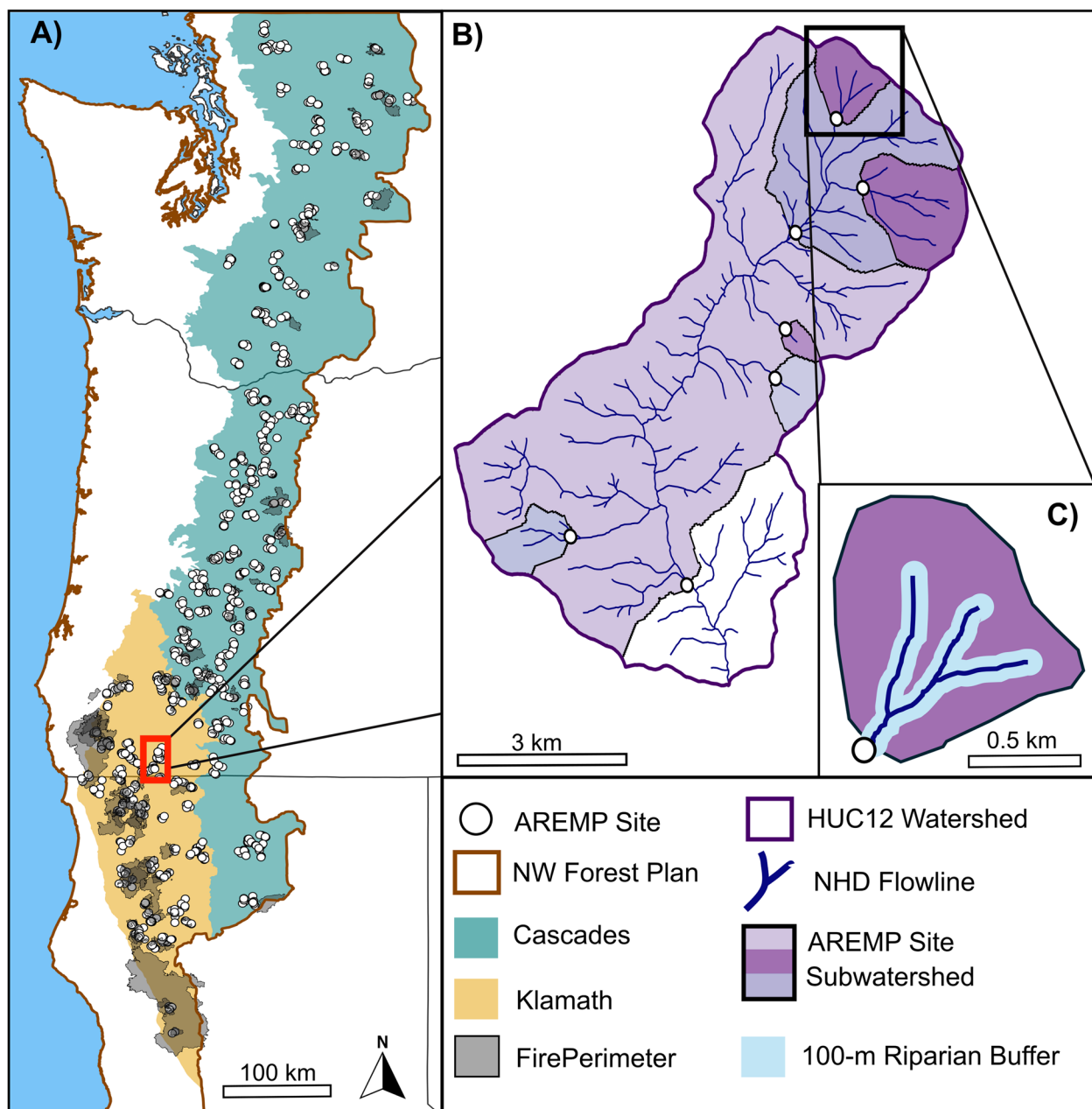


Fig. 1 **A** Map of the study area with study sites shown in white, study fires shaded in grey, and NW Forest Plan outlined in brown. Only wildfires analyzed in this study are shown on the map. These wildfires occurred between 1987 and 2020. Regions of interest (Cascades and Klamath) are shown. **B** Example AREMP HUC12 monitored watershed with AREMP site subwatersheds are outlined in black. NHD flow lines are shown in dark blue. **C** Zoomed in view of an AREMP subwatershed and site. NHD flows lines are shown in dark blue and the riparian buffer is shown in light blue

of the Northern Spotted Owl (*Strix occidentalis caurina*; Fig. 1). Stream and riparian conditions differ across the area because of variability in environmental and geophysical conditions, and management factors. The NWFP can be classified in terms of physiographic regions based on similar geologic history, landforms, and climate (Dunham et al. 2023). Generally, eight aquatic physiographic

regions have been used by AREMP to capture the interaction between geophysical conditions and ecosystems (Dunham et al. 2023). In this study, we considered only the Klamath and a consolidated Cascades region (including the North Cascades, Western Cascades, and High Cascades; Fig. 1A).

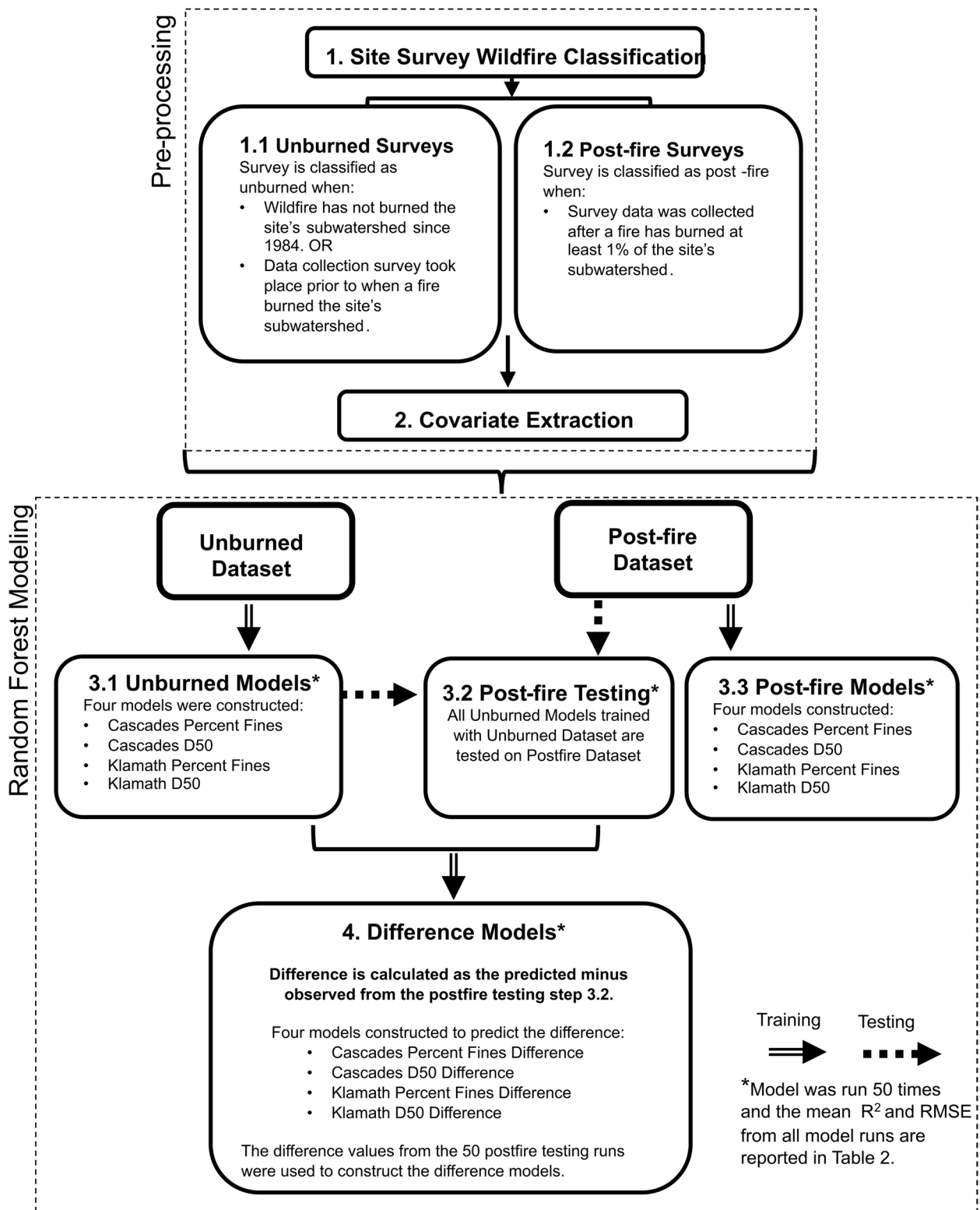


Fig. 2 Procedural framework for assessing the response of streambed sediment size to wildfires in Pacific NW streams

Of the 1400 total AREMP sites that span 220 HUC12 watersheds, this study analyzes 906 sites that span 164 HUC12 watersheds in the Klamath and Cascades regions (Fig. 1). Data collection for our sites of interest took place between 2002 and 2021. All HUC12 watersheds have at least 25% federal land ownership along the length of streams delineated by the NHDPlus 1:100,000 resolution. HUC12 watersheds were selected by AREMP for sampling using a spatially balanced random sampling method subject to logistic constraints, within which sites for field sampling were selected using a similar spatially balanced random selection process, excluding non-wadeable streams, creating a nested sampling design of sites within HUC12 watersheds (Fig. 1B; Dunham et al. 2023). The sampled stream lengths are 20 times the bankfull width (e.g., 160 to 460 m). Selected sites represent varied stream types from low to high gradient, fish bearing and non-fish bearing, or with intermittent to perennial flow (Dunham et al. 2023). The Cascades and Klamath regions vary from each other in terms of climate, lithology, and historic fire regimes. The moist, temperate climate of the Cascades supports highly productive coniferous forests that are dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) at low to middle elevations and Pacific silver fir (*Abies amabilis*) and mountain hemlock (*Tsuga mertensiana*) at middle to higher elevations (Reilly et al. 2021). In this region, wildfire has a historic return interval of 150 to over 400 years (Reilly et al. 2021). This mountainous region is underlain primarily by Cenozoic volcanics that have been affected by glaciation (Pater et al. 1998). The warmer and drier Klamath Region is dominated by Ponderosa Pine (*Pinus ponderosa*) forests and has a historic wildfire return interval of 0–35 years (Reilly et al. 2021). Mountains in this region are highly dissected and underlain by igneous, sedimentary, and metamorphic rocks (Pater et al. 1998). The Cascades and Klamath regions both have a mild Mediterranean climate with long summer droughts and cool, wet winters (Reilly et al. 2017).

Measurement of variables

Streambed grain size distributions AREMP field crews conducted modified Wolman Pebble Counts to measure streambed sediment size (Dunham et al. 2023). Wolman Pebble Counts were conducted at equally spaced transects for all sites. The number of transects, datapoints per transect, and total number of measurements (105–300) collected varied across years (Dunham et al. 2023). The substrate particle sizes were measured along the *b*-axis, which represents the particle's width. At each site, particle sizes are summarized across all transects as the

percent fines (particles ≤ 2 mm) and the median particle size (D50, mm).

Subwatershed metrics We compiled an array of landscape characteristics from the subwatersheds that contribute to each AREMP site that we analyzed (Table 1). These subwatershed characteristics describe topography, lithology and soils, climate, vegetation land cover, and wildfire characteristics (Table 1). We extracted subwatershed topographic metrics by analyzing 10-m digital elevation models from the National Elevation Dataset (NED) using ArcGIS (ArcMap Version 10.8.2; USGS 2019a). We extracted lithology, soil, climate, and road density metrics, using the US EPA Stream Subwatershed (StreamCat) dataset (Hill et al. 2015). From this database, we extracted each subwatershed's average rock compressive strength and hydraulic conductivity. Pre-fire soil properties extracted from StreamCat included average pre-fire organic matter (OM) content, average soil permeability, soil depth to bedrock, and the soil erodibility factor. Climate metrics from this database included the 30-year average precipitation, subwatershed mean annual runoff, 30-year mean annual temperature, average subwatershed baseflow index, and average seasonal water table depth. We also extracted the dominant lithology for each subwatershed using the U.S. Geological Survey (USGS) state lithology layer in ArcGIS (Horton et al. 2017). Vegetation metrics such as the mean subwatershed stand age and mean subwatershed canopy cover were sourced from an Oregon State University dataset (LEMMA 2020). These vegetation metrics were extracted for the specific year that each corresponding site was surveyed.

We were limited by data availability in choosing our covariates of interest. While ideally, we would have used precipitation metrics that account for 15-min storm intensity, such datasets are not readily available for the PNW. Additionally, we used many metrics that represent the average values for our study subwatersheds, such as the average soil permeability, soil depth, and soil organic matter content. These average values may not represent the nuances of each subwatershed and therefore may limit our models' predictive ability. We chose to use these data, however, because they were accessible for our area of interest.

Site-scale stream metrics Field-measured stream metrics were collected by AREMP crews (Table 1). AREMP field crews measured bankfull width at multiple transects along each site (Dunham et al. 2023). We summarized these multiple bankfull width measurements by using the average bankfull width across all transects for each site. To account for observation variability, we also calculated the relative bankfull width as the average bankfull width

Table 1 Summary table of response variables and model covariates

Variables	Unit	Cascades		Klamath		Spatial Extent	Category
		Unburned Mean (SD)	Postfire Mean (SD)	Unburned Mean (SD)	Postfire Mean (SD)		
Percent Fines	%	16 (16)	13.5 (12.1)	13.5 (12.1)	12.3 (12.2)	Reach	Response
D50	phi	5.2 (1.9)	5.2 (1.5)	5.3 (1.3)	5.1 (1.4)	Reach	Response
Percent Fines Difference	-	-	5.7 (9.8)	-	0.8 (9.8)	Reach	Response
D50 Difference	-	-	-0.7 (1.3)	-	0.5 (1.1)	Reach	Response
SITE ID	Categorical	-	-	-	-	Reach	Location
Watershed ID	Categorical	-	-	-	-	HUC12 Watershed	Location
Survey Year	Years	2011 (5)	2015 (4.6)	2015 (4.6)	2013 (5.6)	Reach	Temporal
Mean Bankfull Width	m	8.9 (6.6)	9.2 (6.7)	6.2 (3.8)	7.2 (4.7)	Reach	Stream Morphology
Relative bankfull	-	1.0 (0.2)	0.9 (0.2)	1 (0.2)	1 (0.2)	Reach	Temporal
Streambed Slope	Degrees	0.07 (0.06)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	Reach	Stream Morphology
Valley Confinement	Categorical	-	-	-	-	Reach	Stream Morphology
Instream Large Wood	Units/km	141.9 (121.3)	137.9 (113.6)	74.5 (67.2)	80.8 (63.3)	Reach	Stream Morphology
High Flow Count	-	41.2 (22.3)	40.5 (22.9)	45.3 (26.4)	43.6 (26.9)	Nearest USGS Gage	Climate
Subwatershed Area	km ²	22 (35)	46.7 (58.7)	16.7 (31.3)	29.6 (48.7)	Subwatershed	Topography
% of subwatershed with slopes > 23 degrees	%	31.5 (23.6)	34.1 (22.5)	42.5 (22.1)	45.7 (22.3)	Subwatershed	Topography
Mean Elevation	m	1298 (371)	1,489 (318)	1,207 (374)	1,145 (299)	Subwatershed	Topography
Baseflow Index	%	66.2 (10.2)	69 (8.4)	54.4 (10)	51.3 (8.1)	Subwatershed	Climate
30-year Normal Precipitation	mm	2,008.7 (671.2)	1,584 (403)	1,424 (410)	1,622 (502)	Subwatershed	Climate
30-year Mean Temperature	Celsius	6.9 (2.1)	5.7 (2.4)	10.1 (1.4)	10.8 (1)	Subwatershed	Climate
Mean Rock Compressive Strength	megaPascals	107.1 (28.4)	108.2 (25.9)	115.4 (39.7)	129.8 (28.4)	Subwatershed	Lithology/Soils
Mean Lithological Hydraulic Conductivity	Micrometers/s	4.9 (16)	3.6 (23.6)	0.5 (2)	0.2 (0.7)	Subwatershed	Lithology/Soils
Dominant Geology	Categorical	-	-	-	-	Subwatershed	Lithology/Soils
Mean Soil Erodibility Factor	-	0.23 (0.04)	0.2 (0)	0.3 (0)	0.3 (0)	Subwatershed	Lithology/Soils
Soil Permeability	cm/h	8.9 (5.1)	10.9 (7.2)	5.3 (2.7)	5.5 (2.5)	Subwatershed	Lithology/Soils
Mean Soil Depth to Bedrock	cm	125.5 (13.6)	131.7 (10.9)	91.9 (12.4)	89.7 (10.7)	Subwatershed	Lithology/Soils
Soil Organic Matter Content	%	2.4 (0.9)	1.8 (0.8)	1.6 (0.5)	1.6 (0.5)	Subwatershed	Lithology/Soils
Mean Tree Age	Years	163.6 (42.8)	135.2 (35.1)	134.9 (23.9)	133 (24.9)	Subwatershed	Land Cover
Mean Canopy Cover	%	75.5 (8.9)	60 (15.2)	66.6 (10.3)	58.1 (14.9)	Subwatershed	Land Cover
Road Crossings	Crossings/sqkm	0.009 (0.01)	0.01 (0.01)	0.01 (0.01)	0.008 (0.01)	Subwatershed	Land Cover
Upslope Road Density	km/sqkm	1.2 (0.8)	0.9 (0.8)	1.5 (0.9)	1.2 (0.9)	Subwatershed	Land Cover
Years Between Survey and Fire	Years	-	9.3 (7.4)	-	13.6 (9.9)	Subwatershed	Fire
Area of Subwatershed Burned	Sqkm	-	7.6 (9.9)	-	4.1 (6.8)	Subwatershed	Fire
Area of Subwatershed Burned at Himod	Sqkm	-	4.8 (6.6)	-	2.1 (3.6)	Subwatershed	Fire
Area of Riparian Area Burned	Sqkm	-	0.88 (1.4)	-	0.5 (1)	Riparian	Fire
Area of Riparian Area Burned at Himod	Sqkm	-	0.44 (0.74)	-	0.2 (0.4)	Riparian	Fire
Area of Reach Burned	Sqkm	-	0.02 (0.03)	-	0.02 (0.02)	Reach	Fire
Area of Reach Burned at Himod	Sqkm	-	0.01 (0.02)	-	0.01 (0.02)	Reach	Fire
Fire Rank	Count	-	1.1 (0.23)	-	1.3 (0.6)	Subwatershed	Fire

for a particular survey divided by the average for a site across all the surveys at that site over time. The frequency of large wood at a site was also measured by AREMP field crews. Large wood frequency included the number of

pieces of large wood that were within the bankfull width and exceeded 30 cm in diameter and 7.6 m in length for each site (Dunham et al. 2023). The stream slope for each site was sourced from the National Hydrography

Medium Resolution (30-m) Dataset (NHD; USGS 2019b) and valley confinement data for each site was sourced from McManamay and DeRolph (2019).

We also analyzed the number of high flow events that took place in the year prior to each survey for each site. We chose to limit this data to 1 year due to varying gaps in data availability at some of the gage locations. To calculate this metric, we located the USGS stream gage nearest to each site (USGS 2025). We then calculated the 95th quantile streamflow for each gage for the entire period that the gage had available data. Next, for each survey, we counted how many times the 95th percentile flow was exceeded in the 1 year prior to the survey.

Wildfire metrics In the western PNW, distinct thresholds for the percent of a watershed needed to burn to influence instream sediment size have not been determined. Therefore, we chose to classify a subwatershed upstream of a field-sampled site to be influenced by fire if greater than 1% of its area had burned prior to the survey year (Fig. 2). Otherwise, we classified the site as “unburned”. We chose this percent burned threshold to keep as much variation in the dataset as possible so that we could best investigate these threshold relationships and not censor any results from our dataset. If a site was surveyed pre- and post-fire, the pre-fire survey was classified as “unburned”, and the post-fire survey was classified as a “post-fire” site (Fig. 2). Our study examines 93 different fire perimeters that burned 72 different HUC12 watersheds between 1987 and 2020. The surveys we analyzed span from 1 to 34 years post-fire.

Fire perimeter and burn severity data for all fires examined in this study were sourced from the USGS Monitoring Trends in Burn Severity (MTBS) project (MTBS 2024). MTBS data collection began in 1984, thus we examined wildfires that burned from 1984 to 2021. Some subwatersheds burned more than once during this time period so we selected the fire that burned the most area in a subwatershed as the fire to use in our analysis. Additionally, if more than one fire burned in a subwatershed, we included the total count of fires between 1984 and the survey date as the “fire rank” metric in our analysis (Table 1). MTBS provides burn severity data classified as low, medium, and high based on comparisons between pre- and post-wildfire vegetation reflectance values from Landsat 7 or Landsat 8 30 m resolution imagery. Using the classified severity rasters, we calculated burn severity metrics (total subwatershed area burned and the subwatershed area burned at moderate or high severity) at three different spatial extents: contributing subwatershed, contributing riparian area, and site. The riparian area was delineated as 100-m buffers around the medium resolution NHD lines (Fig. 1C). While we originally included

wildfire metrics that reported the percent of each subwatershed burned and the percent burned at moderate and high severity, we ultimately chose to only use burned area metrics because it slightly improved model predictive power and the area burned metrics ranked slightly higher on the variable importance plots (refer to supplementary materials).

Model development

Random forest

Random Forest (RF) models are a type of classification or regression tree analysis used to evaluate complex relationships between predictor and response variables by combining observations from an ensemble of trees (Cutler et al. 2007). We chose to use RF models for our analysis because they are good at evaluating non-linear relationships and they are robust when dealing with collinearity (Roy and Larocque 2012; Kaveh et al. 2023). We developed and ran RF models using the ranger package in R (Wright and Ziegler 2017). To capture variation across regions, we constructed different RF models for subwatersheds in the Klamath and the Cascades regions (Fig. 2).

We constructed RF models for each region that predict unburned percent fines, unburned D50, post-fire percent fines, and post-fire D50 (Table 2; Fig. 2). The “unburned” models predict streambed percent fines and D50 in the absence of fire and were trained using all surveys from unburned subwatersheds and from surveys that took place prior to fire burning a subwatershed (Fig. 2). We then tested the “unburned” models on post-fire surveys to evaluate their performance (Fig. 2). We also constructed the post-fire models to predict percent fines and D50 using all surveys from the burned subwatersheds (Fig. 2). Next, we used the RF models to predict the differences from the post-fire testing (Fig. 2). These models predict the difference between what the “unburned” model predicts streambed percent fines and D50 to be in the absence of fire compared to what is actually observed post-fire for each survey (Fig. 2).

Model construction and tuning

We used RF machine learning models to predict streambed percent fines and D50 to evaluate the relative importance of landscape controls. Though RF models are generally robust to multicollinearity (Roy and Larocque 2012; Kaveh et al. 2023), we first eliminated the most highly correlated (>0.85) predictor variables to reduce our list of subwatershed metrics. While some studies suggest that collinearity can influence RF model predictive accuracy (Scornet and Hooker 2026), we felt comfortable keeping collinear variables because our models

Table 2 Models summary table

Region	Response variable	Model Name	Data	n	nTrees	Min. Node	mtry	Mean R ²	RMSE
Cascades	Percent Fines	Unburned	Unburned surveys	1390	875	2	7	66.3	9.8
		Unburned	Postfire surveys	197	n/a	n/a	n/a	36.4	11.3
		Postfire	Postfire surveys	197	1150	3	10	58.4	7.8
	Difference (percent fines-predicted)	Difference	Difference between Unburned Model predictions and postfire surveys	197	875	2	12	39.8	7.6
Klamath	Percent Fines	Unburned	Unburned surveys	424	500	2	7	51.2	8.9
		Unburned	Postfire surveys	324	n/a	n/a	n/a	38.7	9.8
		Postfire	Postfire surveys	324	500	3	8	56.3	8.1
	Difference (percent fines-predicted)	Difference	Difference between Unburned Model predictions and postfire surveys	324	625	6	1	35.7	7.8
Cascades	D50	Unburned	Unburned surveys	1390	750	2	10	62.8	1.1
		Unburned	Postfire surveys	197	n/a	n/a	n/a	33.3	1.5
		Postfire	Postfire surveys	197	812	3	10	68.4	0.8
	Difference (D50 - predicted)	Difference	Difference between Unburned Model predictions and postfire surveys	197	500	6	9	55.0	0.9
Klamath	D50	Unburned	Unburned surveys	424	750	1	2	41.8	1.0
		Unburned	Postfire surveys	324	n/a	n/a	n/a	41.8	1.2
		Postfire	Postfire surveys	324	1325	1	5	54.8	0.9
	Difference (D50 - predicted)	Difference	Difference between Unburned Model predictions and postfire surveys	324	500	12	2	30.5	0.9

are being used for exploratory rather than predictive purposes. In the case that two variables were highly correlated, we retained the variable whose influence on instream sediment size was more strongly supported by the literature. The exceptions to this were wildfire metrics and subwatershed road density metrics, which were retained regardless of correlation. Predictor variables that were used in the RF modeling are shown in Table 1. We also included site and HUC12 watershed identifying covariates to account for the nested nature of our study sites (Table 1; Fig. 1).

Next, we tuned each individual model to find the best model structure. Random Forest performance relies predominately on the numbers of trees, the number of variables used at each split, and the minimum size of data points before splitting a tree (Rocher-Ros et al. 2023). To tune these model parameters, we used the tidymodels package in R (Kuhn and Wickham 2020). To find the best parameters for our models, we conducted a grid search, in which combinations of a broad range of parameters were evaluated to find the model that performed best, evaluated in a tenfold cross-validation. After this broad

grid search was performed, we repeated the process with a narrower range of values to select the final, best-performing model (Table 2).

Model training

To investigate which subwatershed characteristics drive instream responses in unburned subwatersheds, we constructed the “unburned” RF models that predict percent fines and D50 using all surveys from unburned subwatersheds and pre-fire surveys from burned subwatersheds (Fig. 2). To investigate which subwatershed characteristics drive instream responses in burned catchments, we constructed the “post-fire” RF models that predict percent fines and D50 using all surveys from subwatersheds where at least 1% of their area burned (Fig. 2). The covariates used in the “unburned” models describe subwatershed topography, climate, landcover, lithology and soils, stream characteristics, and location (Table 1). The “post-fire” models used all of the same covariates as the “unburned” models as well as wildfire metrics (Table 1). To account for slight variations in model performance when running RF models, we ran each model 50 times

and reported the summarized output, including the mean R^2 and mean root mean square error (RMSE). To investigate which subwatershed characteristics influence the response variables, we constructed variable importance plots and partial dependence plots that summarize outputs from all 50 model runs. We chose to assess variable importance in our models using mean decrease in accuracy (MDA) measurements because it is one of the most widely used variable importance metrics used in RF modeling (Scornet and Hooker 2026). MDA is calculated by evaluating the difference in RF predictive performance if a variable is included vs excluded from a model. We used the decrease in percent mean square error (%MSE) to calculate MDA for our models. The variable importance plots rank variables by this decrease in %MSE for all variables across all model runs. Partial dependence plots show the marginal effect a covariate has on the predicted response.

Running unburned models with post-fire survey data

To investigate how well the drivers that explain percent fines in an unburned subwatershed apply in a post-fire environment, we tested the unburned model on post-fire surveys and assessed model fit (Fig. 2). To do this, we stored all 50 model runs from the training of the unburned model and applied them to the post-fire survey data. We then evaluated model fit by examining mean R^2 and mean RMSE from all model runs (Table 2; Fig. 2).

Modeling the difference between unburned model and predictions with post-fire data

To explore factors driving differences between unburned model predicted percent fines and D50 in the absence of fire vs. post-fire field observations, we calculated the difference from the unburned model tests on the post-fire survey data (Fig. 2). Difference was calculated as the predicted minus the observed values. Because we tested 50 unburned RF model runs on the post-fire surveys, we had 50 datasets of predicted and observed values to examine. To model these differences, we looped through all 50 datasets and constructed RF models that predicted the difference for each. We used the same covariates included in the post-fire models to predict the difference. We then evaluated model fit for all model runs by reporting mean R^2 and mean RMSE. To investigate which subwatershed characteristics influence the differences between predicted and observed values, we constructed variable importance plots and partial dependence plots that summarize outputs from all 50 model runs. It is important to note that constructing models to predict other modeling output will increase uncertainty in the results. Because we are using the difference models to examine broad relationships and not as prediction or forecasting tools,

we believe that results from the difference models are still useful in providing insights for addressing our research objectives.

Results

Identifying controls on instream percent fines and D50 in the absence of wildfire

The unburned percent fines model had a higher mean R^2 in the Cascades ($R^2=66.3$ and $RMSE=9.8$) compared to the Klamath ($R^2=51.2$, $RMSE=8.9$) (Table 2). Similarly, the D50 unburned model had a higher R^2 in the Cascades ($R^2=62.8$ and $RMSE=1.1$) compared to the Klamath ($R^2=41.8$, $RMSE=1.0$) (Table 2).

Random forest variable importance plots of unburned sites using the unburned model identified temporal trends (survey year) as the main driver of instream percent fines in both the Cascades (72% MSE) and the Klamath (36% MSE) (Fig. 3A). In both regions, percent fines have a negative relationship with survey year (Fig. 3A). In comparison, the unburned D50 models in both the Cascades and the Klamath show mean bankfull width to be the most important driver (33% MSE and 20% MSE, respectively; Fig. 4A). In both regions, mean bankfull width has a positive relationship with D50. In the Cascades unburned D50 model, the majority of the variable importance is attributed to stream morphology metrics (e.g., bankfull mean, confinement and stream slope; 80% MSE; Fig. 4A).

Do the drivers explaining sediment size in the absence of fire continue to control instream percent fines and sediment size (D50) post-fire?

When the unburned percent fines model was applied to percent fines data from post-fire subwatersheds, the R^2 decreased in both the Cascades and Klamath regions ($R^2=36.4$ and 38.7 , respectively), and RMSE increased (11.3 and 9.8, respectively) (Table 2). Similarly, when data from burned subwatersheds were used in the unburned D50 models for the Cascades, model performance also declined ($R^2=33.3$, $RMSE=1.5$). However, when D50 data from burned subwatersheds were used in the unburned model in the Klamath, model explanatory power ($R^2=41.8$, $RMSE=1.2$) was similar to unburned data results (Table 2).

In the Cascades post-fire model (developed using post-fire data), mean bankfull width ranks as the most important driver of instream percent fines (Fig. 3B). Out of the top ten most important variables in the Cascades post-fire percent fines model, the majority of importance is attributed to soil and lithology metrics (40% MSE), followed by wildfire metrics (23% MSE), and stream morphology (20% MSE; Fig. 3B). Mean bankfull width is also

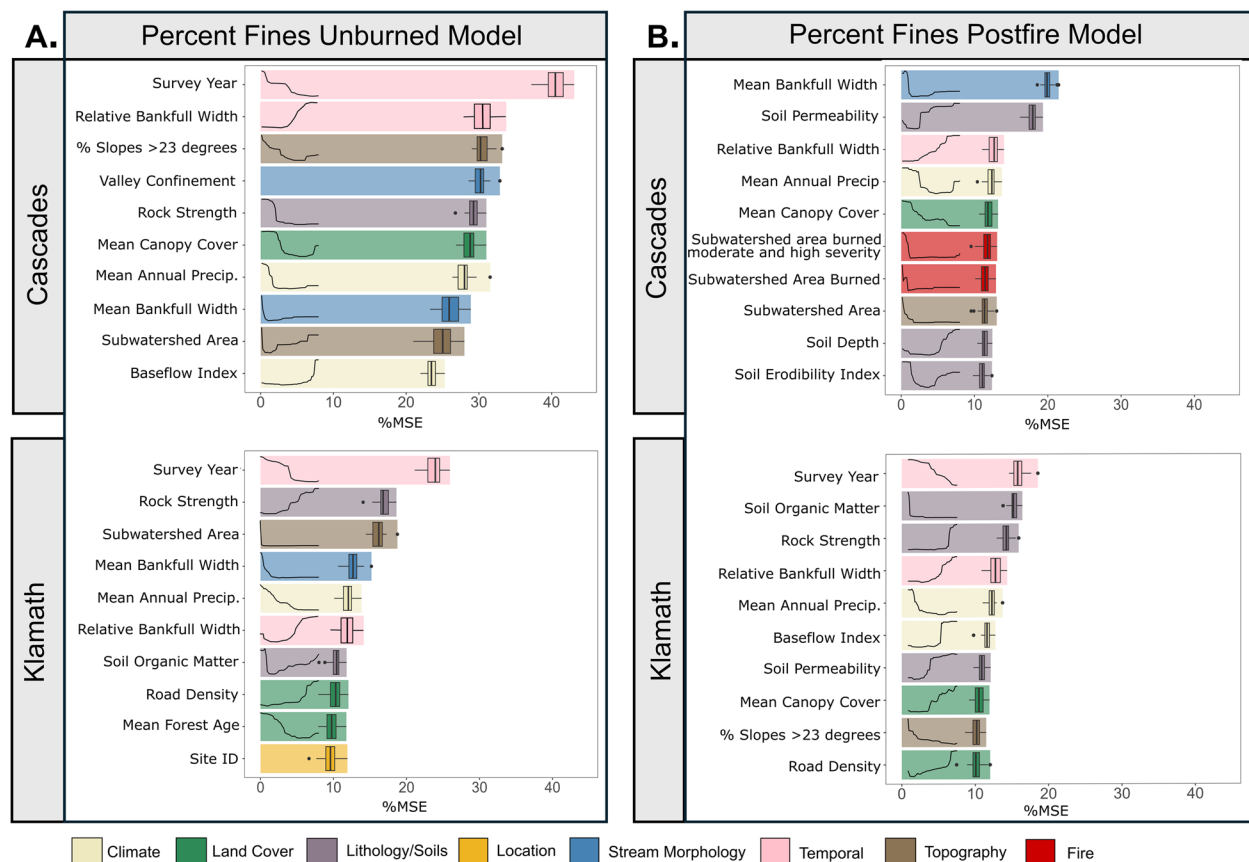


Fig. 3 Variable importance plots showing the top ten most important predictor variables for percent fines. Boxplots summarize the importance output from 50 model runs. Lines represent the generalized partial dependence plots for each predictor variable and are not to scale. Categorical covariates do not have partial dependence plots depicted. Full variable importance plots and detailed partial dependence plots can be found in the supplementary materials. **A** Variable importance plot for the Unburned Percent Fines model that was trained using solely unburned and pre-fire data for the Cascades (top) and Klamath (bottom) regions. **B** Variable importance plot for the Postfire Percent Fines model that was trained using solely postfire data for the Cascades (top) and Klamath (bottom) regions

the most important driver of instream D50 for the Cascades post-fire model (Fig. 4B). Out of the top ten most important variables in the Cascades post-fire D50 model, the majority of importance is attributed to soil and lithology metrics (52% MSE), followed by topography (27% MSE), and stream morphology (20% MSE). Wildfire metrics have a combined 12% MSE (Fig. 4B).

In the Klamath post-fire model (developed using post-fire data), survey year is the most important variable driving instream percent fines (Fig. 3B). Out of the top ten most important variables in the Klamath, the majority of importance is attributed to soil and lithology metrics (40% MSE), followed by temporal trends (29% MSE), and climate metrics (24% MSE). No wildfire metrics rank within the top ten most important variables for the Klamath post-fire percent fines model (Fig. 3B). Mean bankfull width is the most important driver of instream D50 for the Klamath post-fire model (Fig. 4B). Out of the top ten most important variables, the majority of

importance is attributed to soil and lithology (44% MSE), followed by topography (28% MSE), stream morphology (26% MSE), and wildfire metrics (24% MSE; Fig. 4B).

Which landscape characteristics might be explaining the differences that we are observing between streambed sediment size in burned and unburned watersheds?

The percent fines difference model had a similar mean R^2 in the Cascades ($R^2=39.8$ and $RMSE=7.6$) compared to the Klamath ($R^2=35.7$, $RMSE=7.9$) (Table 2). The D50 difference model had a higher R^2 in the Cascades ($R^2=55.0$ and $RMSE=0.9$) compared to the Klamath ($R^2=30.5$, $RMSE=0.9$) (Table 2).

In the Cascades, random forest variable importance plots of the difference models identified canopy cover to be the main driver of difference for both the percent fines and D50 difference models (Figs. 5A and 6A). Canopy cover was followed in importance by instream large

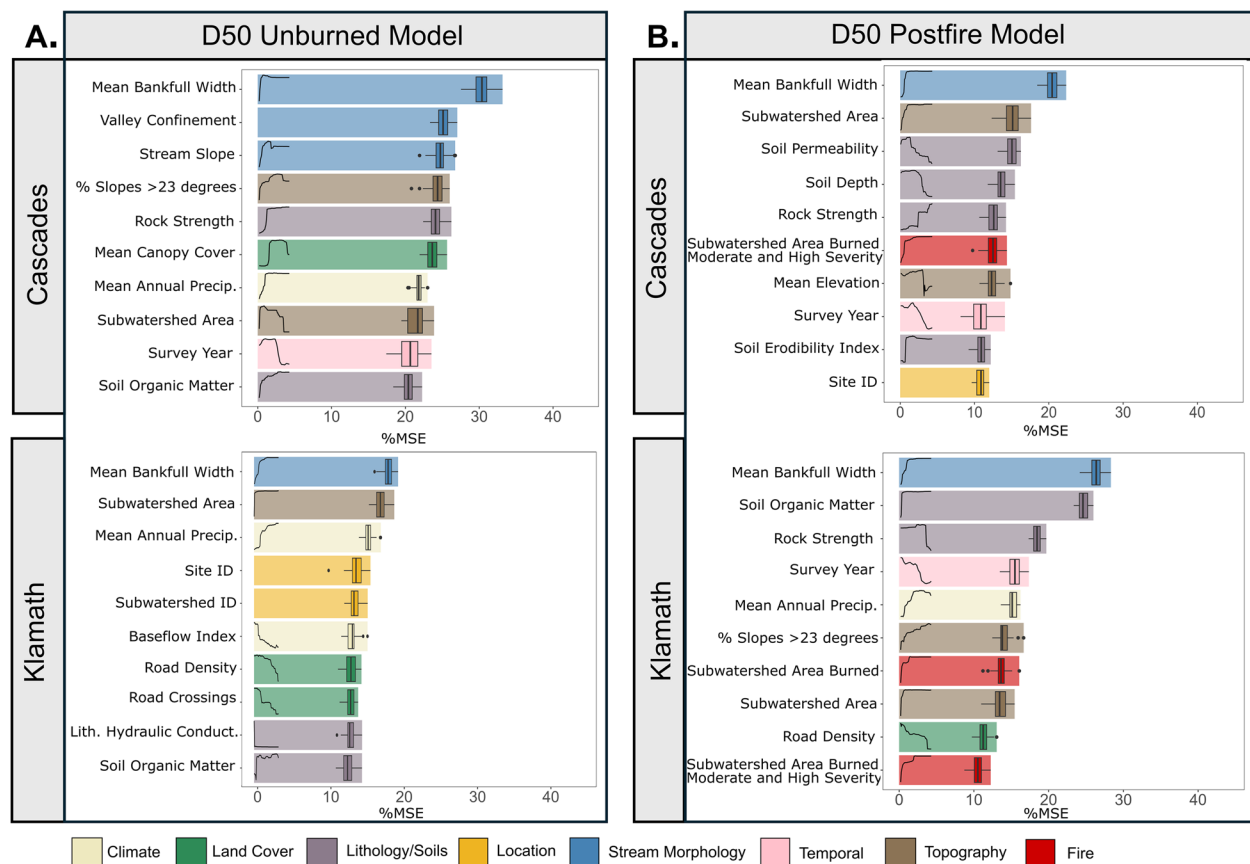


Fig. 4 Variable importance plots showing the top ten most important predictor variables for D50. Boxplots summarize the importance output from 50 model runs. Lines represent the generalized partial dependence plots for each predictor variable and are not to scale. Categorical covariates do not have partial dependence plots depicted. Full variable importance plots and detailed partial dependence plots can be found in the supplementary materials. **A** Variable importance plot for the Unburned D50 model that was trained using solely unburned and pre-fire data for the Cascades (top) and Klamath (bottom) regions. **B** Variable importance plot for the Postfire D50 model that was trained using solely postfire data for the Cascades (top) and Klamath (bottom) regions

wood frequency for the percent fines difference model (Fig. 5A) and by mean bankfull width for the D50 difference model (Fig. 6A). Two wildfire metrics ranked in the top ten most important variables for the percent fines and D50 difference model (number of years since the fire and the subwatershed area burned at moderate and high severity, and the riparian and subwatershed area burned at moderate and high severity, respectively), and all combined, wildfire metrics are associated with 61% MSE in the percent fines model and 50% MSE in the D50 difference model (Figs. 5A and 6A).

In the Klamath, random forest variable importance plots of the difference models identified soil and lithologic metrics (rock compressive strength, pre-fire soil organic matter content, dominant subwatershed lithology) to be the top three most important drivers of difference in the percent fines (Fig. 5B) and D50 difference models (Fig. 6B). No wildfire metrics ranked in the top ten most important variables for either the percent fines

or D50 difference models. All combined, wildfire metrics are associated with 42% MSE in each of the percent fines and D50 difference models.

Discussion

In this study, we constructed models to evaluate (1) how the presence and severity of wildfire explain streambed sediment size in PNW watersheds of the Cascades and Klamath regions, and (2) how watershed characteristics and context influence the effects of wildfire on streambed sediment size. We found distinct patterns in how fire appears to influence instream sediment in the Cascades compared to the Klamath, which may be explained by differences in fire regime and land management trends between the two regions. Our novel approach used the AREMP dataset to investigate broad trends and relationships across climatic gradients and fire regimes. These results offer insight into complex relationships among landscape characteristics, wildfire, and aquatic habitat. In the Cascades, post-fire

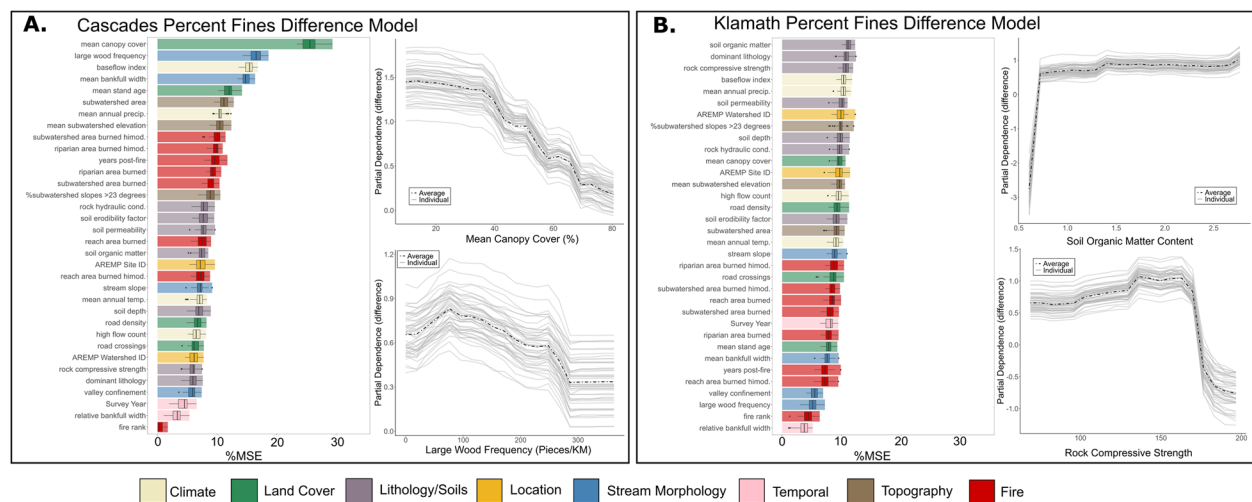


Fig. 5 Difference is calculated as predicted minus observed from the post-fire testing stage (see Fig. 2). **A** Variable importance plot for all variables examined in the Cascades Percent Fines Difference Model. Variables are ranked by average %MSE, which were summarized from all 50 model runs. Boxplots represent the summary from 50 model runs (left). Partial dependence plots for the Cascades Percent Fines Difference Model showing the relationship between difference and catchment canopy cover (upper right) and instream large wood frequency (lower right). Individual model runs shown in grey and the mean partial dependence across all model runs shown in the black dotted line. **B** Variable importance plot for all variables examined in the Klamath Percent Fines Difference Model. Variables are ranked by average %MSE, which were summarized from all 50 model runs. Boxplots represent the summary from 50 model runs (left). Partial dependence plots for the Klamath Percent Fines Difference Model showing the relationship between difference and pre-fire soil organic matter content (upper right) and mean catchment rock compressive strength (lower right). Individual model runs shown in grey and the mean partial dependence across all model runs shown in the black dotted line

canopy cover appears to be driving differences in observed post-fire stream sediment compared to expected unburned conditions, while soil and lithology characteristics are the main drivers of difference in the Klamath region.

Controls on streambed sediment size in unburned and post-fire subwatersheds

In the unburned subwatersheds, percent fines decreased over time in both the Cascades and Klamath regions. Out of the suite of covariates analyzed for the unburned models, temporal trends (survey year) were the key driver of instream percent fines (Fig. 3A). This overall decrease in percent fines is consistent with trends observed across the entire AREMP area between 2002 and 2018 which could be attributed to land use legacies and changes in active forest and road management since the implementation of the NWFP in 1994 (Dunham et al. 2023). Since the establishment of the NWFP, there has been a 7% reduction in road length across the region, with a particular focus on decommissioning roads with high landslide risk (Dunham et al. 2023). Between 1993 and 2019, the Klamath region exhibited the largest absolute decrease in sediment delivery from roads to channels compared to all other AREMP regions (Dunham et al. 2023).

In the post-fire subwatersheds in the Klamath, survey year remains the most important covariate driving percent fines (Fig. 3B). In addition, road metrics (i.e.,

subwatershed road density and upstream road crossings) rank within the top ten most important drivers for all unburned and post-fire Klamath models. In the Klamath, we observed a positive relationship between road density and percent fines and a negative relationship between road density and D50 across unburned and post-fire subwatersheds. This suggests that more roads in the subwatershed is related to a fining of the grain size distribution, which is consistent with findings from Al-Chokhachy et al. (2025). The quantity of largest size class of wood measured by AREMP size has also been declining across the AREMP study area, which could be contributing to the observed declines in percent fines, as large woody debris plays a crucial role in fine sediment storage (Dunham et al. 2023; Rengers et al. 2023; Zelt and Wohl 2004). Overall, we found that the influence of road decommissioning and other management changes, declines in large wood, and other factors driving temporal trends, might play a larger role in influencing instream grain size distributions than wildfire in this region.

Mean bankfull width was a key driver for many of the models in both the unburned and post-fire subwatersheds (Figs. 3 and 4). In the post-fire subwatersheds in the Cascades, mean bankfull width was the most important covariate driving percent fines (Fig. 3B). In this model, percent fines exhibited a negative relationship with mean bankfull width. Additionally, across all D50

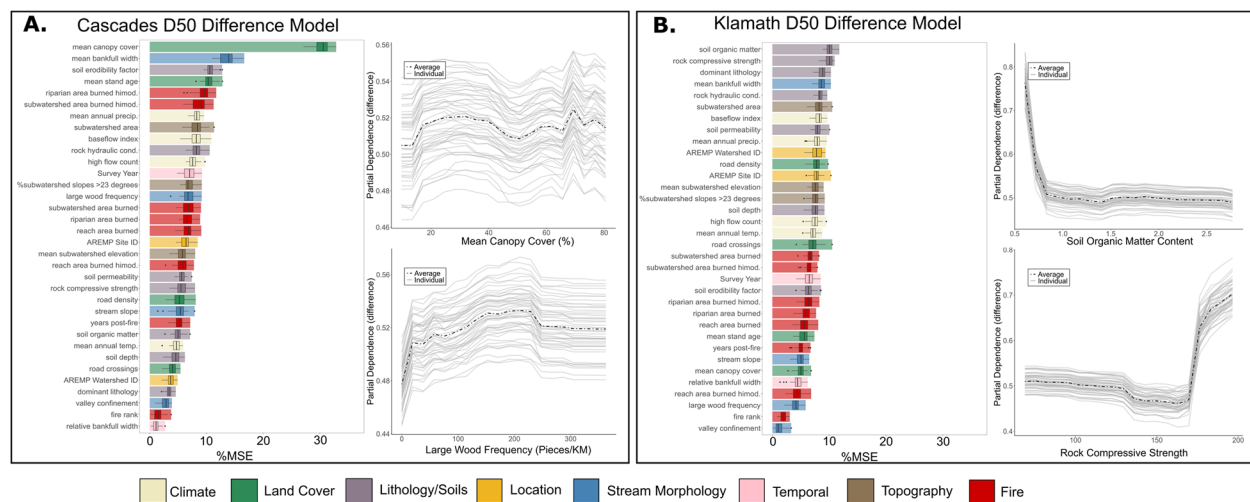


Fig. 6 Difference is calculated as predicted minus observed from the post-fire testing stage (see Fig. 2). **A** Variable importance plot for all variables examined in the Cascades D50 Difference Model. Variables are ranked by average %MSE, which were summarized from all 50 model runs. Boxplots represent the summary from 50 model runs (left). Partial dependence plots for the Cascades D50 Difference Model showing the relationship between difference and catchment canopy cover (upper right) and instream large wood frequency (lower right). Individual model runs shown in grey and the mean partial dependence across all model runs shown in the black dotted line. **B** Variable importance plot for all variables examined in the Klamath D50 Difference Model. Variables are ranked by average %MSE, which were summarized from all 50 model runs. Boxplots represent the summary from 50 model runs (left). Partial dependence plots for the Klamath D50 Difference Model showing the relationship between difference and pre-fire soil organic matter content (upper right) and mean catchment rock compressive strength (lower right). Individual model runs shown in grey and the mean partial dependence across all model runs shown in the black dotted line

models, mean bankfull width was the primary driver, and exhibited a positive relationship with D50 (Fig. 4). These findings suggest that wider bankfull widths in our study corresponded with less percent fines and a coarser bed material in both unburned and post-fire subwatersheds. Because bankfull width scales with drainage area and thus discharge (Castro and Jackson, 2001; Erikson et al. 2024), bankfull width could be acting as a proxy for stream power in our models (Bull 1979), with wider bankfull widths representing higher stream power. This would make sense that wider sites in our study had coarser bed material across all watersheds, as fine sediment is flushed out of the system by the higher stream power in the wider channels (Carson and Griffiths 1987). We investigated other channel morphology metrics that also influence stream power and flow dynamics (i.e., stream slope and valley confinement), but these metrics only ranked highly in one model (Cascades Unburned D50).

For the post-fire models, wildfire metrics were key drivers in both the Cascades and Klamath D50 models (Fig. 4B). In the Cascades, wildfire metrics (total subwatershed area burned and area burned at moderate and high severity) exhibited a negative relationship with percent fines, suggesting that as the area burned in the subwatersheds increased, percent fines in the study reaches decreased. Similarly, the important

wildfire metrics for the D50 models in the Cascades and Klamath exhibited a positive relationship with D50, suggesting that as wildfire burns more area, the full grain size distribution becomes coarser. While an influx of fine sediment into channel networks immediately post-fire has been observed in the literature (Busby and Wilcox 2024; Eccleston 2008; Gillard 2019), this fine sediment is often flushed out of the system in subsequent years following fire, which leads to an overall coarsening of the bed material (Brogan et al. 2019; Busby and Wilcox 2024; Chin et al. 2019; Short et al. 2015). This relationship between more area burned and a coarsening of the bed material could be attributed to post-fire increases in streamflow (Hallema et al. 2017; Long and Chang 2023; Canham et al. 2025; Pirani and Coulibaly 2025). In the PNW, large fires have been observed to increase annual river flow for at least 5 years post-fire, with the amount of flow increasing with the area of the subwatershed burned (Hallema et al. 2018; Loiselle et al. 2020). The surveys used in this analysis range from 1 to 33 years post-fire, with a median of 8 years post-fire. Therefore, these results could be indicative of post-fire increases in streamflow and subsequent coarsening of the bed material multiple years after fire.

Assessing shifts in post-fire instream sediment

The mechanisms driving instream sediment size in unburned subwatersheds in the Cascades are different from the processes driving instream sediment size in burned subwatersheds (Table 2). In contrast, in the Klamath, the drivers explaining sediment size in the unburned subwatersheds are better able to also explain sediment size in burned subwatersheds, suggesting that the fire effect on streambed sediment is less strong in the Klamath compared to the Cascades.

Variability in fire effect between the Cascades and the Klamath could be related to differences in fire regimes. In the Cascades, where the climate is generally wetter, the wildfire return interval spans from 150 to over 400 years with fire burning at mixed and high severities (Reilly et al. 2021). In contrast, in the Klamath, where the climate is warmer and drier, the wildfire return interval is 0 to 35 years with fire burning at mixed severities (Reilly et al. 2021). The post-fire surveys used in our analysis for the Klamath range from 1 to 34 years post-fire, with a median of 12 years post-fire. Therefore, the amount of time post-fire that some of our surveys were conducted is on the same time scale as the fire return interval in this region. Because our wildfire data begins in 1984, it is possible that surveys we classified as “unburned” or “pre-fire” in this study actually burned relatively recently prior to 1984. It is possible that the stronger fire effect we are observing in the Cascades could simply be explained by the less frequent, more severe, fire regime in this region. The longer recovery period post-fire in the Cascades could enable us to better differentiate the “unburned” landscape vs the post-fire landscape in this region. In the Klamath, however, where wildfire is occurring more frequently, it may be challenging to tease out the long-term impacts of wildfire on aquatic systems.

Fire recurrence interval differences between the Cascades and Klamath could also be influencing the sediment availability in burned subwatersheds, which could in turn impact downslope aquatic habitat. Studies have found that sediment availability, more so than topography or soil characteristics, may be the most important control on post-fire sediment yields from hillslopes (Moody and Martin 2009; Wall et al. 2023). While wildfire is known to increase sediment yields in the short term (first 2 years) after fire (Moody and Martin 2009; DiBiase and Lamb 2013; Santi and Macaulay 2021) erosion and debris flows produced from catchments following a fire can evacuate channels of sediment and reduce the magnitude and frequency of debris flows in the long term (Hoch et al. 2021; Thomas et al. 2021). Therefore, any sediment yields after the initial post-fire geomorphic response are likely dependent on colluvium production and hollow refill rates (Reneau et al. 1990; Benda and

Dunne 1997; Reneau et al. 2007). Because wildfire occurs more frequently in the Klamath, it is possible that subwatersheds are supply limited post-fire, reducing post-fire geomorphic change, and resulting in post-fire response being controlled by upslope sediment production (Roda-Boluda et al. 2017). Therefore, we hypothesize that the lithologic factors influencing colluvium production and hollow refill rates are driving where there is a greater fire effect in the Klamath. In the Cascades, where fire occurs less frequently, there is more time for post-fire vegetation recovery, sediment recruitment, and soil development. How streams respond to wildfire in the Cascades could, in contrast, be controlled by the factors that influence hillslope sediment transport dynamics and instream sediment transport and aggradation processes.

Drivers of difference between unburned and post-fire grain size distributions

Wildfire metrics were not found to be the most important drivers of difference in the Cascades and Klamath percent fines or D50 difference models (Figs. 5 and 6). While wildfire metrics do not rank as the most important variable in either region, our results indicate that wildfire metrics are playing a more important role in the Cascades models (50–60%MSE) compared to the Klamath (40%MSE). These results suggest that the influence of wildfire on instream sediment is filtered through other landscape characteristics. How fire might influence a river system seems to be more reliant on upslope subwatershed cover, soil, and lithology characteristics and instream channel morphology. This supports findings from other studies that have investigated how wildfire influences erosion regimes (Moody and Martin 2009, 2001; Wagenbrenner and Robichaud 2014) and channel morphology (Brogan et al. 2019; Busby and Wilcox 2024; Chin et al. 2019), which have found that how wildfire impacts a watershed is highly variable and depends on an array of landscape factors.

We found that for both the percent fines and D50 Cascades difference models, subwatershed canopy cover is by far the most important driver of expected to observed differences associated with wildfire (Figs. 5 and 6). For the Cascades percent fines difference model, we observed that as post-fire canopy cover increases, the difference between what the unburned model predicts and what is observed post-fire decreases (Fig. 5A). This suggests that the less canopy cover there is after a fire, the more wildfire influences instream sediment size. For the D50 Cascades difference model, we observed a less clear relationship (Fig. 6A). Canopy cover could be an important driver of difference for percent fines for multiple reasons. For one, canopy cover could represent a proxy for live trees in the subwatershed. As post-fire tree mortality increases over

time, root strength declines, which can increase sediment yields from burned hillslopes via shallow landslides and debris flows (Reilly et al. 2023; Selander et al. 2025; Wondzell and King 2003). Additionally, less canopy cover can lead to increases in rainsplash erosion and subsequent surface erosional processes, further leading to increased sediment yields post-fire (Hammer 2022; McGuire et al. 2024; Santi and Rengers 2022). Further, less live trees in a subwatershed can reduce evapotranspiration, leading to increased hydrologic runoff, increased baseflows, and higher streamflow for many years post-fire (Hallema et al. 2018; Kang et al. 2024; Loiselle et al. 2020). Finally, the canopy cover measurement could reflect the availability and amount of large woody debris that could reach the channel network, which in turn may drive instream sediment changes post-fire (Zelt and Wohl 2004; Short et al. 2015; Rengers et al. 2023). For example, after the 2020 Labor Day Fires in Oregon, Busby and Wilcox (2024) observed a 50% increase in the number of large wood pieces in burned reaches compared to unburned reaches over the same time frame, which contributed to sediment aggradation and bar formation.

In the Cascades percent fines difference model, canopy cover is followed in importance by instream large wood. Interestingly, we observed a negative relationship between the quantity of large wood and difference for the Cascades percent fines difference model, finding that the more large wood there was in a reach post-fire, the less difference between expected unburned conditions and post-fire observations. It is possible that large wood in streams could slow down and mitigate the effects of increased post-fire streamflow. Other research has found that large woody debris is a critical factor influencing post-fire bed material change (Rengers et al. 2023; Short et al. 2015). For example, Short et al. (2015) found that the delivery of large wood into channels over a 7-year period post-fire was a dominant factor in how post-fire erosion was reorganized in the channel as bed material. For the Cascades D50 difference model, we observed a positive relationship between the quantity of large wood and the difference, suggesting that the more large wood there was in the reach post-fire, the more the unburned model expected D50 to be coarser than was really observed post-fire.

In the Klamath, we found that the key drivers of difference were factors that most influence upslope sediment supply. Rock compressive strength, soil organic matter content, and the subwatershed's dominant lithology were the top three most important drivers of difference for both the percent fines and D50 difference models (Figs. 5 and 6). Rock compressive strength has been found to directly control the size of sediment weathered from hillslopes (Riebe et al. 2015; Roda-Boluda et al. 2017;

Sklar et al. 2017), where coarser grain size are expected from stronger rocks. In our difference model, we found that as rock strength increases, the difference between the unburned model predictions and what is observed post-fire increases. This could suggest that sediment yields from rocks with higher compressive strengths are more altered by wildfire than weaker rocks; however, future research will be needed to thoroughly investigate this relationship.

Pre-fire soil organic matter (OM) content was also found to be an important control on difference in the Klamath. For the percent fines difference model, we observed that when OM content is lowest, the unburned model under-predicts and expects there to be less percent fines than are really observed post-fire. As OM increases, the percent fines difference appears to decrease. Similarly, for the D50 difference model, when OM content is lowest, the unburned model overpredicts and expects the grain size distribution to be coarser than is really observed post-fire. Like the percent fines model, as OM content increases, the D50 difference gets closer to zero. OM has been found to be significant in predicting post-fire sediment yields and debris flow generation after fire (Cannon et al. 2010; Wall et al. 2023). Soil organic matter is an important agent for maintaining soil structure and the quantity of soil organic matter has been found to directly influence soil aggregation (Mataix-Solera et al. 2011). When soil organic matter is incinerated during wildfire, hydrophobic compounds are produced, which lead to reduced soil infiltration rates (Certini et al. 2011; DeBano 1981; Ice et al. 2004). The severity of post-fire hydrophobicity has been directly related to the quantity of soil organic matter incinerated by the fire (DeBano 2000, 1981), which in turn could have implications for post-fire sediment yields (Cannon et al. 2010; Wall et al. 2023). It is also possible that we are observing less difference between the expected unburned conditions and what is observed post-fire when OM is higher, because OM could serve as a proxy for places with more biomass pre-fire and therefore more potential for rapid revegetation.

Conclusion

In this study, we used the AREMP dataset to investigate broad trends and relationships across climatic gradients and fire regimes in the Cascades and Klamath regions of the western PNW. We examined 93 different fire perimeters that burned across 72 HUC12 watersheds, spanning from western Washington to Northern California. By using this extensive dataset, we examined long-term post-fire trends in aquatic habitat, with surveys taking place between 1 and 34 years post-fire. For unburned subwatersheds in our study region, we found

temporal trends to be key drivers of instream percent fines. This finding is consistent with trends observed across the AREMP study area that suggest percent fines are decreasing due to land management legacies and changes to land management with the establishment of the NWFP. Survey year was also a key driver of post-fire percent fines in the Klamath, suggesting that these land management factors may be playing a larger role in driving post-fire percent fines in this region compared to wildfire effects.

We found distinct patterns in how fire appears to influence instream sediment in the Cascades compared to the Klamath, which could be explained by differences in fire regime and land management practices between the two regions. In the Klamath, where wildfire occurs more frequently, it is possible that subwatersheds are sediment supply limited post-fire, reducing post-fire geomorphic change, and resulting in post-fire response being controlled by upslope sediment production. In this region, we found that catchments with greater pre-fire soil OM content exhibited the least amount of difference between unburned expected conditions and post-fire observed instream sediment. In contrast, in the Cascades, where fire occurs less frequently, there is more time for post-fire vegetation recovery, sediment recruitment, and soil development. In the Cascades, we found that subwatershed canopy cover and the amount of large wood in the reach post-fire were the key controls on the difference between unburned expected conditions and post-fire observations. How streams respond to wildfire in the Cascades could therefore be controlled by the factors that influence hillslope sediment transport dynamics and instream sediment transport and aggradation. Our findings offer insight into which landscape controls influence whether aquatic habitat might be vulnerable to or resilient to change post-fire, across different regions in the PNW.

Abbreviations

AREMP	Aquatic Riparian Effectiveness Monitoring Program
PNW	Pacific Northwest
D50	Median grain size
NWFP	Northwest Forest Plan
NED	National Elevation Dataset
StreamCat	US EPA Stream Subwatershed dataset
OM	Pre-fire soil organic matter content
USGS	U.S. Geological Survey
MTBS	Monitoring Trends in Burn Severity
NHD	National Hydrography Dataset
RF	Random Forest
RMSE	Root mean square error
%MSE	Percent mean square error

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

SW conducted the analyses and was the major contributor in writing the manuscript. MS provided guidance on the analyses and provided multiple reviews of the manuscript. RB provided guidance on the analyses and provided multiple reviews of the manuscript. DHW provided and cleaned data for analysis. MS, RB, BF, JE, CH provided feedback through the analysis process and provided multiple rounds of feedback on the written manuscript. All authors read and approved the final manuscript.

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Data availability

The datasets analyzed for the current study will be made available in a public data repository before publication. The code used for the analysis can be found at https://github.com/snyderdmn/AREMP_wildfire_substrate/.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

The authors declare no competing interests.

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