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Wildfire and forest treatments mitigate–but cannot forestall–climate-driven changes in streamflow regimes in a western US mountain landscape

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Abstract

Warming temperatures and increasingly variable precipitation patterns are reducing winter snowpack and critical late-season streamflows. Here, we used two models (LANDIS-II and DHSVM) in linked simulations to evaluate the effects of wildfire and forest management scenarios on future snowpack and streamflow dynamics. We characterized the biophysical attributes of the areas with the greatest potential for treatments to improve hydrologic functioning and we examined projected trends in flow regimes over the 21st century.

We found that, despite a projected increase in total annual flows, there was a steep decline in snowpack and late-season flows. Wildfire was an important factor influencing streamflow and snowpack dynamics, with increasing burned area partially offsetting climate-driven declines in

snowpack and spring flows. Forest thinning treatments contributed modest increases to annual flows, although effects were overshadowed by the influences of climate and wildfire. Warmer winter temperatures extinguished snowmelt-driven flows in low- and mid-elevation watersheds, causing a transition from spring snowmelt- to autumn rain-dominated streamflow regimes.

Our results complement prior empirical studies showing that forest treatments can improve snowpack retention and annual streamflow, and they emphasize the importance of wildfire as a primary factor governing landscape hydrology. We found that neither land management practices nor wildfire could completely compensate for the top-down controls of future climate on landscape hydrology. Declines in snowpack retention and a regime shift in the timing of peak flows will have dramatic consequences for forest health, human water resources, and Pacific salmon populations.

Introduction

Warming temperatures and increasing variability in precipitation are causing declines in winter snowpacks and late-season low flows throughout western North America (Mote et al. 2018, McCabe and Wolock 2009). Forests and their disturbance processes also mediate snowpack dynamics and surface water flows (Bisson et al. 2003, Boisramé et al. 2017, Nippgen et al. 2011, Jones et al. 2012). Yet, it is not clear how the bottom-up influence of vegetation may amplify or impede the top-down influences of climate, or similarly, how climate effects on forests (Aitken et al. 2008, Germain and Lutz 2020, McDowell et al. 2020, Povak and Manley 2024) will interactively mediate future trends in landscape hydrology.

The role of forest disturbances

Historically, frequent wildfire in the dry landscapes of western North America maintained a complex mosaic of forests and nonforests (Churchill et al. 2013, Hessburg et al. 2016, 2019, Hagmann et al. 2021, Povak et al. 2023). Forests were patchy and fractional coverage was low (Hessburg et al. 2005), and this heterogeneity maintained snowpack late into the spring (Dickerson-Lange et al. 2021, Boardman et al. 2025). Forest densification over the past century has had detrimental impacts on snowpack in some forests as denser tree cover intercepts more snow in the canopy (Dickerson-Lange et al. 2021, Sun et al. 2022), increases evapotranspiration (ET), and can hasten spring snowmelt via decreased albedo and re-emitted long-wave radiation (Lundquist et al. 2013).

Wildfire effects on streamflow dynamics vary in both space and time (Goeking and Tarboton 2022, Biederman et al. 2022). Initially, wildfires increase streamflows by reducing ET and vegetation cover (Seibert et al. 2010, Boisramé et al. 2017, Maxwell and St Clair 2019, Saksa et al. 2020), but post-fire vegetation responses (e.g., rapid growth of shrubs) can offset and even reverse these effects within a short time frame (Goeking and Tarboton 2020). Severe fire also changes soil hydrophobicity and infiltration (Ebel and Moody 2013, Loiselle et al. 2020), altering hillslope erosion processes, groundwater recharge, and water quality.

The role of forest treatments

Forest treatments are underway throughout the mountain West to reduce wildfire risk and bolster climate resilience (WA DNR 2024, USDA Forest Service 2022). Thinning has been shown to increase snowpack retention and reduce ET (Sun et al. 2018, Lundquist et al. 2013, Dickerson-Lange et al. 2023), which together can increase streamflows (Jones and Post 2004, Saksa et al. 2017). Thus, forest adaptation treatments (i.e., selective thinning to increase climate and wildfire resilience) may have the potential to increase winter snowpack and late-season low flows (Saksa et al. 2020, Boardman et al. 2025), thereby achieving multiple ecological benefits and mitigating impacts of climate warming on snowpack-dependent species such as Pacific salmon (Flitcroft et al. 2016, Fullerton et al. 2022). Thinning treatments also impact forest soils, but the focus of this study is on the above-ground vegetation dynamics so we did not consider changes in soil properties in our analyses.

Objectives

Here, we combined a large forest landscape succession and disturbance model (LANDIS-II; Scheller et al. 2007) with a process-based distributed hydrology-soil-vegetation model (DHSVM; Wigmosta et al. 1994) to disentangle effects of forest treatments, vegetation regrowth, and fire on mountain snowpack and flow regimes in the Eastern Cascades of Washington. We addressed three research objectives:

1) Evaluate the interactive effects of climate, wildfire, and forest treatments on future snowpack and streamflow.
2) Compare several alternative management strategies (thinning, prescribed fire, and wildland fire use) on landscape hydrology over a 100-yr simulation period.
3) Identify the biophysical characteristics and treatment rates in areas with the greatest potential for treatment improvements to snowpack and streamflow.

Methods

Study area

We conducted our study in the Wenatchee and Entiat sub-basins, a 452,420-ha landscape on the eastern slopes of the Cascade Mountains in central Washington State (Fig. 1) with elevations ranging from 187 m to 2870 m. We used the Hydrologic Unit Codes (HUC) to delineate the study domain, with sub-basins (defined as 8-digit HUCs; Seaber et al. 1987) used to define our study domain and subwatersheds (HUC12-level) used to subdivide the study area into smaller domains for subsequent analyses. The climate is characterized by warm-dry summers, cold-wet winters, and most precipitation falling as snow. Land ownership is primarily public (USDA Forest Service), with 54% of the study area managed as wilderness or roadless areas (hereafter, "wildlands") and 31% as actively managed forests (Table 1, Fig. 1). The remaining area comprises industrial timber lands (all privately owned), urban and rural development, and agricultural lands.

Vegetation in the study area is heterogeneous due to steep elevational gradients, dissected terrain, and complex disturbance histories (Fig. 1; Povak et al. 2022, Furniss et al. 2022). Dry forests exist at lower elevations and south-facing slopes feature shrub-steppe communities alongside open canopy ponderosa pine (*Pinus ponderosa* Dougl. *ex* Laws.) and Douglas-fir (*Pseudotsuga menziesii* Mirb. Franco) forests. These dry forests were historically subject to low- and mixed-severity fires with intervals of 5–25 years (Everett et al. 2000, Hessburg and Agee 2003, Hessburg et al. 2007). Moist forests exist at mid-elevations and on steep north facing slopes, dominated by Douglas-fir, western larch (*Larix occidentalis* Nutt.), western white pine (*Pinus monticola* Douglas *ex* D. Don), and grand fir (*Abies grandis* (Douglas *ex* D. Don) Lindley). The moist forests also experienced mixed-severity burns, with a higher percentage (20–25%) of high-severity and longer fire return intervals of 25–80 years (Hessburg et al. 2005, 2007). Cold forests in upper elevations are dominated by subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.), Engelmann spruce (*Picea engelmannii* Parry *ex* Engelm.), whitebark pine (*Pinus albicaulis* Engelm.), and subalpine larch (*Larix lyallii* Parl.). Cold forests here experienced moderate- and high-severity fires with return intervals of 75–150 years (Povak et al. 2023, 2025, Prichard et al. 2017).

Landscape simulation modeling

We used LANDIS-II with the NECN v6.8 (Scheller et al. 2011), SCRPPLE v3.2 (Scheller et al.

2019), and Biomass Harvest v4.0 (Gustafson et al. 2000) extensions to simulate vegetation dynamics (growth, succession, recruitment, and mortality), wildfire, and climate adaptation treatments (mechanical thinning, Rx fire, and wildland fire use) over a 100-yr simulation period (2020-2120). Wildfire and harvest activities were simulated on a 1-yr timestep, with regeneration in disturbed pixels applied following the disturbance. Forest succession in the absence of disturbance was simulated at a 10-yr timestep. We classified the initial landscape into eight land cover types to delineate zones required for climate inputs and harvesting prescriptions: grassland, shrubland, hardwood, alpine meadow, dry mixed conifer, moist mixed conifer, cold-moist conifer, and cold-dry conifer.

Initial vegetation layers were derived from TreeMap (Riley et al. 2021), a raster-based imputation of forest inventory data (Forest Inventory and Analysis [FIA], circa 2016), projected to the 90-m spatial resolution of our model. We linked the imputed FIA plot codes from TreeMap with the full FIA database to derive attributes not directly available in the TreeMap tree list (tree age, understory composition). Overstory vegetation was represented at the species level, and we grouped understory vegetation into four functional types (nitrogen (N) fixing resprouters, non-N-fixing resprouters, non-N-fixing non-resprouters, and grass/forbs). In LANDIS-II, vegetation in each pixel is given as the amount of biomass per "cohort" (unique species and size class combinations), with an unlimited potential number of cohorts per pixel (e.g., a simple pixel may have 100 g/m^2 of 50-yr old Douglas fir, 150 g/m^2 of 80-yr old ponderosa pine, 50 g/m^2 of N-fixing resprouting shrubs, and 2 g/m^2 of grass/forb).

Evaluating the performance of forest landscape models is challenging because model outputs cannot be distilled into a single metric (e.g., streamflow) that can be compared against empirical data. Consequently, model performance must be evaluated by comparing model performance among multiple metrics that all vary in space and time (biomass trajectories by forest type, area burned, fire sizes, patch size distributions, etc.). In short, we calibrated and validated the LANDIS-II model using empirical data (MTBS and FPA-FOD datasets; Eidenshink et al. 2007, Short et al. 2022) and forest growth estimates from the Forest Vegetation Simulator (FVS; Crookston and Dixon 2005) and found that the LANDIS-II model could reliably simulate forest growth and wildfire dynamics in the study landscape. Full details regarding model development, calibration, and validation were documented in Furniss et al. 2022 and 2023.

Future climate forecasts were generated using the MACAv2-METDATA dataset (Abatzoglou and Brown 2012). Climate for years 2100-2120 were not available in the MACA dataset (it ends in 2099), so we performed a random resampling procedure using years 2080-2099 to extend the dataset through 2120. We used only the RCP8.5 climate scenario to focus on the effects of different management and wildfire scenarios rather than on uncertainty in climate forecasts.

Management scenarios

We employed a partial factorial design of treatment tactics including mechanical thinning ("harvest"), prescribed fire ("Rx"), and wildland fire use ("WFU") to compare tradeoffs and synergies between strategies. We designed management scenarios to reflect real-world objectives for the land ownership and management zones in the study area, and treatment rates were set to approximate current implementation rates (Table 1).

The four management scenarios were: (1) *Wildfire + WFU*, (2) *Wildfire + Rx fire + WFU*, (3) *Wildfire + Harvest*, and (4) *Wildfire + Harvest + WFU*. We also simulated two reference scenarios to compare against treatment scenarios: (1) "*Grow Out*", a simulation of forest growth without any wildfire or treatments, and (2) *Wildfire Only*, which included wildfire and "business-as-usual" suppression practices (calibrated to suppressed wildfire activity from 1984-2019).

We applied different thinning-based mechanical harvest treatments based on the forest type and land ownership objectives within each of four management zones (Table 1; Fig. 1). These treatments applied differential cut rates that were based on the cohorts present within each stand at the point of harvest, allowing treatments to be "customized" to each stand. These treatment methods have been described in greater detail by Furniss et al. (2023, 2024). Briefly, dry forests had thinning from below (~90% reduction in surface and ladder fuels) to achieve fuel reduction objectives in large treatment patches (20-100 ha in size); moist forests had variable retention patch cuts (1-3 ha gap size) to increase heterogeneity (~75% mean reduction in density for trees <120 years old, no removal of older trees); industrial timber lands had clearcutting to maximize economic returns (100% harvest); and in wildlands, we did not apply any mechanical treatments.

Simulated harvest treatments occurred at the patch-level (5-20 ha), where patches were randomly selected and evaluated for harvest eligibility. Patches were developed using an unsupervised aggregation algorithm that identified spatially contiguous polygons sharing similar ownership, topographic setting, and potential vegetation. Treatments started in one patch and would spread to additional patches until the target harvest area was reached. Patches could be treated multiple times during the 100-yr simulation, with a minimum re-treatment interval set to prevent patches from being re-treated continuously without allowing for realistic regrowth between treatment cycles (10 years for dry forests, 30 years for moist forests).

We simulated wildland fire use (WFU) management practices by adjusting the level of suppression applied compared to the baseline *Wildfire Only* scenario. For the WFU scenarios, we applied less suppression effort to natural ignitions during mild and moderate weather conditions in wildlands. In contrast, more suppression effort was applied in urban/rural areas and in the wildland urban interface. For the Rx fire scenarios, Rx fire was applied to approximately 5,000 ha/year in all USFS lands, including wildlands and actively managed forests. Additional details and specific model parameters may be found in Furniss et al. 2023 and 2024.

Hydrology modeling

We modeled treatment effects on flow regimes by translating annual LANDIS-II outputs into input layers for the DHSVM (Wigmosta et al. 1994, Furniss et al. 2023, Povak et al. 2022). This resulted in dynamic vegetation surfaces that were updated annually throughout the 100-yr simulation period for four key vegetation parameters: leaf area index-LAI, canopy height (HT), fractional cover (FC), and forest type. For DHSVM inputs that were not available directly from LANDIS-II (HT and FC), we used Forest Inventory and Analysis (FIA) data to fit generalized linear mixed effects models that estimated plot-level HT and FC. The HT model used ln(age) and ln(biomass) to predict individual tree height with species and forest type as fixed effects, and we calculated plot-level canopy height as the 90th percentile of tree heights. The FC model used a third-order polynomial of stand biomass, stand age, and elevation to predict fractional coverage, with forest type as a fixed effect. We fit these models using the lme4 package in R (Bates et al 2015, R Core Team 2023).

The DHSVM model was calibrated using historical climate data from the 1/16° Livneh dataset (2015) in conjunction with empirical observations of snow water equivalent (SWE) from a nearby SNOTEL station (Trinity Snow Telemetry site) and streamflow records for the Wenatchee and Entiat sub-basins (USGS gauges 12456500, 1245800) for water years 1997-2003 and 1966-1971, respectively. We chose these water years to isolate periods of streamflow that were minimally impacted by water management (dam releases), upstream water withdrawals (diversions for agriculture), and winter icing conditions. Model performance was evaluated using Nash Sutcliffe Efficiency (NSE) and Kling-Gupta Efficeinty (KGE) metrics, resulting in NSE =

0.758 and KGE = 0.786 for the Entiat watershed and NSE = 0.796 and KGE= 0.873 for the Wenatchee watershed. DHSVM was calibrated using current vegetation as high-resolution maps of historical vegetation for the calibration period do not exist.

Future climate forecasts were derived from the MACAv2-LIVNEH climate dataset (Abatzoglou and Brown 2012). Future landscape hydrology was summarized using peak SWE amount, peak SWE date, monthly flow, total annual flow, and spring melt-out date (first snow-free day in the spring). Snow-based variables were generated as 90-m raster maps and flow variables were summarized at the HUC12 level. The raster-based hydrologic outputs were generated at an annual resolution and streamflow by HUC12 was output monthly.

Treatment efficacy

We assessed positive treatment effects on streamflow by comparing hydrology outputs between the *Wildfire Only* scenario and the four alternative future management scenarios. We integrated these metrics into an overall "treatment efficacy" value by calculating landscape-scale mean based on area-weighted values for each patch, then calculating the difference in landscape-level mean between scenarios. Positive treatment efficacy indicated that a treatment scenario resulted in better-than-expected results across hydrological metrics compared to the *Wildfire Only* scenario.

Results

There was considerable interannual variability in future landscape hydrology, but important trends emerged over the 100-yr simulation period (Fig. 2). Across all scenarios, peak snow water equivalent (SWE) decreased from 2020-2120, with most of that decline occurring during the first half of the simulation (Fig. 2). Mean annual flows declined until ~2060 then increased from

2060-2120, despite a relatively steady trend in precipitation (Fig. S1). Peak SWE date did not show a sustained shift in either direction, while average spring melt-out date shifted earlier by ~3 weeks from early-June to mid-May (Fig. 2).

Differences between the *Grow Out* scenario (no wildfire or treatment) and the *Wildfire Only* scenario highlighted the effects of wildfire on flow regime. In the absence of wildfire, peak SWE continued to decline throughout the latter half of the century, while scenarios involving wildfire had relatively stable levels of peak SWE from 2080-2120. The *Grow Out* scenario also had lower streamflows compared to *Wildfire Only*, and that difference increased over the course of the simulation (Fig. 2).

There was enormous interannual variability in all hydrology metrics (Fig. S4). Interannual fluctuations in SWE and flows were much greater in magnitude than both the differences between scenarios and the long-term trend (Fig. 2). Variability in peak SWE date and spring melt-out increased over the simulation period, while variability in peak SWE amount and mean annual flows remained relatively constant (Fig. S4). This variability was reduced, but not eliminated, when looking at 10-yr rolling means (Fig. 2).

Treatment efficacy

Examining treatment effects further revealed differences among management scenarios. Scenarios involving mechanical harvest produced the greatest SWE and mean annual flow for the first half of the simulation period. After an uptick in fire activity around 2060 (Fig. S2), however, this trend shifted and the two scenarios with the greatest high-severity area burned (*Wildfire Only* and *Wildfire + Harvest*) had the highest SWE and streamflows (Fig.3). Despite the gradual increase in wildfire activity that we observed among all scenarios, the shifting scenario ranking in response to feedbacks in wildfire activity (Furniss et al. 2024, Povak et al.

2023) emphasizes the dominant role of wildfire on hydrologic functioning in this landscape.

At the HUC12-scale, total area treated was positively related to increases in mean annual flows, although the relationship was weak ($R^2 = 0.07$; Fig. 4). Treating any amount was often enough to increase flows, but treating at least 50% of the total area was required to reliably increase flows in some watersheds. This treatment ratio is obviously sensitive to the intensity of treatments in our simulations, and further work will be required to examine how treatment area and intensity may interact to modify the treatment area required to have a tangible impact on landscape hydrology. Proportion area burned was the strongest predictor of increased flows ($R^2 = 0.32$), while total area burned was also weakly related. Although we did not directly consider fire severity in this analysis, area burned was positively correlated with proportion of high-severity (Fig. S2) so it is likely that the subwatersheds with the greatest area burned also burned with at higher severities. Mean burned per HUC12 was nearly twice the area affected by harvest treatments (mean area treated per HUC12 = 2,200 ha, mean area burned per HUC12 = 5,800 ha; Fig. 4), causing wildfire to be the primary driver of flows at the landscape scale given the treatment area and intensity applied in our simulations. Neither elevation nor HUC12 size were related to treatment effects on streamflow (Fig. 4, bottom row).

Overall treatment efficacy was highest in dry and moist mixed-conifer vegetation types (Fig. 5), which had the greatest total area and proportion area treated. Treatment efficacy was also high in hardwood forests despite having low total and proportion area treated, possibly because these forests are primarily occupying riparian habitat and may therefore have a disproportionate impact on hydrology. Grouping by land ownership type revealed that treatment efficacy was highest for industrial forests, followed by actively managed federal lands (Fig. 6). These stand-scale effects did have significant impact on landscape-scale results since private lands covered only 4% of the landscape (Table 1; Fig. 6). Although treatment efficacy was lower in actively managed federal forests, they covered a much larger area (31%) and therefore contributed more to the landscape-level results.

Changes in Seasonal Flow

Monthly hydrographs revealed how changes in temperature and snowpack dynamics caused changes in the timing of snowmelt and streamflow throughout the year. We observed a significant decline in late-season (August – September) streamflows over the course of the simulation the entire study area, and a shift from snowmelt- to rain-dominated flow regimes in low- and middle-elevation watersheds (Fig. 7). Peak flows in upper-elevation watersheds (greater than ~1,200 m) continued to be driven by spring snowmelt, but increasing temperatures and rain-on-snow events led to the emergence of a secondary peak in the fall and lower late-season flows.

This shift in streamflow regimes was a gradual transition rather than a distinct tipping point. Thus, we found it useful to examine results by grouping decades relative to the timing of this transition from a snow- to rain-dominated streamflow regime. This revealed two distinct regimes: the early-mid-21st century, where the hydrograph was dominated by spring snowmelt among all watersheds, and the early-22nd century where peak flows in low- and mid-elevation watersheds were driven by fall rains. The late-21st century was a period of transition, where fall flows increased steadily among all watersheds and eventually overtook the spring peak at lower elevations. Below, we further examine projected trends in the seasonal hydrographs during each of these three periods.

- **Early-mid 21st century (2020-2060)**: The seasonal hydrograph under present-day climate conditions were characterized by a large, snowmelt-dominated peak in the spring through early summer (June-July) that was evident across all watersheds in the sub-basins (Fig. 7). "*Harvest*" scenarios had subtle, yet still detectable, effects on these trends, with mechanical treatments conferring a slight increase in spring flows (Fig. 8), especially in actively managed watersheds (see Fig. S5).

- **Late 21st century (2060-2100)**: This was a period of transition, with peak flows in low- and mid-elevation watersheds shifting from spring to fall by the latter decades of the century (red and orange lines in Fig. 7). Fall flows increased in high-elevation watersheds, but not enough to surpass the snowmelt-driven peak in the spring. There was a growing divergence between the *Grow Out* scenario and *Wildfire Only*, while the differences between treatment scenarios remained subtle (Fig. 8) as the relative impacts of wildfire began to overshadow the effects of mechanical treatments (Fig. 3).
- **Early 22nd century (2100-2120)**: The shift from spring snowmelt- to fall rain-dominated streamflow regimes in warmer watersheds was solidified during this period as the fall peak grew and the spring peak diminished. High elevations remained dominated by a snowmelt-driven peak in the spring, although the fall flows developed into a prominent second peak (Fig. 7). Positive treatment effects were dwarfed by wildfire influences, despite continuous application of mechanical treatments throughout the simulation.

Discussion

Ongoing climate changes are causing widespread declines in snowpack across the western US (Mote et al. 2018). Our modeling demonstrates how these changes impact snow retention and streamflows at the landscape scale, and how future wildfire and management scenarios can mediate top-down climate impacts. We found that in this mountainous, snow-dominated study region, projected climate trends will result in more winter precipitation falling as rain, earlier snowmelt dates, and an overall reduction in peak SWE and late-season streamflows. Mechanical treatments increased snowpack retention (Fig. 2) and maintained higher spring flows (Figs. 8, S5), but these effects were small compared with the impact of wildfire (Fig. 3). The beneficial impact of wildfires and thinning on flows grew over time (Figs. 2, 8), but simulated management actions could not offset the effects of warming on the shifting seasonality of flows (Fig. 7). Climatic influences drove a shift from snow- to rain-dominated flow regimes, especially for low- and mid-elevation watersheds, demonstrating the overriding effects of climate warming on forest landscape hydrology.

The role of wildfire

Despite relatively stable levels of annual precipitation over the coming century (Fig. S1), forest regrowth and wildfire dynamics shaped trends in mean annual flows over the course of the simulation (Fig. S3). Mean annual flows tracked trends in forest biomass, with a decline during the first half of the simulation period as forest biomass accumulated (Figs. 2, S3) followed by an increase during the latter half of the simulation as wildfire activity accelerated (Fig. S2) and forest biomass began to decline (Fig. S3). The finding that mean annual flows remained relatively stable under the baseline *Grow Out* scenario underscores the importance of vegetation and disturbance regimges on streamflow dynamics.

Evidence for the dominance of wildfire as a driver of future landscape hydrology was evident in other results as well. The differences between the *Wildfire Only* and *Grow Out* scenarios were ultimately far greater than differences between active management scenarios (all of which contained wildfire), and the proportion area burned was the strongest predictor of improvements to hydrology metrics ($R^2 = 0.32$; Fig. 4). Together, these results underscore the importance of wildfire as a keystone process in fire-adapted, wildland-dominated landscapes of the western US.

While the scenarios with the greatest area burned (*Wildfire Only* and *Wildfire + Harvest*) had the greatest improvements to hydrology metrics, these benefits were achieved at the expense of other important ecosystem services (e.g., carbon storage), reflecting the inevitability of tradeoffs in managing for diverse ecosystem services. Recent papers by Furniss et al. (2023, 2024) and Povak et al. (2022, 2024) explore these tradeoffs in greater detail.

These results provide evidence for the strategic use of wildfire to partially compensate for climate change impacts on snowpack and streamflow (North et al. 2015, 2021, 2024, Calkin et al. 2015, Stephens et al. 2016). A key finding was that hydrology metrics responded positively to area burned, regardless of whether that area burned was achieved through Rx fire, WFU, or wildfire. Wildfire will continue to affect far more area than is treatable with mechanical methods alone (Churchill et al. 2022, Larson et al. 2022, WA DNR 2022), and wildfire is the dominant driver of vegetation dynamics and climate adaptation in forests of the Interior West (North et al. 2012, Hessburg et al. 2021, 2022, Stephens et al. 2021, Furniss et al. 2024). Restoring naturally diverse patch size distributions using mixed- and high-severity fire in subalpine and moist-mixed conifer forests may be an appropriate target for WFU practices (Hessburg et al. 2007, 2016, 2021), and our results demonstrate the potential for such practices to improve snowpack retention and late-season streamflows as well.

Mechanical treatments and wildfire management decisions

Our results suggest that treatments can have beneficial impacts on mountain hydrology if they are used to increase—rather than decrease—area burned (Reinhard et al. 2008, North et al. 2012, Young et al. 2019, Thompson et al. 2022). The key to achieving benefits is that fuel reduction and climate-adaptation treatments are strategically applied to facilitate *more* wildfire, enabling managers to let more fires burn while protecting human communities and vulnerable ecosystems.

Reducing the existing wildfire deficit (Parks et al. 2025) is a key part of climate and wildfire adaptation strategies (Schoennagel et al. 2017, North et al. 2015), and intentionally preparing landscapes for fire using landscape restoration principles (Hessburg et al., 2015, Stephens et al., 2021) can result in more desirable wildfire effects (Taylor et al. 2022, Chamberlain et al. 2024, Shive et al. 2024). If treatments are instead used to increase suppression efficacy and reduce overall acres burned, our results indicate there would be negative consequences for snowpack retention and streamflows.

Limitations and generalizability

The spatial resolution of our model (90-m cells) did not allow us to account for fine- to meso-scale (<1 ha) variability in canopy gap patterning (*sensu* Larson and Churchill 2012, Churchill et al. 2013, Chamberlain et al. 2023), or to simulate restorative treatments in riparian areas such as floodplain restoration and beaver introduction (*sensu* Justice et al. 2017, Fullerton et al. 2022). Fine-scale heterogeneity and riparian restoration have been shown to mediate snowpack dynamics (Lundquist et al. 2013, Sun et al. 2018, Dickerson-Lange et al. 2023, Justice et al. 2017), and it is therefore possible that we underestimated treatment effects due to our modeling resolution. This limitation reflects the fundamental tradeoff between resolution and scale that exists in any spatial simulation model.

Another limitation is that we did not consider wildfire effects on soil infiltration rates in DHSVM. Wildfire and thinning treatments do impact soil carbon values in LANDIS-II, but we did not use these values to update the DHSVM soil layers. The purpose of this study was to focus on above-ground vegetation dynamics, so we kept our model integration limited to changes in vegetation cover and height.

The results of this study are most relevant in fire-adapted forest landscapes with cold winters and large snowpacks. The importance of snowpack retention is obviously much lower in landscapes without a persistent snowpack, and we would therefore expect treatments and wildfire to have less of an impact on snowpack and streamflow dynamics in rain-dominated landscapes. We also recognize that wildfire is not always an appropriate management tool, and restoring natural wildfire regimes may be an unrealistic goal due to patterns of dispersed human development and rapidly shifting climatic conditions.

Downstream implications

Forest ecosystems and aquatic species throughout the western United States are dependent on mountain snowpacks to provide snowmelt late into the summer when precipitation is low and temperatures are high. Human communities and water resource managers are similarly dependent on the winter snowpack to serve as a natural reservoir with storage capacity that can greatly exceed the volume of water stored in artificial reservoirs. Foundational changes in the timing of streamflow, such as those we observed in this study, are likely to have profound consequences for ecosystems and human communities that are adapted and accustomed to snowmelt-derived flow regimes. These changes will increase summer water deficit in forest ecosystems, reshaping forest elevational zones and negatively impacting fish and wildlife species that rely on snowmelt and late-season streamflows. This offers a dire warning for Pacific salmon and coldwater trout species, as snowmelt is of acute importance for maintaining cool stream temperatures and providing spawning habitat (Mote et al. 2003, Battin et al. 2007, Naik and Jay 2011, Wenger et al. 2011, Falke et al. 2015). The effects of altered streamflow regimes on interconnected ecosystems is an important topic for future research as these changes will have major downstream consequences for ecosystem health and resilience (Bisson et al. 2003).

Conclusions

Projected warmer winter temperatures will increase the proportion of precipitation falling as rain, greatly reducing spring snowpacks and late-season flows. Elevated future wildfire activity may offset some of these climate impacts, but neither wildfire nor mechanical treatments is likely to forestall a transition from snow- to rain-dominated streamflow regimes in low- and mid-elevations in the eastern Cascades by the end of the 21st century. The benefits of thinning in our study were relatively small compared to the overwhelming effects of wildfire, underscoring the importance of wildfire as a primary driver of landscape and watershed dynamics. Our results provide support for more widespread use of wildfire in landscape management, and suggest that landscape-scale adaptation treatments involving the restoration of natural wildfire regimes may reduce or delay some of the most deleterious effects of warming on future snowpack and streamflows.

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TABLES

TABLE 1. Management zones and target treatment rates. The wildlands zone was defined as wilderness and roadless areas that are managed with minimal human intervention and therefore did not receive any mechanical treatments. Industrial managed forests were located on private lands and represented the most intensive management category. Thinning prescriptions on public lands were applied differently based on real-world management objectives in dry versus moist forests.

	Area		Area treated/ year	
Management zone	**Ha**	**% of total**	**Ha**	**% of mgt zone**
Wildlands	243,556	54%	0	0%
Industrial forests	19,866	4%	667	3%
Dry managed forests	83,491	18%	3,361	4%
Moist managed forests	59,269	13%	524	1%
Other (urban/rural, water, rock)	44,788	10%	0	0%
Total	450,970	100%	4,552	1%

FIGURES

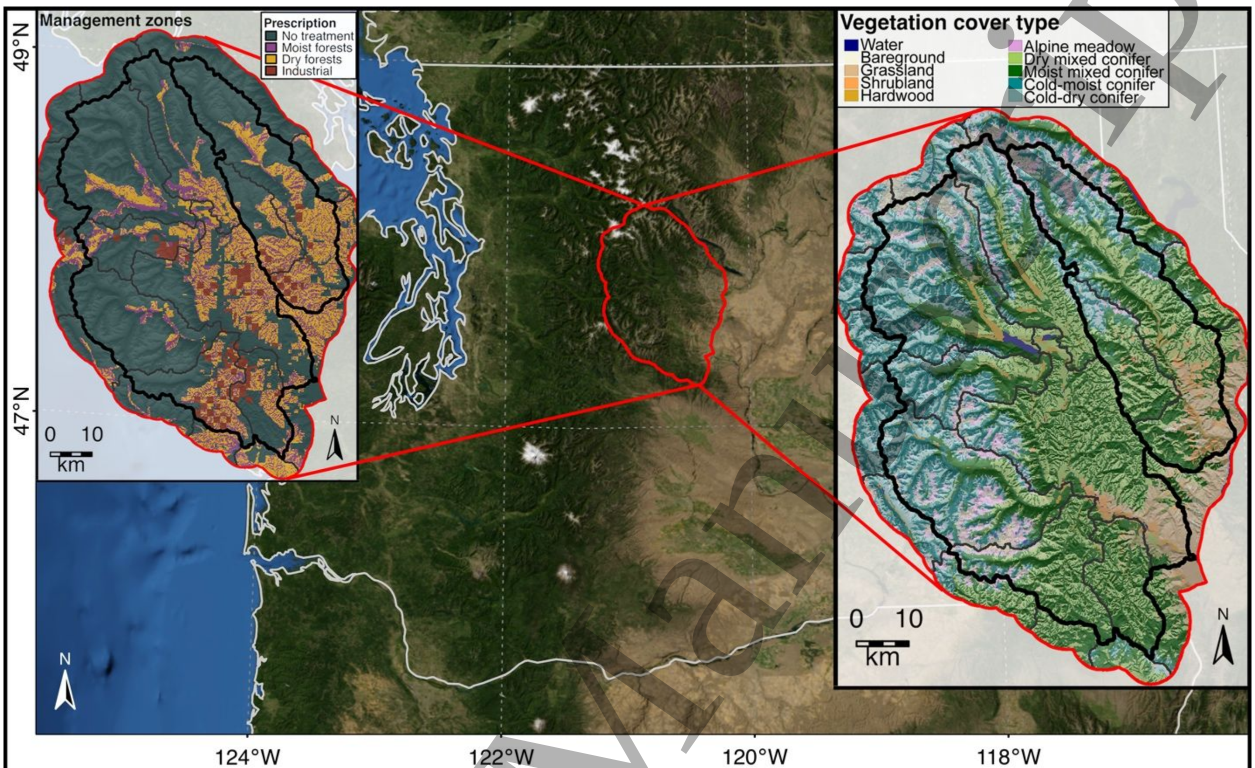

FIGURE 1. Vicinity map and study area of the Wenatchee and Entiat River subbasins in central Washington State. The study landscape is wildlands (54%), with the remainder comprising a mix of actively managed forests, industrial timber lands, and urban/rural development (left). Vegetation in the study domain is heterogeneous, spanning from grass and shrub-dominated vegetation types in the lowlands to subalpine forests and alpine vegetation at the upper elevations (right). The thick black lines in the nested panels denote the boundaries of the Wenatchee and Entiat sub-basins (HUC8-level), while the thin grey lines indicate HUC10-level watersheds. The red perimeter represents a 5-km buffer that was included in the simulations to account for edge effects.

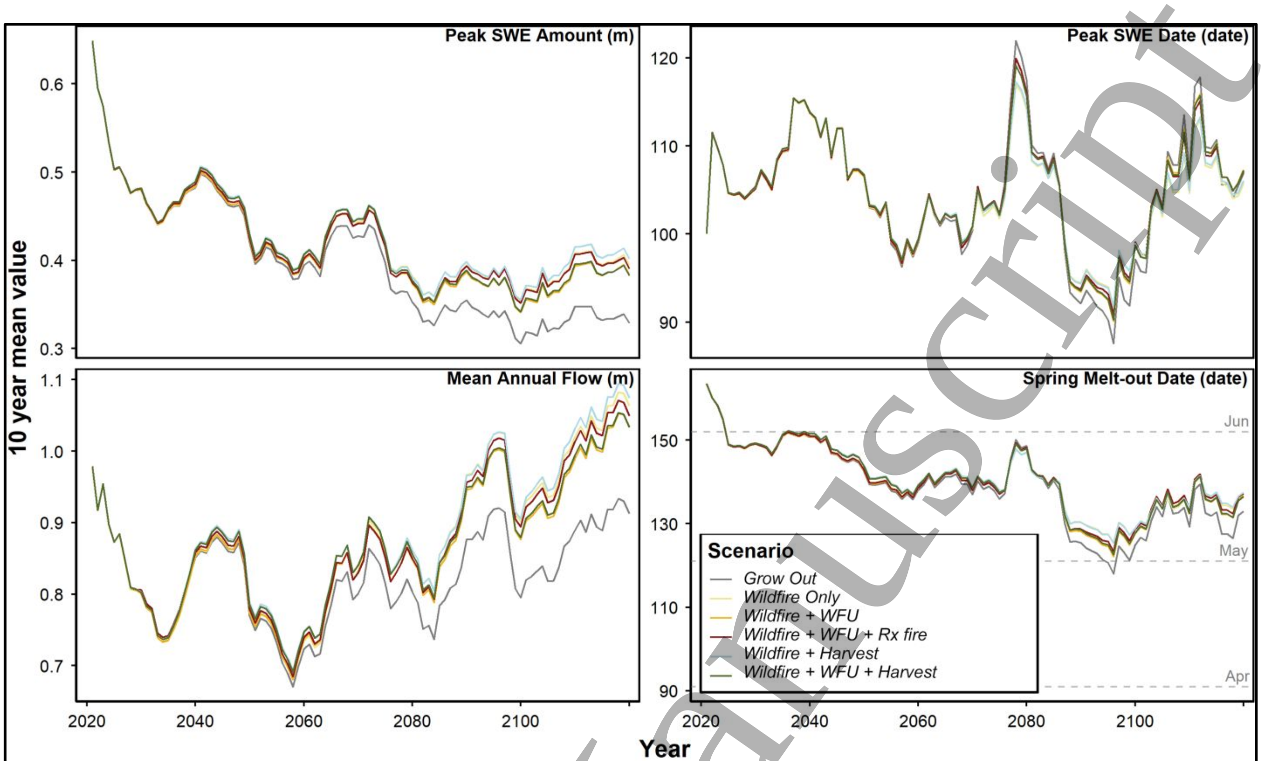

FIGURE 2. Simulated future stream flow and snowpack dynamics (10 year rolling mean) under an RCP 8.5 emissions scenario for the Wenatchee and Entiat subbasins. Values represent landscape-level averages across the study domain. Units for peak SWE and mean annual flow are in meters, units for the right two panels are day of year. The RCP8.5 scenario without treatments (grey line) represents a no fire "grow-out" scenario; one with neither treatment nor wildfire. Unsmoothed trend lines may be found in Fig. S6. Lines represent simulated hydrologic dynamics under different management scenarios. Differences between scenarios were much smaller than interannual fluctuations due to inter- and intra-annual climatic variability. Over the 100-yr simulation period, there was an overall decline in peak snow water equivalent (SWE), a two-week shift towards earlier melt-out date, and an increase in mean annual flows.

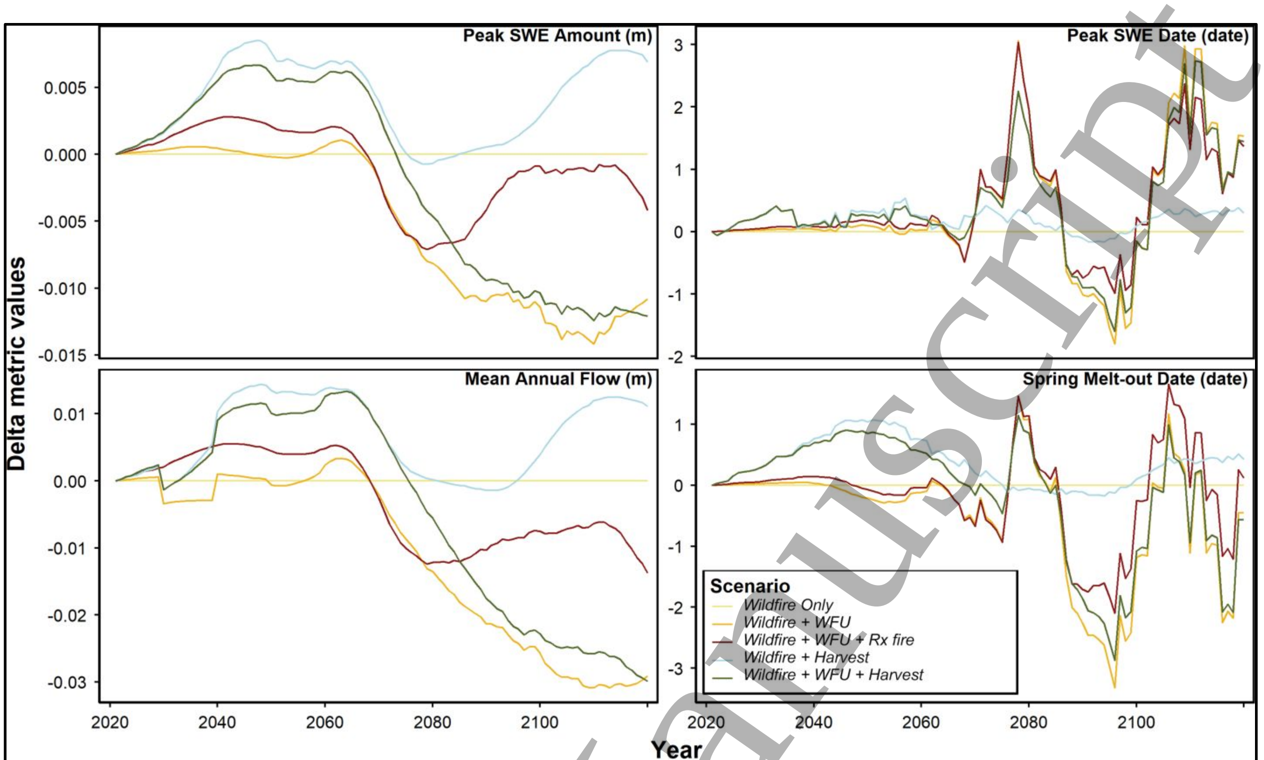

FIGURE 3. Differences in hydrology metrics between scenarios, where the *Wildfire Only* (i.e., the RCP 8.5 no treatment) scenario was held constant (horizontal line at 0). Each panel corresponds to the same metrics reported in Fig. 2, but values are differenced with the *Wildfire Only* scenario. Values above zero indicate better performance than no treatment, while values less than zero indicate poorer performance relative to the *Wildfire Only* scenario. All scenarios involving mechanical treatment or Rx fire performed better than the *Wildfire Only* scenario for the first half of the simulation, but relative rankings changed after 2060 as area burned under *Wildfire Only* increased sharply, leading to greater peak SWE and mean flows in the *Wildfire Only* scenario. By the end of the simulation, the two scenarios with the greatest area burned, *Wildfire Only* and *Wildfire + Harvest*, had the best outcomes across hydrology metrics.

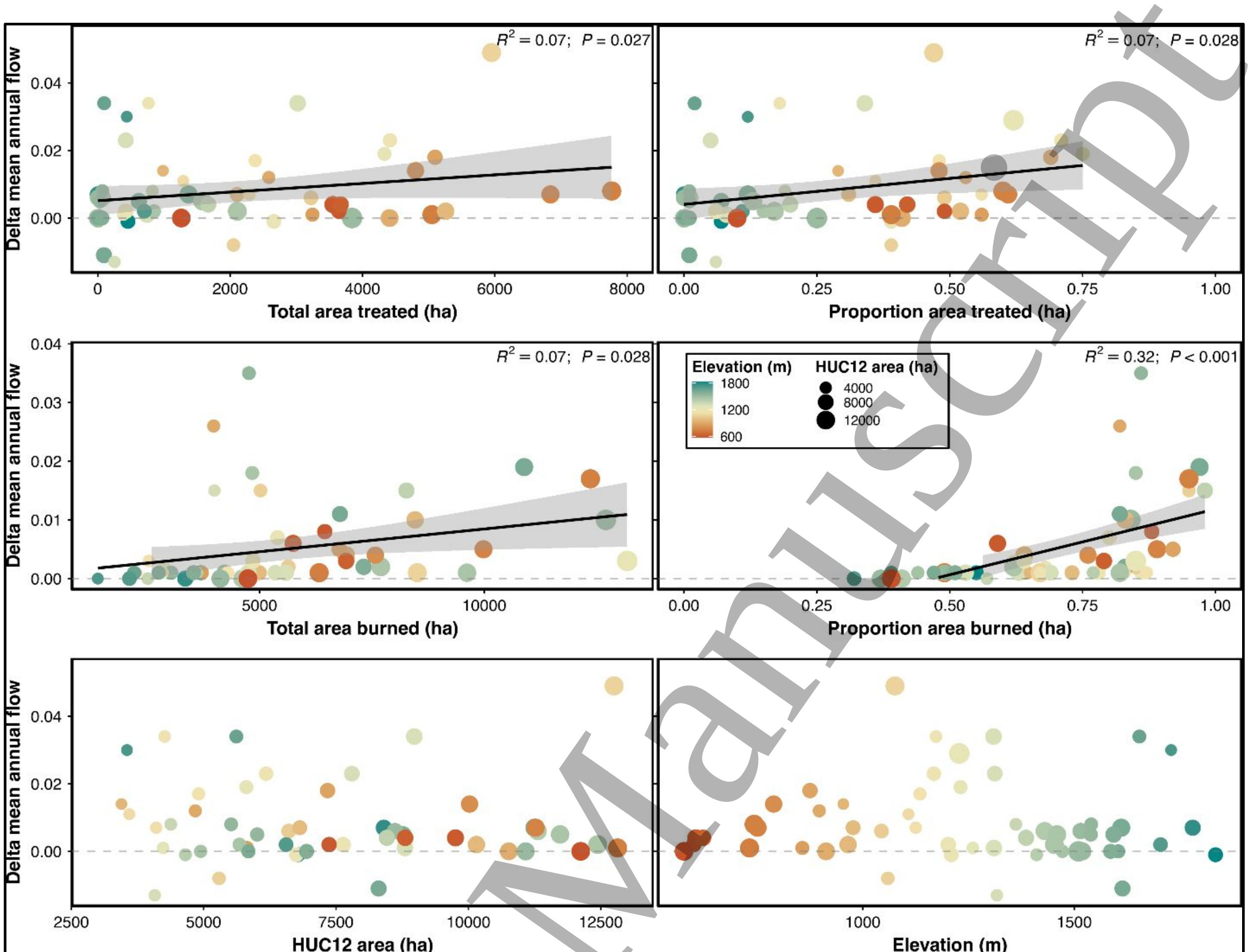

FIGURE 4. Efficacy of harvest treatments (top row) and wildfire (middle row) in terms of mean annual stream flow (m/unit area/year) for all HUC12 subwatersheds. Harvest-induced changes in flow are also shown as a function of watershed area and elevation belt (bottom row). Mean flows represent differences in flow between scenarios at the simulation midpoint (year 2070). Delta flow values for the harvest treatments (top row) represent differences between *Wildfire Only* and *Wildfire + Harvest* scenarios, while delta values for area burned represent differences between the *Grow Out* and *Wildfire Only* scenarios. Solid black lines indicate significant relationships, gray shading represents the 95% confidence interval.

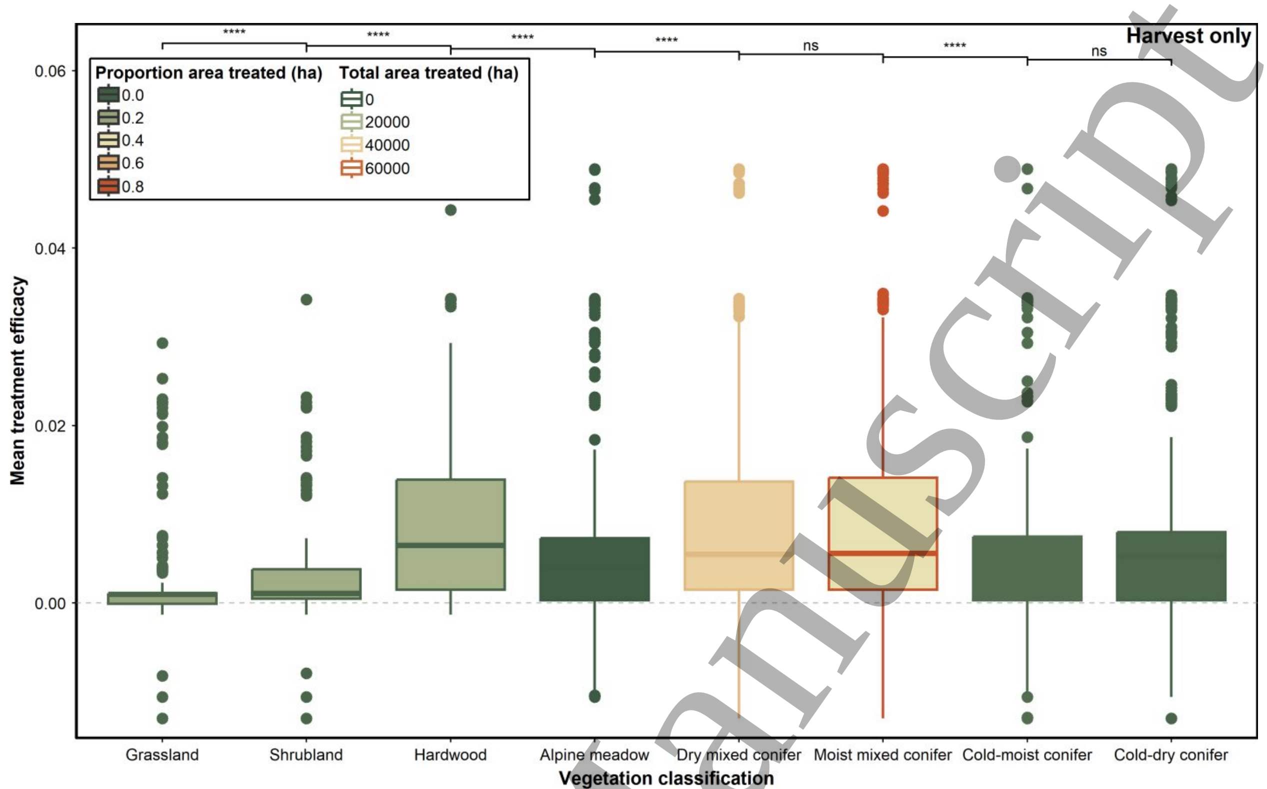

FIGURE 5. Efficacy of harvest treatments by vegetation type. Treatment efficacy represents the potential for mechanical treatments to increase snowpack retention and water yields, calculated as the difference between the *Wildfire Only* scenario and the *Wildfire + Harvest* scenario, averaged among all hydrology metrics. As scenario differences also include indirect effects of altered wildfire regimes, treatment efficacy can be non-zero even when treated area was negligible. Asterisks indicate degree of significant difference between the bars (****: $p \leq 0.001$; ns: not significant). Fill colors represent proportion area treated (area treated / total area per vegetation class), while border represents total area treated within each vegetation class. Warmer colors indicating high proportion (or total area) and greens indicating low proportion (or total area). Treatment efficacy was highest in dry and moist mixed conifer vegetation types, both of which had both high proportion area treated and high total area treated.

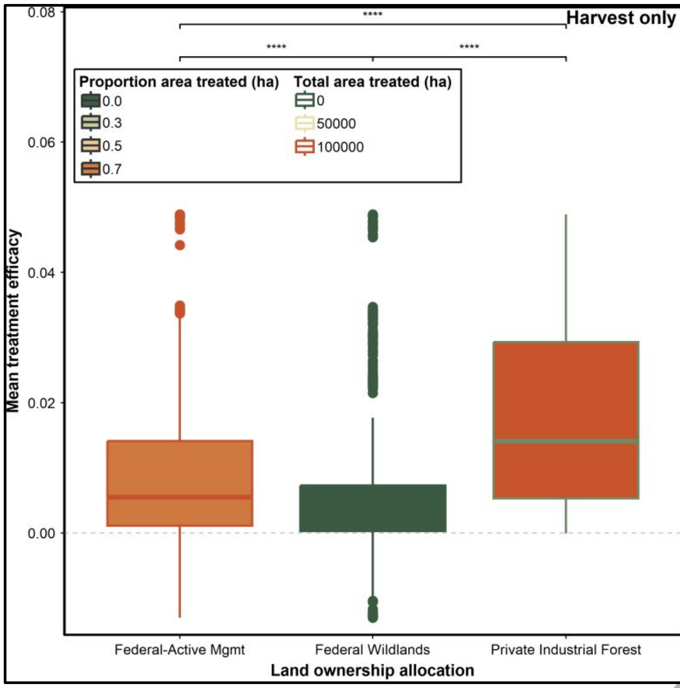

FIGURE 6. Treatment efficacy by land ownership. Treatment efficacy represents the potential for restorative forest treatments to increase snowpack retention and water yields, calculated as the difference between the *Wildfire Only* scenario and the *Wildfire + Harvest* scenario. As scenario differences also include indirect effects of altered wildfire regimes, treatment efficacy can be non-zero even when treated area was negligible. Asterisks indicate degree of significant difference between the bars (****: $p \leq 0.001$; ns: not significant). Fill colors represent proportion area treated (area treated / total area per vegetation class), while border represents total area treated within each vegetation class. Warmer colors indicating high proportion (or total area) and greens indicating low proportion (or total area). Industrial forests (right) had a high proportion area treated despite low total area, while actively managed federal lands (left) had a high proportion area treated and large total area.

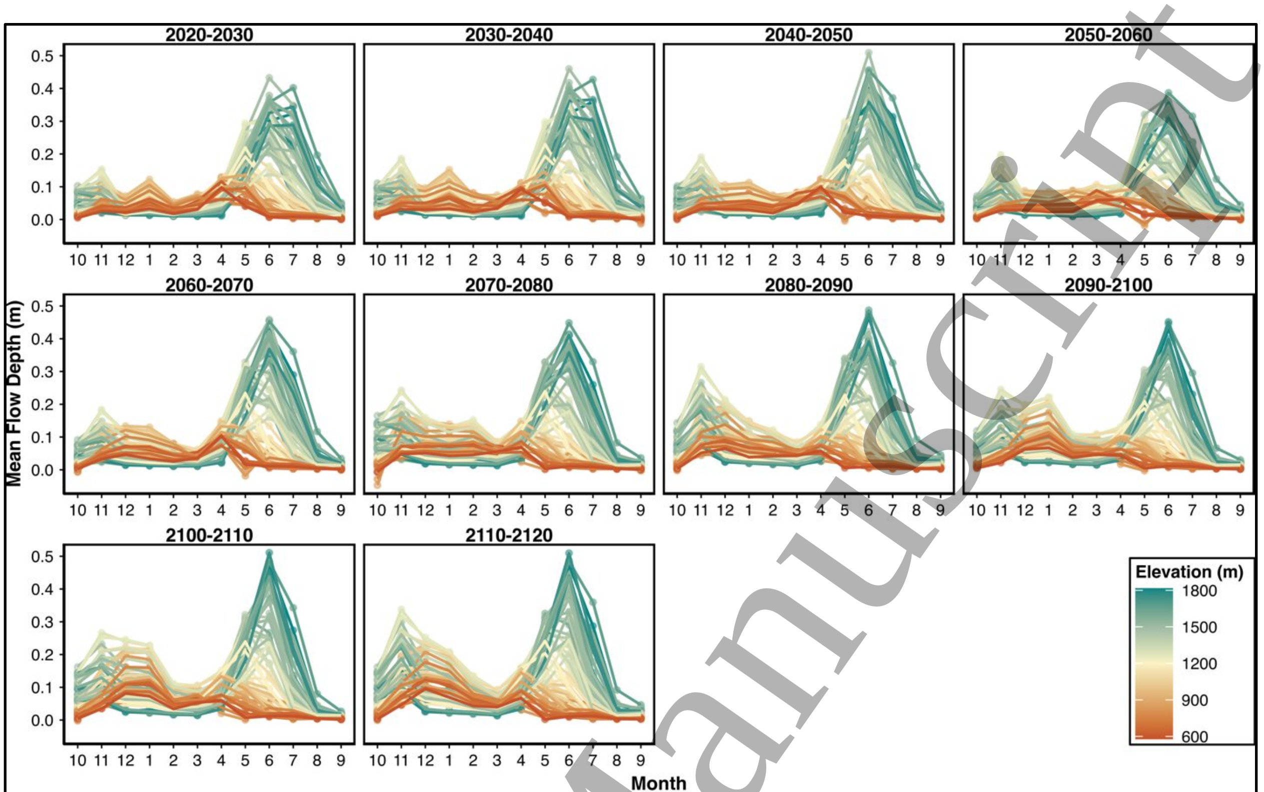

FIGURE 7. Seasonal hydrographs showing monthly mean flows by decade under the climate change RCP8.5 emissions scenario and *Wildfire Only* management scenario. Lines represent flows in each of the 91 subwatersheds (HUC12-level) in the study domain, colored by mean watershed elevation. Currently (2020-2030), peak flows occur in the spring for all subwatersheds, indicating a snow-dominated hydrologic regime. By the end of the simulation period, however, peak flows in low elevation watersheds (less than approximately ~1,200 m elevation) occur in the fall, indicating a transition to rain-dominated flow regimes.

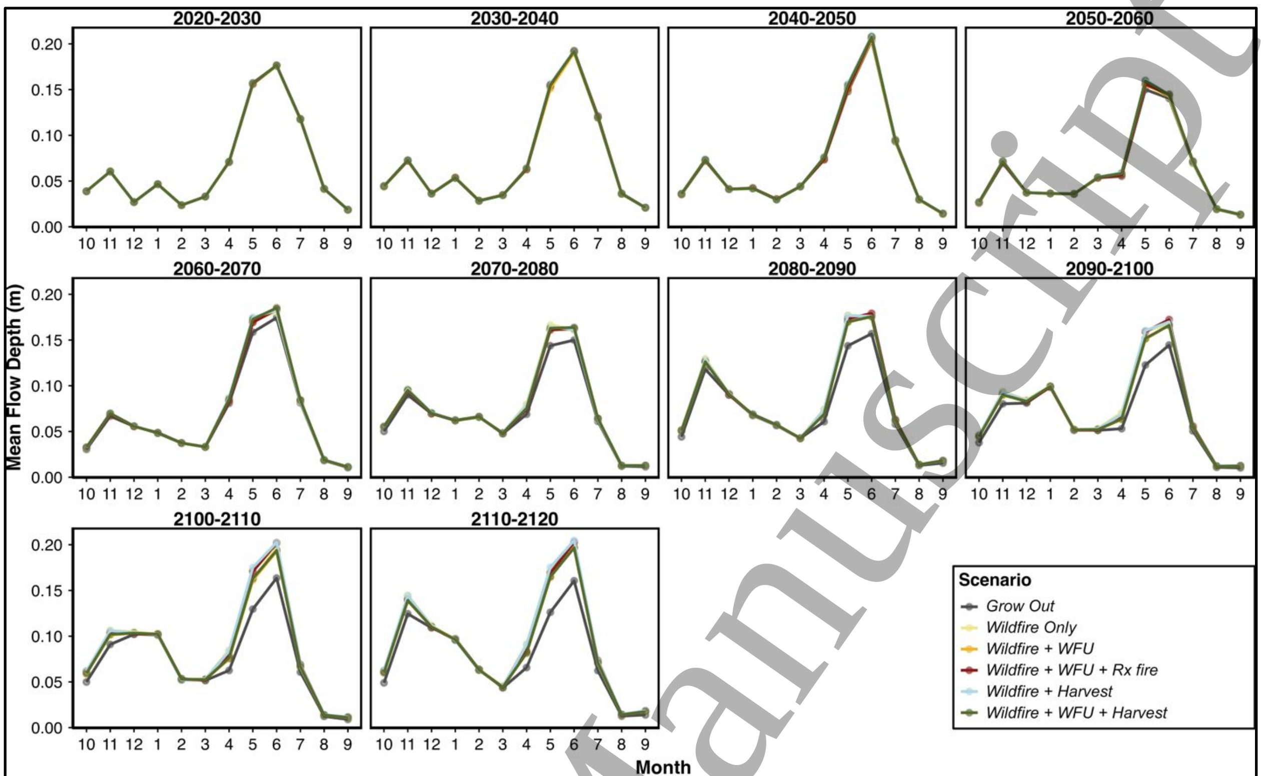

FIGURE 8. Seasonal hydrographs showing monthly mean flows by decade under the RCP8.5 climate scenario for all management scenarios. Flows represent average flow per HUC12 for all subwatersheds within the Wenatchee and Entiat subbasins. Differences between HUCs are displayed in Figure 7. Scenario differences were minimal, but differences between all scenarios that included wildfire and the no disturbance scenario (labelled "Grow Out") were pronounced.