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Simulated Future Shifts in Wildfire Regimes in Moist Forests of Pacific Northwest, USA

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Key Points:

- Climate change may drive shifts to fire regimes with more frequent and larger fires in the moist temperate forests of the Pacific Northwest
- Describing uncertainties of how, when, and where climate change may alter fire regimes helps bracket expectations for the future
- The largest increases to burn probability, fire size, and number of fires are projected to occur in the cooler, wetter parts of the region

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Fire is an integral natural disturbance in the moist temperate forests of the Pacific Northwest of the United States, but future changes remain uncertain. Fire regimes in this climatically and biophysically diverse region are complex, but typically climate limited. One challenge for interpreting potential changes is conveying projection uncertainty. Using projections of Energy Release Component (ERC) derived from 12 global climate models (GCM) that vary in performance relative to the region's contemporary climate, we simulated thousands of plausible fire seasons with the stochastic spatial fire spread model FSim for mid-21st century (2035–2064) under RCP8.5 emissions scenario for five northwestern pyromes. The magnitude of projected changes to burn probability, fire size, and number of fires varied among pyromes and GCMs. We projected the largest increases in burn probability and fire size in the cooler and wetter northern parts of the region (North Cascades, Olympics & Puget Lowlands) and Oregon West Cascades, with more moderate changes projected for the Washington West Cascades and Oregon Coast Range. We provide new insights into changing fire regimes characterized by the possibility of shifts toward more frequent and large fires (especially >40,000 ha), as well as shifts in seasonality, including more fires burning at the beginning of fall when extreme synoptic weather events have the potential to increase fire spread. Our work highlights the potential geographic variability in climate change effects in some of the most productive moist temperate forests of the world and points to a rapid acceleration of fire in the coming decades.

Plain Language Summary The moist temperate forests of the Pacific Northwest are among the world's most productive. Fire has always existed in these ecosystems, but throughout much of recorded history has occurred infrequently [80–800 years] relative to a human timescale. Future climate change will likely introduce more frequent warm and dry weather, which increases opportunities for fire ignition and spread. However, not all climate models project the same magnitude of changes, so there is uncertainty on when and where fire regimes will be impacted. Using a fire spread model, we investigate how several different plausible projections of mid-21st century climate could alter fire regimes for the moist temperate forests of the Pacific Northwest and bracket the range of possible fire regime shifts that could be expected in the region. The largest increases to burn probability and fire size are likely to occur in the cooler, wetter northern forests (the Olympic Peninsula and Washington North Cascades) and the Oregon West Cascades, with more moderate changes for the Oregon Coast Range and Washington West Cascades. Overall, our work highlights the potential geographic variability of climate change effects in the region and points to a rapid acceleration of fire in the coming decades.

1. Introduction

Fire regimes are shifting due to climate change in many temperate forest regions of the world (Abram et al., 2021; Higuera & Abatzoglou, 2021; McWethy et al., 2021; Parisien et al., 2023). Larger, more frequent fires are having important social and ecological consequences affecting human communities and biodiversity (Schoennagel et al., 2017). Climate is an important driver of fire regimes (Agee, 1993; Power et al., 2008), thus increases in temperature and growing season moisture deficits in temperate forests are expected to contribute to altered wildfire activity (Clark et al., 2021; Gao et al., 2021; Krawchuk et al., 2009). Understanding how fire regimes will change under future climate scenarios is an essential contribution for developing adaptation strategies for the future. However, characterizing the potential for alterations in fire regimes requires investigation of multiple metrics of fire activity over broad spatial and temporal scales (e.g., burn probability, size, number of fires, and

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seasonality), and incorporating the uncertainty of climate change is challenging as projections vary and mechanisms of change are interacting and complex.

A major challenge for interpreting and communicating potential changes in fire regimes is conveying uncertainty related to future climate. Global climate models (GCM) project a wide range of shifts in components of climate related to fire and vary in the skill with which they reproduce observed contemporary climate (Rupp et al., 2013). Studies that use multiple GCM projections are thus able to capture the wide variety of plausible future fire regimes by incorporating a range of diverse potential climate trajectories (Barros et al., 2021; Clark et al., 2021; Dye et al., 2023; Heidari et al., 2021). Capturing this range is important for regional studies because, while most GCMs can reliably model continental or global patterns, they can be much more variable at regional scales (Langenbrunner et al., 2015; Mote et al., 2011). As we move into non-analog futures, additional uncertainty will arise if there is non-stationarity in the climate-fire relationship (Littell et al., 2018; McKenzie & Littell, 2017), in particular for complex disturbance regimes characteristic of many temperate moist forests where climate change may outpace ecosystem recovery (J.S. Halofsky, Conklin, et al., 2018).

Extrapolating statistical relationships of recent fire activity into the future is a common approach in many studies projecting changes to future fire regimes (Brown et al., 2021; Davis et al., 2017; Ellis et al., 2021). These studies assume that altered fuel aridity through climate change is the primary pathway to change based on empirical relationships between climate and recent fire activity. However, because statistical models often depend on correlations between monthly climate means and area burned, they can miss critical factors like daily weather and its effect on fire spread across topographically complex landscapes. Some fire behavior and spread simulators (e.g., Clark et al., 2008; S.H. Peterson, Halofsky, & Johnson, 2011; Zigner et al., 2020) and physics-based models (e.g., Linn et al., 2002; Mell and Jenkins, 2007) can achieve this, but are often only used locally and over short time periods due to high computational costs and calibration complexity. An alternative approach that provides an acceptable middle ground to modeling fire involves using stochastic ignition and spread simulators that combine the strengths of statistical models with the additional capability to model spatial fire spread across a complex landscape under multiple climate scenarios for many fire seasons (e.g., FSim, Finney et al., 2011). The stochastic nature of such models enables additional insights for complex fire regimes where fires may be infrequent and a purely statistical model may be constrained by limited availability of contemporary fire data (McEvoy et al., 2021). In addition, multiple components of fire regimes can be modeled, including burn probability, size, number of fires, and seasonality, providing a more nuanced look at future fire activity than is possible with most purely statistical models.

Moist temperate forest ecosystems of the Pacific Northwest (PNW) “Westside” (i.e., the U.S. states of Oregon and Washington west of the Cascade Mountain crest) experienced a large increase in area burned in the last several decades (Reilly et al., 2017), including a recent series of large, high-consequence fires driven by a synoptic east wind event in 2020 (Abatzoglou et al., 2021; Mass et al., 2021; Reilly, Zuspan, et al., 2022). Temperature in the PNW has also increased by 0.6°–0.8°C over the last century (Abatzoglou et al., 2014), with further increases of 0.1°–0.6°C per decade expected through the 21st century (Mote & Salathé, 2010). Precipitation is expected to increase but projections are more uncertain and increases may not offset the effects of the temperature increases on summer drought (Holden et al., 2018; Mote & Salathé, 2010). Taken together, future climate change in the PNW is generally expected to result in more area burned (J. S. Halofsky, Donato, et al., 2018; Littell et al., 2010), more frequent fires (Heidari et al., 2021), and more frequent weather conditions suitable for burning (Brown et al., 2021; Davis et al., 2017; Gergel et al., 2017). Because these productive moist forests are deeply engrained in the socio-ecological systems of the PNW, changing future fire regimes puts further pressures on surface drinking water sources (Nolin, 2012), timber resources (Latta et al., 2010), ecosystem services (Seidl et al., 2016), biodiversity (Spies et al., 2019), and carbon stocks (Case et al., 2021; Raymond & McKenzie, 2012). Forest managers in the PNW are aware of these ongoing changes and the need to develop resilient adaptation strategies to coexist with changing fire regimes (Dunn et al., 2020; Halofsky et al., 2011; J. E. Halofsky, Peterson, & Prendeville, 2018; D. L. Peterson, Halofsky, & Johnson, 2011).

In this paper, we contribute to the ongoing discussion of future fire in the PNW Westside by using the spatial fire behavior and spread simulator FSim to model mid-21st century changes to Westside fire regimes. FSim is predominantly used as a spatial tool to evaluate regional wildfire risk and exposure (e.g., Ager et al., 2013; Ager et al., 2019; Dye et al., 2021; Gannon et al., 2021; Haas et al., 2013; Scott et al., 2012; Scott et al., 2017; Thompson, Scott, Langowsk, et al., 2013; Thompson, Scott, Helmbrecht, & Calkin, 2013), land management plans (e.g., Ager et al., 2010; Ager et al., 2020; Scott et al., 2016; Thompson et al., 2022; Young et al., 2022), and suppression costs (Riley et al., 2018; Thompson et al., 2015) under contemporary climate, but has more recently gained use as a tool to explore climate change effects on future fire behavior (Dye et al., 2023; McEvoy et al., 2020; Riley & Loehman, 2016). To explore how future fire regimes may change, we ran FSim for five pyromes (regions of relatively homogeneous fire regime; Short et al., 2020) on the Westside driven by projections of mid-21st century Energy Release Component (ERC) from 12 different downscaled GCMs. Each of these 12 GCMs projects a unique, plausible version of the future and provides context for disentangling uncertainties associated with climate change, but each varies in the skill with which they replicate contemporary PNW climate. Using FSim as a tool, we investigated changes to 5 key components of Westside fire regimes: burn probability, fire rotation, fire size, number of fires, and seasonality. We then compared each of these components with the present-day fire regime to examine the magnitude and variability of projected future changes within and between the five pyromes.

2. Materials and Methods

2.1. Study Region

The study area is dominated by long-lived conifers and covers approximately 9.5 million hectares characterized by mountain ranges with steep topographic and climatic gradients (Figure 1, Table 1). Most precipitation throughout the region falls during the winter, often as snow at higher elevations. Climate is generally cooler and wetter toward the north in the inland mountains and coastal regions. Toward the south, climate transitions to warmer and drier summers with greater inter-annual temperature variability. The Douglas-fir/western hemlock forest zone is dominant at lower and middle elevations and transitions to the Pacific silver fir zone at higher elevations where snow becomes the most dominant form of precipitation. The highest elevations are dominated by the mountain hemlock zone. See Franklin and Dyrness (1973) for more information on forests of the region.

We aggregated analysis at the spatial scale of pyromes, or regions of relatively similar fire regimes defined by fire size, frequency, intensity, and seasonality (Short et al., 2020). The Olympics and Puget Lowlands are characterized by very wet winters and warm summers in the temperate rainforests of the western portion of the pyrome, with cooler temperatures persisting throughout summer at high elevation in the Olympic Mountains. The rain shadow effect of the Olympic Mountains creates much drier conditions in the eastern part of the pyrome, including the eastern Olympic Peninsula and Puget Lowlands. The Washington (WA) North Cascades are cool and wet, transitioning southward to slightly warmer and drier conditions toward the WA West Cascades immediately to the south. The Oregon (OR) West Cascades represent the southern end of the Cascade Mountain Range considered in this study and are generally intermediate in temperature and precipitation. The OR Coast Range is characterized by warm summers and wet winters. Coastal portions of the Olympics and OR Coast Range receive the greatest annual precipitation, often experiencing a summer fog layer along the coast that can partially moderate summer moisture stress (Dye et al., 2020). Urban and agricultural development is predominantly located in the Puget Lowlands of Western Washington (e.g., Seattle, Tacoma, Olympia, Bellingham) and Willamette Valley of Oregon (e.g., Portland, Salem, Eugene; incorporated in the OR Coast Range pyrome). Summer lightning is a relatively rare source of ignition with the exception of the southern part of the OR West Cascades (Short, 2022), and historically, indigenous burning was an important ignition source across the Westside (Boyd, 1999).

Historical fire regimes over the last several centuries vary considerably across the region and are primarily characterized by a moderately frequent, mixed severity regime and an infrequent high severity regime (Agee, 1993; Reilly et al., 2021). Fire in the Westside is typically not fuel-limited—but can be limited by the cool, moist climatic conditions, meaning that fuels are not available to burn in many years, as is the case in many tropical or other temperate ecosystems (Bradstock, 2010; Krawchuk & Moritz, 2011). Few large-scale fire history studies exist and most of the understanding on historical fire regimes is derived from uncross-dated age structure or fire scars dated in the field, primarily from relatively small landscape scale studies (Fahnestock & Agee, 1983; Hemstrom & Franklin, 1982; Impara, 1997; Morrison and Swanson, 1990; Teensma, 1987; Weisberg & Swanson, 2003). Infrequent, high-severity fires at centennial scales occurred in cooler, high elevation parts of the region in the Olympic and Cascade Mountains. Estimates of historical fire rotations from western WA range from 465 to 800 years (Fahnestock & Agee, 1983; Hemstrom & Franklin, 1982). Intermediate and warm climatic settings at middle and lower elevations are characterized by a moderately frequent, mixed severity regime that experienced non-stand-replacing fires multiple times a century (Weisberg & Swanson, 2003), as well as infrequent, high severity fires. Estimates of historical fire rotation in the inland part of the OR Coast Range and central OR West Cascades range from 78 to 271 years (Impara, 1997; Morrison and Swanson, 1990; Teensma, 1987). Relatively little is known about historical fire sizes, though records from the mid-1800s and early twentieth century document the occurrence of very large high severity fires (>40,000 ha) associated with

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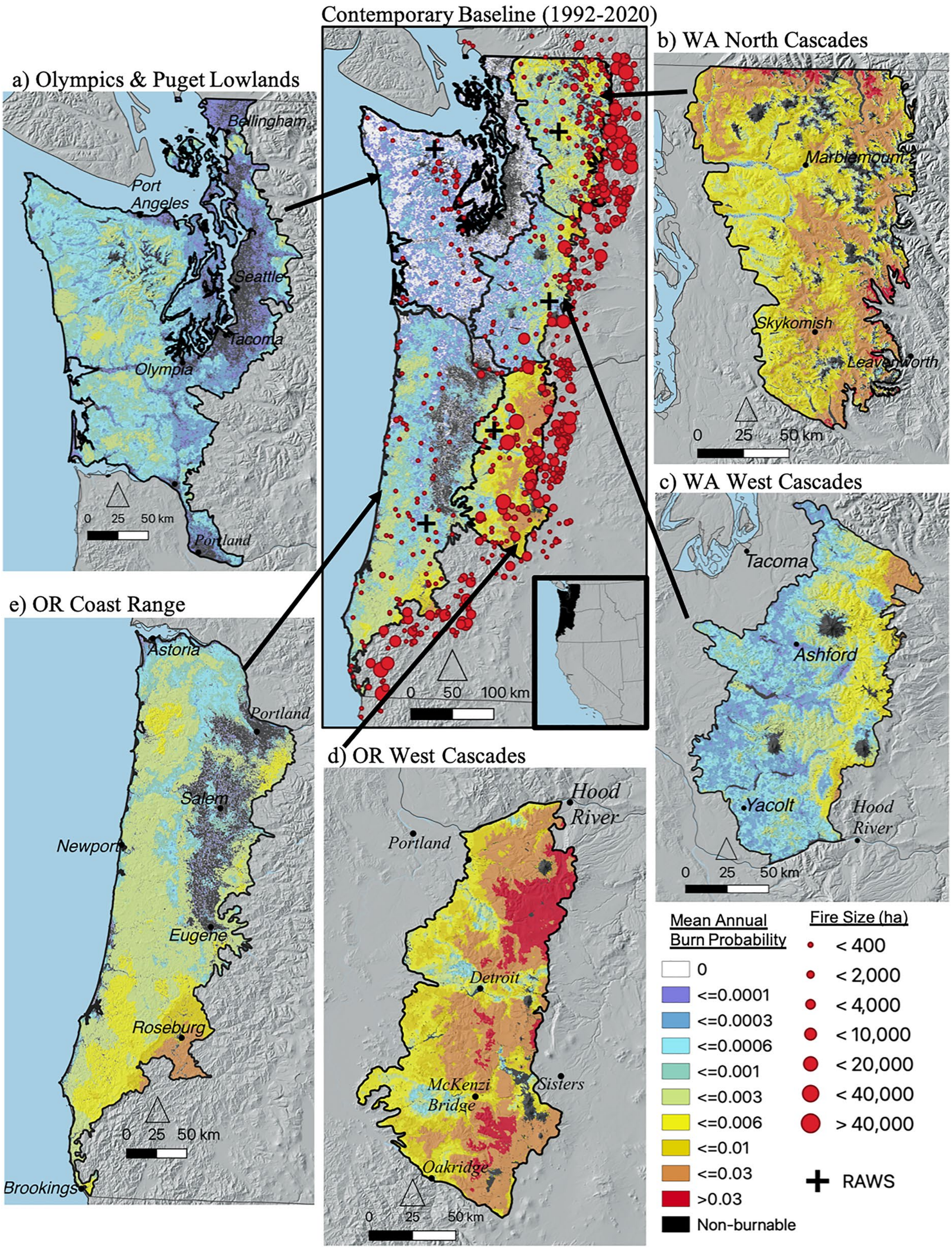

Figure 1. In center, Westside reference map shows simulated contemporary baseline (1992–2020) burn probability and ignition locations and sizes of fires from the historical fire occurrence database that were used to inform model calibration; note that all fires ignited within a 30 km buffer of the pyrome boundary (the fire occurrence area, or FOA) are included in the map. Remote Automatic Weather Stations (RAWS) are shown with a cross symbol. Inset map shows the full study area in the context of the Western United States. Maps on the margins show the per-pixel mean burn probability of all 12 GCM-based simulations for mid-21st century (2035–2064) for (a) Olympics & Puget Lowlands; (b) Washington North Cascades; (c) Washington West Cascades; (d) Oregon West Cascades; and (e) Oregon Coast Range.

Table 1
Environmental and Climatic Setting for Five Westside Pyromes

Pyrome	Elevation (m)[a]	Annual precipitation (mm)[b]	July precipitation (mm)[b]	Annual temperature (°C)[b]	July temperature (°C)[b]
Olympics & Puget Lowlands	0–2432	445–5611	11–90	2–12	10–20
WA North Cascades	6–3283	996–5276	12–103	0–11	9–19
WA West Cascades	3–4388	835–4644	6–81	-5–12	3–20
OR West Cascades	3–3421	803–3667	6–38	0–12	8–20
OR Coast Range	0–1250	823–4738	6–36	8–13	14–22

[a]LANDFIRE, 2020. [b]PRISM Climate Group, 2023. Reported values are the range (min-max) of the 30-year normals for all 4 km pixels overlapping each pyrome.

synoptic dry, east wind events during the late fall (Reilly, Zuspan, et al., 2022). Smaller, high severity fires (<10,000 ha) were likely common under more moderate conditions, particularly in the interior of the OR Coast Range and OR West Cascades, but very little is known about the size and frequency of non-east wind driven fires. Fire ignition across the Westside is primarily climate-limited, due to typically ample year-round biomass across the majority of the region.

2.2. The Large-Fire Simulator (FSim)

FSim computes a daily large-fire ignition probability based on the logistic regression between historical large fire ignition records in the study area and the daily Energy Release Component (ERC) for fuel model G of the National Fire Danger Rating System (Andrews et al., 2003), the standard fuel model used for ERC generation in FSim (Finney et al., 2011). ERC is an indicator of fuel dryness and is calculated from the fuel moistures of four dead fuel timelag classes (1, 10, 100, and 1000 hr), and live woody and herbaceous fuel moistures, all of which require daily temperature, humidity, precipitation, and solar radiation for calculation. See Cohen and Deeming (1985) and Fosberg and Deeming (1971) for detailed descriptions of standard parameters and equations used to calculate ERC.

During a full simulation of a specific climate period, FSim generates a set of tens of thousands of statistically plausible ERC streams based on recent weather observations. These iterations of ERC streams are not sequential or temporally related; each annual iteration is a unique, plausible realization of weather that could occur over a calendar year based on the composite fire weather statistics of the climate period of interest. Daily ERC values are generated based on the mean ERC value for that day in the weather records for the period of study, the standard deviation in ERC for the day, and the temporal autocorrelation in ERC, which are used to generate any number of years of synthetic ERC streams, with a typical number of years for the Western U.S. being 10,000 so that robust estimates of burn probability for any given location on the simulation landscape can be produced. We used Fire Family Plus version 5 software (FireFamilyPlus, 2022) to generate unique logit functions for each pyrome using the power law feature that builds a probability model of the number of large fires per day based on the historical relationship between ERC and fire occurrence (Figures S2–S6 in Supporting Information S1). The power law feature allows for FSim to simulate days during which more fires are ignited during a single day than was ever recorded in the historical fire occurrence data. It is particularly useful in areas like the Westside PNW where the recent historical fire record is limited due to relatively infrequent fires. After drawing a daily ERC value during simulation, FSim references the power law functions to determine how many fires it will ignite that day; however, FSim will only ignite a new fire if ERC meets or exceeds the 80th percentile for that region, a threshold that has been described as an important predictor of fire occurrence and spread across the United States (Riley et al., 2013). On each day of the year, FSim also draws a wind speed and direction value from the monthly joint probability distribution for the period being simulated.

Locations of new ignitions are determined probabilistically using a continuous kernel density raster supplied by the user (we used a 75 km nearest neighbor) that represents the spatial point pattern of ignition locations from the historical fire occurrence database (Short, 2022). FSim simulates fire containment through a stochastic perimeter trimming algorithm that mimics temporal fire line construction during suppression efforts, combined with a ruleset that extinguishes fires after meeting a threshold of consecutive days with insufficiently dry weather. A single iteration is completed once FSim reaches December 31. At this point, all existing fires, if any, are ended,

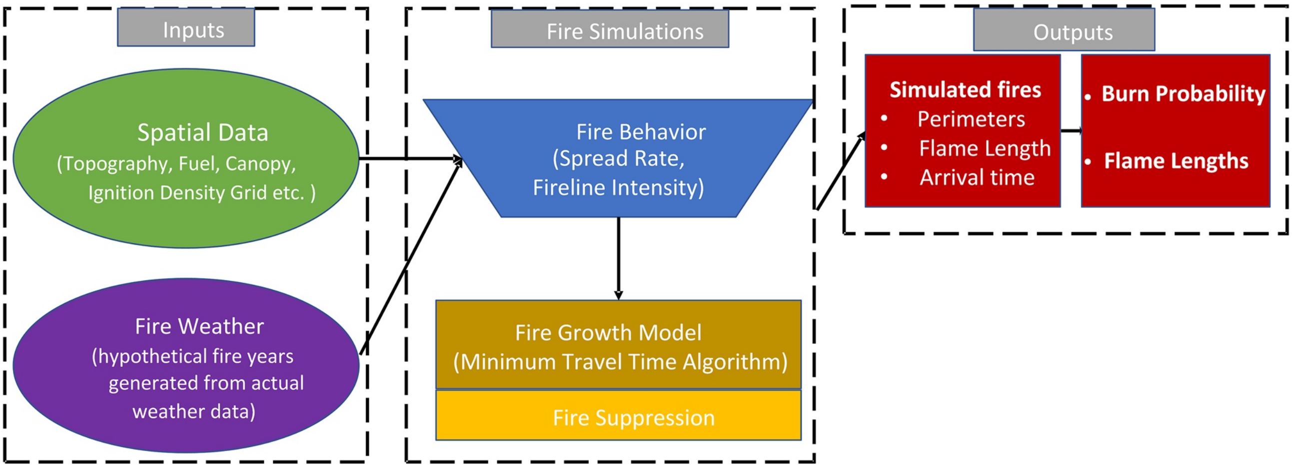

Figure 2. This conceptual diagram describes the basic FSim simulation workflow.

and the next new iteration year begins on January 1. There is no year-to-year memory in FSim, meaning that what burns in the first iteration does not affect what burns in the subsequent iterations; additionally, we removed all day-to-day memory from the model by allowing individual pixels to reburn multiple times over the course of a single iteration. In this way, burns were constrained entirely by whether daily ERC met climatic thresholds for burning rather than whether an area had already burned.

Final outputs include burn probability rasters, flame length rasters (note that we do not use these explicitly in our current analysis), and the ignition location, date, final size, and perimeter of each simulated fire (Figure 2). FSim focuses on modeling only large fires to maintain computational efficiency, and because large fires account for the vast majority of area burned. Referencing historical fire sizes from the study region, we used large-fire thresholds of 57.1 ha for the OR West Cascades, and 24.3 ha for all other pyromes.

FSim requires specification of three spatial boundaries for each pyrome being modeled (Figure S1 in Supporting Information S1). The "analysis area" is the primary region of interest and the area for which final burn probability estimates are valid, equaling the mapped area of the pyrome (Figure 1). The "fire occurrence area" (FOA) defines where FSim allows ignitions to start (Figure S1 in Supporting Information S1). We set the FOA as a 30 km buffer around each pyrome; though we do not produce burn probability estimates for the FOA, fires ignited in the FOA are allowed to spread into the pyrome, at which point they contribute to the final burn probabilities reported for the pyrome. Third, FSim requires a "fire modeling landscape" (LCP) raster, which we set as an additional 30 km buffer surrounding the FOA. FSim does not allow ignitions in this buffer, but fires ignited in the FOA can burn outward into the LCP. We retrieved the LCP layers of slope, elevation, aspect, fire behavior fuel model (Scott & Burgan, 2005), canopy bulk density, canopy base height, canopy cover, and canopy height from the Landscape Fire and Resource Management Planning Tools, or LANDFIRE, version 2.1.0 (LANDFIRE, 2020). LANDFIRE's canopy layers are internally calibrated for use with the Scott and Reinhardt (2001) crown fire model, which we used in our FSim runs. We resampled the default LANDFIRE 30 m raster grids to 270 m to match our desired output resolution, then combined all eight grids using standard tools in FlamMap software (Finney, 2006) to create the required LCP raster. Since LANDFIRE version 2.1.0 does not map 2020 fuel conditions, we implemented a manual adjustment of fuel types so that we could conduct simulations under fuel conditions following the widespread 2020 Labor Day fires, following standard methods outlined by Beauchaine et al. (2015).

2.3. Modeling Protocol

We conducted simulations individually for each pyrome under two climate periods: (a) a contemporary baseline (1992–2020); and (b) mid-21st century (2035–2064) under RCP8.5 emissions climate change scenario.

2.3.1. Contemporary Baseline (1992–2020)

In each pyrome, we selected a Remote Automatic Weather Station (RAWS) with a relatively long, complete data record spanning the historical period of record, 1992–2020 (Figure 1; Table S1 in Supporting Information S1). We chose this period as our contemporary baseline because this was the maximum period of available, complete fire occurrence records available at the time of our study. Gridded climatology, such as gridMET (Abatzoglou, 2013), could alternatively be used in place of RAWS to acquire the contemporary baseline weather records; however, we opted to use RAWS because of their direct representation of local wind patterns (Dye, et al., 2020; Dye et al., 2023) We imported the RAWS records into Fire Family Plus version 5 software (FireFamilyPlus, 2022) to calculate the daily ERC, wind speed, and wind direction statistics required by FSim as described in Section 2.2. Following standard FSim best practices for model calibration, we conducted multiple calibration runs for each pyrome, each run consisting of 10,000 iterations of hypothetical fire years, until both the simulated mean fire size and mean number of fires per year of fires that ignited in the FOA were each within the 70% confidence intervals of the 1992–2020 historical observation means for the same area (Short, 2022). Final calibration statistics are provided in Table S3 in Supporting Information S1. Hereafter, we refer to these fully calibrated, 10,000-iteration FSim runs simulated for the period 1992–2020 as the contemporary baseline, and they are intended to represent the contemporary fire regime of each pyrome for the purposes of this study.

2.3.2. Mid-21st Century (2035–2064)

At the location of each RAWS, we retrieved climate data for both the contemporary baseline and mid-21st century periods for RCP8.5 emissions trajectory from 12 downscaled CMIP5 GCMs in the NEX-DCP30 climate product (Thrasher et al., 2013). We manually selected a subset of available GCMs to approximate a wide range of projected future climate conditions, as well as a range of model skills applicable to the PNW as defined in Rupp et al. (2013), where model skill was defined as a GCM's ability to replicate the recent observed climate of the PNW (Table S2 in Supporting Information S1).

We constructed future climate scenarios by applying a GCM-based delta to the observational RAWS data, based on methods used in Riley and Loehman (2016) and McEvoy et al. (2021). For each GCM, we extracted the monthly mean precipitation, maximum and minimum temperature, and vapor pressure. Then, we calculated the monthly percent change of precipitation and vapor pressure, and the actual monthly change in maximum and minimum temperature, and applied these delta values directly to the contemporary baseline RAWS data to create 12 future climates. This approach preserves the local observed weather conditions and seasonal patterns while adjusting for future climate. An alternative approach could have been to directly use the projected gridded GCM climate to construct the future weather streams for FSim; however, this can introduce additional biases, complicating the direct comparison with the contemporary baseline period (Dye et al., 2023). Calculations of mid-21st century ERC also required a precipitation duration variable, and for this we used the newly adjusted future precipitation amount divided by the contemporary precipitation intensity, where contemporary precipitation intensity was calculated as the precipitation amount divided by the precipitation duration in the RAWS, for our purposes assuming that precipitation intensity would remain constant between the contemporary and future scenarios. On some rare occasions, the future precipitation duration was greater than 24 hr, and in these cases the precipitation duration and amounts generated were rolled over to the next day.

Once we created all future weather streams, we generated the daily ERC statistics required by FSim using Fire Family Plus software in the same way as for the contemporary baseline. Because FSim has built-in restrictions on fire activity related to ERC percentiles, we did not calculate new ERC percentiles from every version of future daily ERCs, but instead replaced the ERC percentiles with the original ERC percentiles from the 1992–2020 period for each pyrome. In this way, we are able to more directly compare future to historical fire activity; otherwise, changing ERC percentiles in the future could have unnecessarily underestimated future fire activity. Then, we conducted a complete FSim run of 10,000 iterations separately for each of the 12 GCM-based future climate scenarios in each pyrome. These 60 simulations (5 pyromes, 12 GCMs each) represent plausible changes to the contemporary fire regime by mid-21st century. To isolate the effect of climate change, and following the approach of Riley and Loehman (2016), we retained the LCP raster, the ignition probability grid, wind distributions, and all model parameters determined during calibration of the contemporary baseline throughout all of the mid-21st century simulations.

2.4. Components of Fire Regime Shifts

2.4.1. Burn Probability and Fire Rotation

FSim produces burn probability rasters for each simulation at 270 m resolution. From these rasters, we calculated a single landscape-wide burn probability metric as the mean burn probability of all pixels in a pyrome. Because the burn probability of a single pixel location is related to fire spread through the adjacent landscape, FSim outputs are not typically used to infer burn probability for a single pixel but can be useful to summarize at the landscape level. Increases or decreases in burn probability are suggestive of more or less fire activity as a result of climate change and by representing broad patterns, this metric may incorporate less uncertainty than pixel-level burn probability.

We analyzed the landscape burn probabilities for the future period simulations in two ways. First, we calculated a single summary metric for each pyrome by producing a raster of the per-pixel average across the 12 GCM-based simulations, with the landscape burn probability as the mean of those averaged pixels, excluding pixels classified as non-burnable (e.g., water). Second, we calculated landscape burn probability individually for each of the 12 GCM-based simulations to enable a more complete assessment of variability in the different climate projections.

We used the landscape-wide burn probability numbers for each pyrome to estimate fire rotation, or the expected number of years for an entire pyrome to burn. Burn probability indicates the chance of burning in any given year; for example, a burn probability of 0.02 represents a 2% chance of burning in any given year (or, 1 fire every 50 years or 2 fires every 100 years). Thus, the fire rotation can be estimated as the number of years required for the annual chance of burning to reach 100%. In this example, an average landscape-wide annual burn probability of 2% suggests a fire rotation of 50 years (100% ÷ 2% = 50). Similar to burn probability, we calculated both a summary fire rotation based on the raster of per-pixel averages of the 12-GCM based simulations, as well as individual fire rotations for each of the 12 GCM-based simulations.

2.4.2. Fire Size, Number of Fires, and Seasonality

FSim outputs ignition date and final fire size of each simulated fire, information that we post-processed to create metrics of average fire size and number of fires (per decade), because decadal is a more meaningful temporal scale for the infrequent fire regimes characteristic of the Westside. Additionally, we translated fire size into a metric of percentage of the FOA burned per decade and number of fires per decade within 7 size classes that are relevant for Westside forests. Note that the FOA is a 30 km spatial buffer surrounding the pyrome (and including the pyrome) where fires are allowed to ignite (Figure S1 in Supporting Information S1). All fire sizes reported are attributed to fires that began in the FOA; however, the entirety of each fire is not necessarily contained solely within the FOA, meaning that the percentage of FOA burned metrics may be somewhat conflated. Some fires may burn into the pyrome (and those portions will then contribute to burn probability metrics), and other fires may burn away from the pyrome into the surrounding landscape (and those portions will not contribute to burn probability but will still contribute to mean fire size and counts).

To visualize and examine changes to future fire seasons, we extracted ignition dates from all simulated fires and calculated metrics of average fire size per month and number of fires (per month per decade). We considered all fires with a start date between the first and last date of each month as occurring in that month, even if the fire ultimately burned multiple days into a consecutive month. We based all fire size and counts statistics from fires igniting in the FOA, the 30 km buffer around each pyrome.

3. Results

3.1. Burn Probability and Fire Rotation

Burn probability for the contemporary baseline period (1992–2020) was highest in the OR West Cascades and WA North Cascades and lowest in the OR Coast Range, WA West Cascades, and the Olympics (Table 2; Figure 1). By the mid-21st century (2035–2064), summary landscape burn probabilities still maintained similar rankings (highest for OR West Cascades, lowest for Olympics; Table 2; Figure 1). Summary landscape burn probabilities/fire rotations changed (increased/decreased) for all pyromes (Table 2).

Results varied widely depending on the GCM projection used, and every pyrome had at least one simulation that led to a more than 600% change (increase/reduction) in burn probability/fire rotation relative to the contemporary baseline (Figure 3). Simulations driven by GCM projections that resulted in increased future burn probability for one pyrome did not necessarily do so for all pyromes, because both the direction of change and magnitude of ERC varied by pyrome (Table S2 in Supporting Information S1). The Olympics were the only pyrome with less variability around the direction of change, as all GCM-based simulations resulted in higher future burn probabilities/shorter fire rotations; in all other pyromes, at least one simulation projected a decrease in burn probability. Projections for the WA West Cascades were highly variable around the zero-change line

Table 2
Annual Burn Probability for the Contemporary Baseline (1992–2020), Where Burn Probability Is Calculated as the Average of All Pixels Within the Pyrome, and Future Mid-21st Century (2035–2064), Where Burn Probability Is Calculated as the Average of All Pixels Within the Pyrome After Taking the Per-Pixel Mean of All 12 GCM-Based Simulations (as Shown in Figure 1)

	Annual burn probability	Fire rotation	Proportional change in burn probability (%)
Olympics and Puget Lowlands			
Contemporary Baseline (1992–2020)	0.009%	11,111 years	
Mid-21st Century (2035–2064)	0.052%	1,235 years	+478%
WA North Cascades			
Contemporary Baseline (1992–2020)	0.214%	467 years	
Mid-21st Century (2035–2064)	0.913%	110 years	+327%
WA West Cascades			
Contemporary Baseline (1992–2020)	0.092%	1,087 years	
Mid-21st Century (2035–2064)	0.164%	610 years	+78%
OR West Cascades			
Contemporary Baseline (1992–2020)	0.705%	142 years	
Mid-21st Century (2035–2064)	1.544%	65 years	+119%
OR Coast Range			
Contemporary Baseline (1992–2020)	0.102%	980 years	
Mid-21st Century (2035–2064)	0.235%	426 years	+130%

Note. The fire rotation is a transformation of burn probability and estimates how many years would be required for the entire landscape to burn, that is, to achieve a burn probability of 100%. The proportional change relative to contemporary is shown; note that a positive proportional change indicates an increase in burn probability accompanied by a decrease in fire rotation.

(seven simulations projected a decrease/increase in burn probability/fire rotation), leading to a slightly negative 12-GCM median; however, the 12-GCM mean skews toward higher future burn probabilities due to several GCMs projecting extreme increases (Figure 3). Generally, the largest increases to future ERC tended to result in the largest increases to burn probability/reductions to fire rotation (Table S2 in Supporting Information S1), and many of these same GCMs were evaluated to have better skill for capturing observed PNW climate (Rupp et al., 2013) (Figure 3).

3.2. Fire Size and Number of Fires

Fire size and number of fires also varied depending on the GCM climate projection used (Figure 4). In FSim, fire size and number of ignitions are the two primary simulation outputs that affect burn probability, and so the relative differences between pyromes were generally similar to those observed for burn probability—for example, all simulations projected larger and more frequent fires for the Olympics, while all other pyromes had at least one simulation projecting a future decline in size and/or number of fires. Generally, simulations that produced more fires also produced larger fires (Figure 4).

In the largest fire size classes, there was potential for increased number of fires for most pyromes (Figure 5). Fires larger than 40,000 ha could occur at a median rate of 0.11 fires per decade (or, 1 fire approximately every 100 years and a +746% 12-GCM median increase from the contemporary baseline) for the Olympics, 1.48 fires per decade for WA North Cascades (+247% 12-GCM median increase), 0.16 fires per decade for WA West Cascades (−40% 12-GCM median decrease), 1.26 fires per decade for OR West Cascades (+54% 12-GCM median increase), and 0.57 fires per decade for OR Coast Range (+14% 12-GCM median increase). WA West Cascades was the only pyrome projecting a 12-GCM median decline in number of fires >40,000 ha; however, several individual simulations still pointed to the potential for large increases in number of fires for these size classes (Figure 5).

The proportion of total area burned by fires larger than 20,000 ha increased strongly in the Olympics and WA North Cascades, with a corresponding decline in the smallest size classes (Figure 6, Figure S7 in Supporting Information S1). WA West Cascades and OR Coast Range both saw small increases in the proportion of total area burned in the smallest size classes and declines in the largest size classes. For OR West Cascades, there was

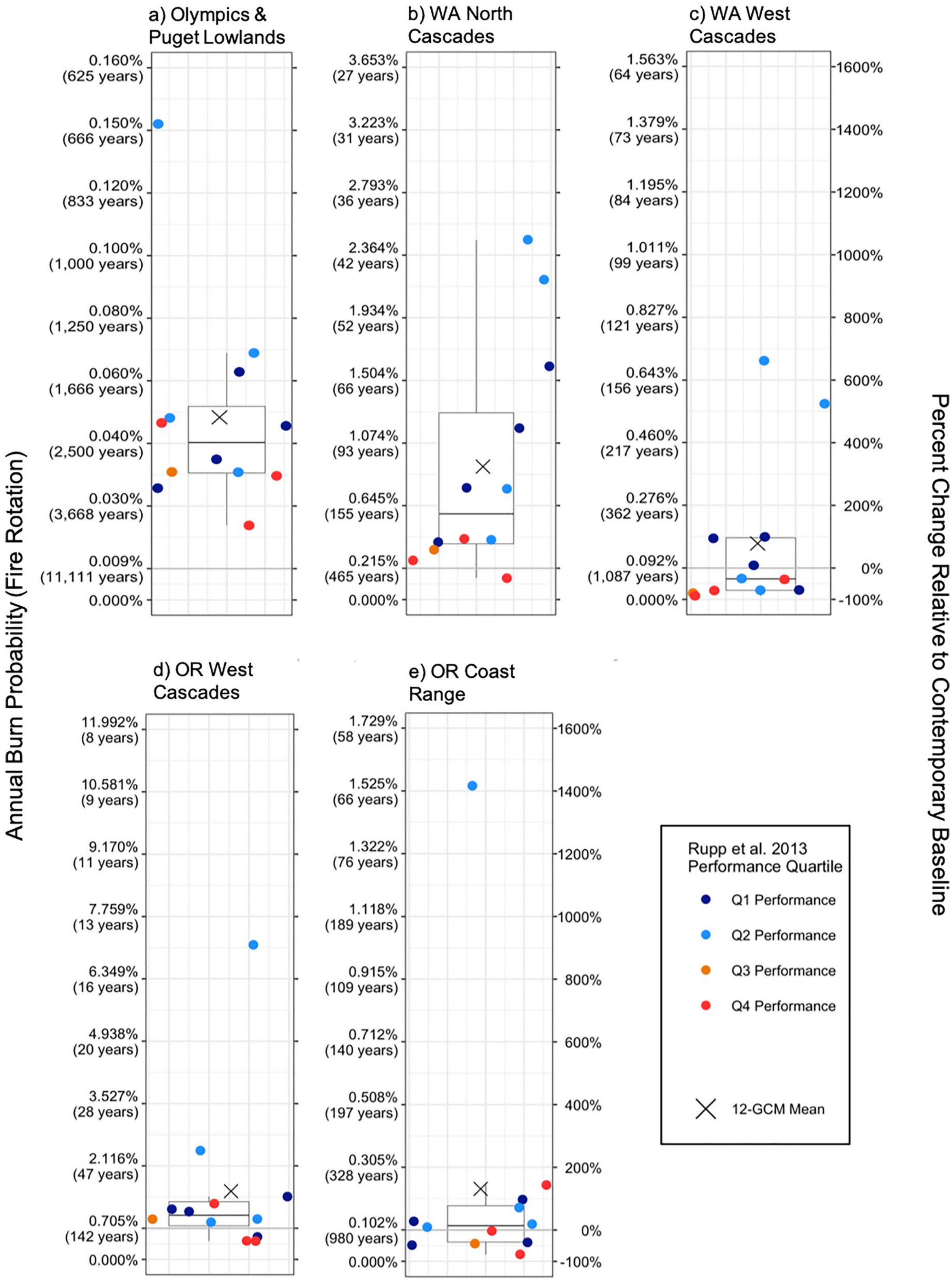

Figure 3. Landscape-wide burn probability and fire rotation for the mid-21st century (2035–2064) (left axis) with corresponding percent future change relative to the contemporary baseline (right axis). Note that the left and right *y* axes are on different scales. Boxes mark the median and first/third quartiles; whiskers extend to ±1.5 * IQR. Points are color-coded according to the performance ranking quartiles of 41 GCMs evaluated for their suitability for replicating the contemporary PNW climate by Rupp et al. (2013), where Q1 indicates the highest-performing quartile (Table S2 in Supporting Information S1). Note that the figure contains no *x*-axis gradient; the points are randomly spaced so that each point can be fully seen.

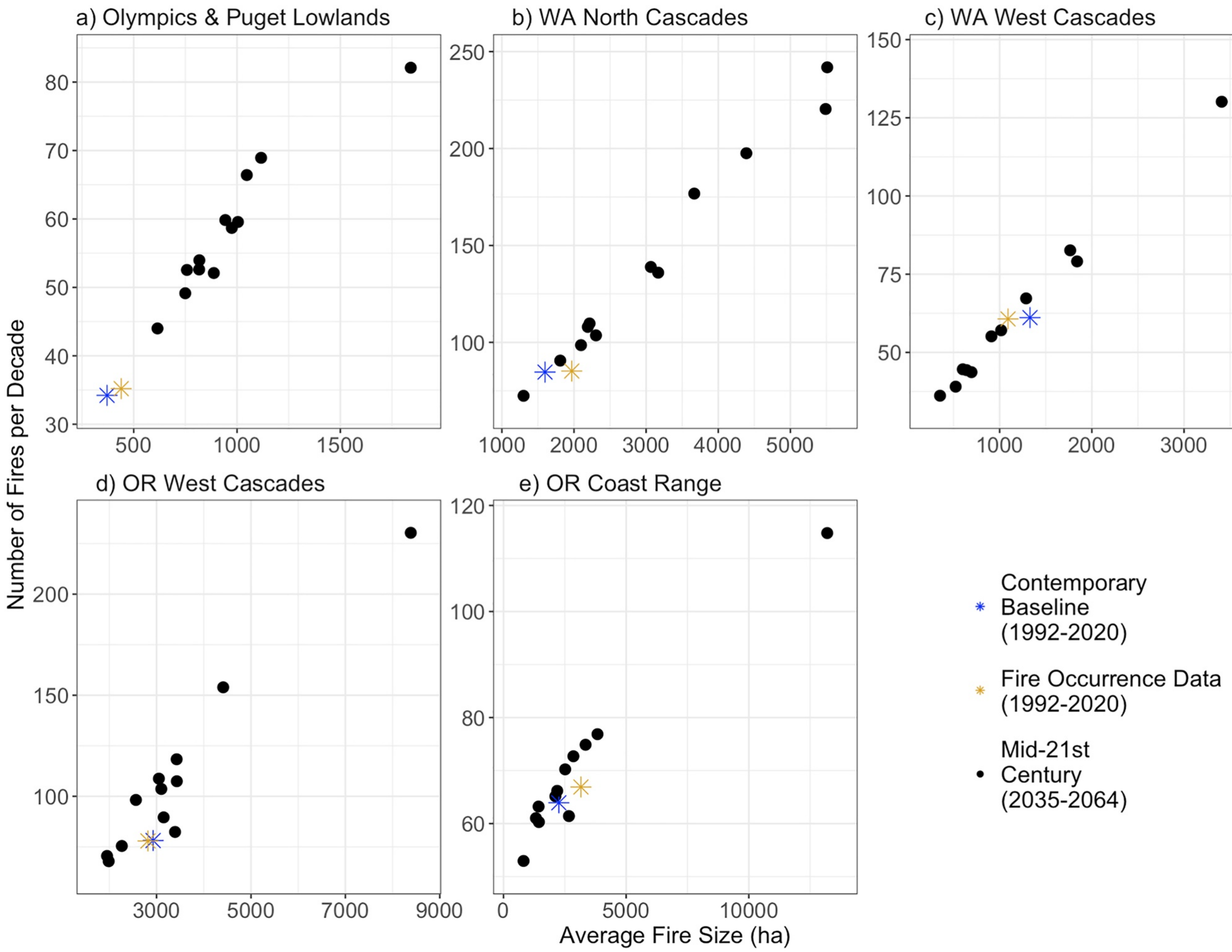

Figure 4. Overall average fire size and number of fires per decade projected by mid-21st century (2035–2064) for each of 12 GCM-based simulations (solid points), relative to the contemporary baseline calibrated simulations (1992–2020; blue star points) and the historical fire occurrence data (1992–2020; gold star points).

a moderate increase in proportion of total area burned for fires >40,000 ha, and moderate declines in all other size classes. Variability between all GCM-based simulations was high, especially for the largest size classes; for example, in the WA West Cascades the proportion of area burned by fires >40,000 ha varied between approximately 10%–50% depending on the GCM climate used (Figure 6).

3.3. Seasonality

By the mid-21st century, simulations suggested a lengthening of the fire season in most pyromes, as evidenced by increasing future fire size and number of fires in many of the spring and autumn months; however, OR Coast Range increased most starkly in July, whereas the shoulder seasons exhibited minimal changes (Figure 7). The specific patterns of seasonality differed by pyrome. For the Olympics, major changes to size and number of fires occurred earlier in the year, from spring to mid-summer, with minimal changes in the autumn. WA North Cascades exhibited large changes from April through October, with small increases in March and November, widening the fire season window beyond what was common in the past. WA West Cascades projected larger and more frequent fires in early spring (March-April), but experienced declines in all other months, including the summer and fall (however, we note again that Figure 6 depicts the 12-GCM medians, and there are many individual GCM projections that do produce much more extreme increases for WA West Cascades). OR Coast Range showed increases in fire size projected for July, and more frequent but smaller fires projected for spring (May, June), and late summer (August). OR West Cascades projected more frequent fires across all months, although these fires were smaller than observed in the historical record during the late summer months of August–September.

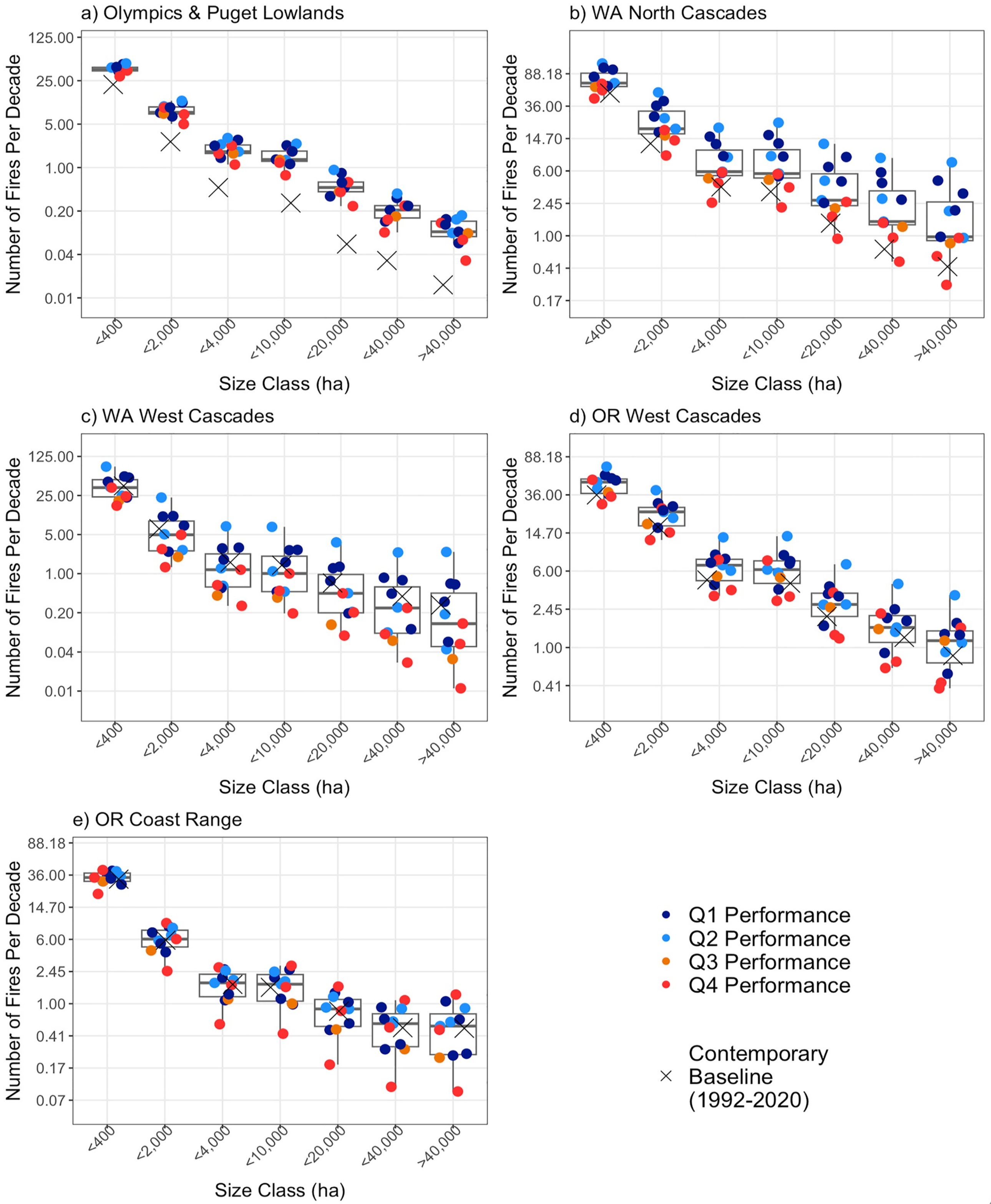

Figure 5. Number of simulated fires per decade for the contemporary baseline and the mid-21st century for fires within each size class. Points are color-coded as in Figure 3, according to the GCM performance rankings from Rupp et al., 2013. Boxes mark the median and first/third quartiles; whiskers extend to ±1.5 * IQR of the mid-21st century simulations. Vertical axis is on a logarithmic scale so larger size classes can be visualized.

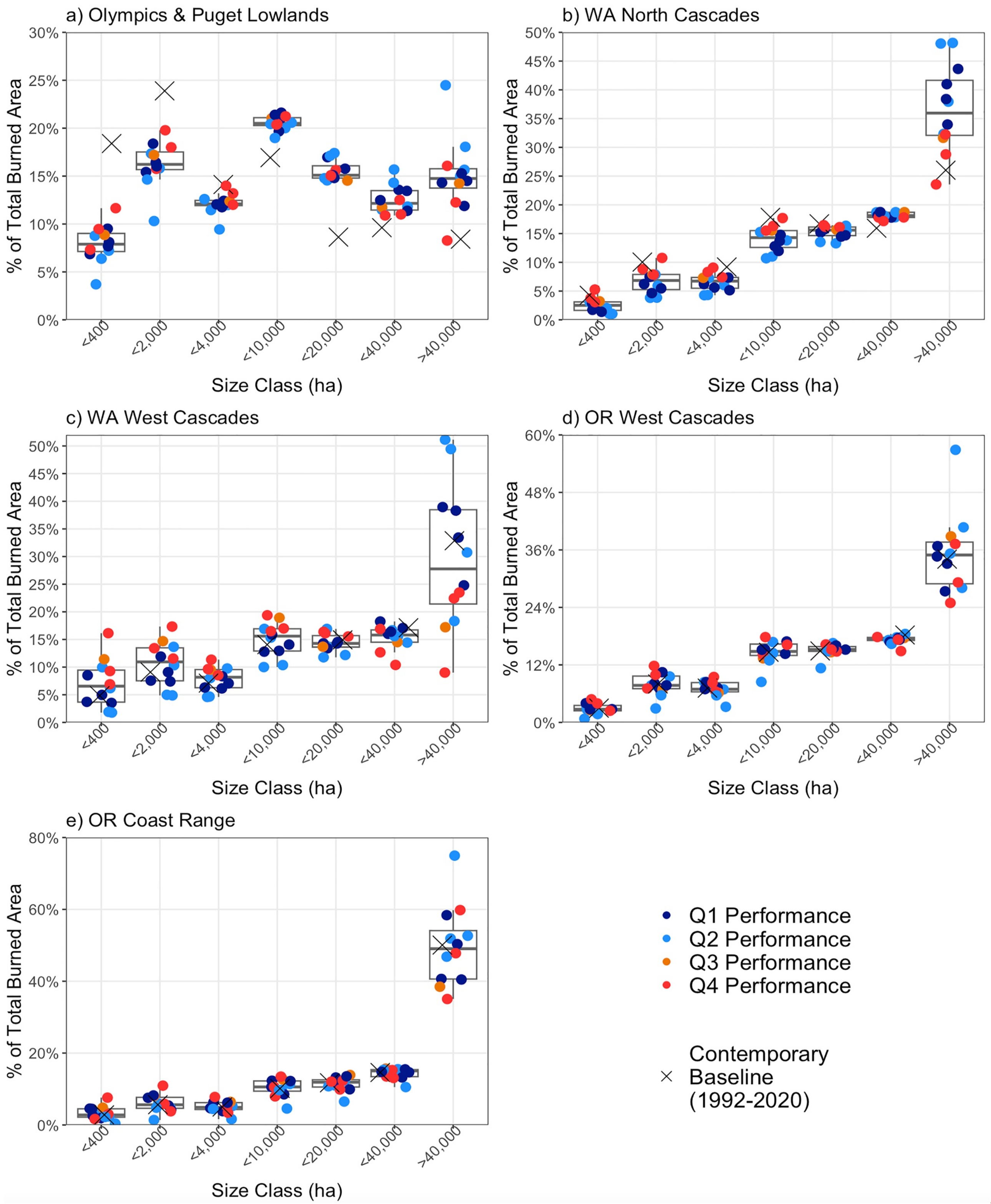

Figure 6. The proportion of total area burned by each of 7 size classes. Boxes mark the median and first/third quartiles; whiskers extend to ±1.5 * IQR. Each point is an individual GCM-based simulation, colored by Rupp et al. (2013) GCM performance ranking quartile as in Figures 3 and 5. In the appendix, see companion Figure S7 in Supporting Information S1 which instead plots the proportion of the fire occurrence area (FOA) burned by size class per decade.

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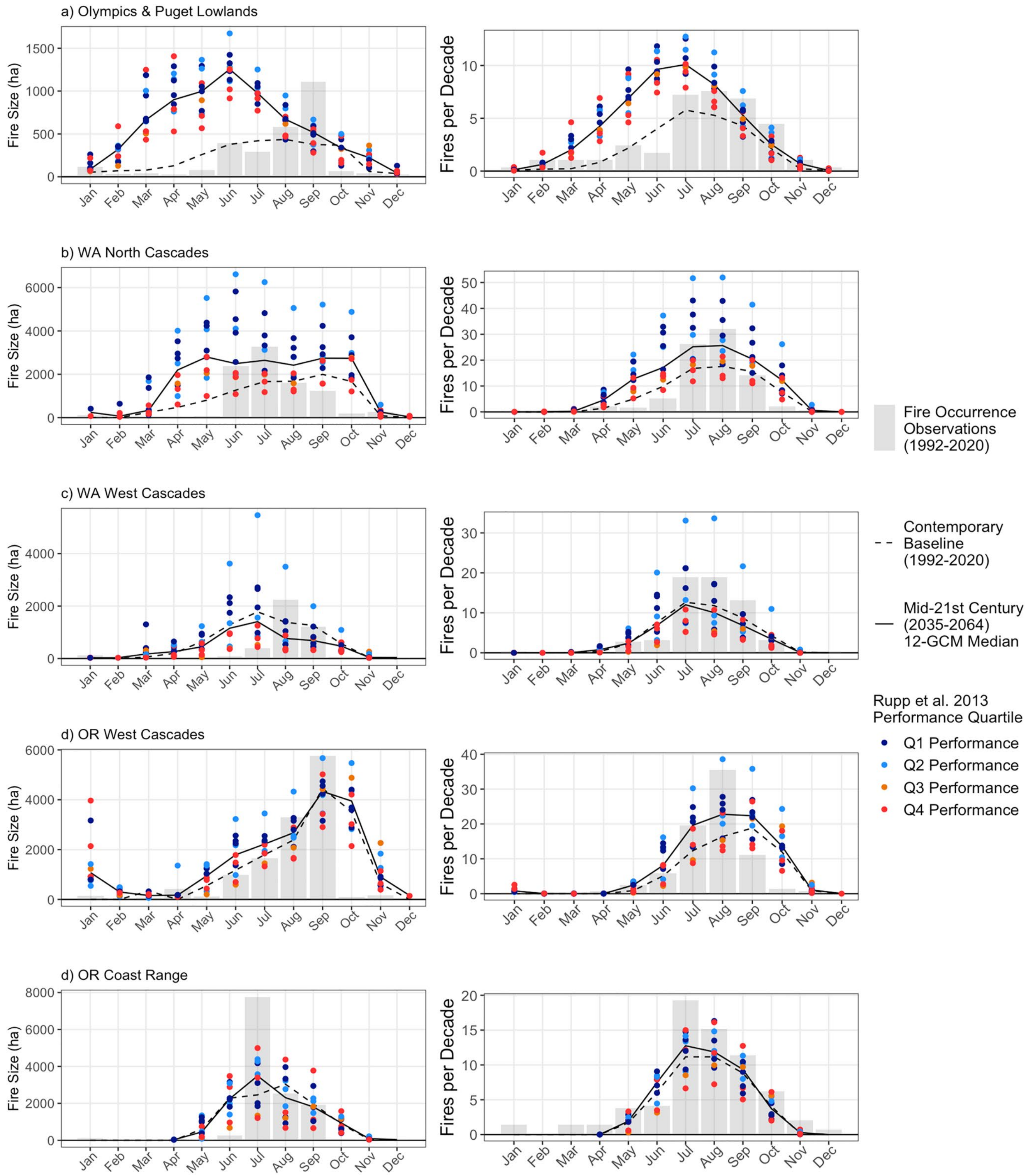

Figure 7. Monthly distribution of simulated fire size and number of fires per decade for the contemporary baseline (1992–2020) and mid-century future (2035–2064) scenarios. For mid-century scenarios, the median monthly value of the 12 GCM-based simulations is drawn as a solid line, and individual points for each simulation are color-coded by their Rupp et al., 2013 GCM performance ranking quartile as in Figures 3, 5 and 6. Observations from the historical fire occurrence database are shown as gray bars in background.

4. Discussion

Our simulations provide additional resolution on geographic patterns of potential future fire activity that enrich the current body of literature for the PNW. Primarily, previous attention to future Westside fire has been wrapped into broader analyses of the entire PNW region as a whole, including or focusing on the dry forests and woodlands of the eastern two-thirds of Oregon and Washington (Davis et al., 2017; Halofsky et al., 2020; Littell et al., 2010), or grouped into national-scale assessments (e.g., Brown et al., 2021; Gao et al., 2021; Gergel et al., 2017; Heidari et al., 2021). Focusing specifically on the high productivity, wet, climate-limited forests of the Westside is advantageous because of its unique, region-specific challenges to modeling future fire that are largely due to the infrequency of large, high-consequence fires relative to the rest of the Western U.S. during the recent historical record (McEvoy et al., 2021; Reilly, Zuspan, et al., 2022). Like the rest of the Western U.S., however, the moist temperate forests of the Westside are vulnerable to climate change (Mote & Salathé, 2010) and climate, as a key driver of fire activity, is likely to significantly alter the future fire regime across most of the Westside (Davis et al., 2017; Halofsky et al., 2020; McEvoy et al., 2020).

In the OR West Cascades, where fire was most frequent historically (Reilly et al., 2021) and has increased the most in the last few decades (Reilly et al., 2017), burn probability is expected to further increase while fire rotation decreases by half. However, the greatest relative increases were projected in the wetter and cooler pyromes in the north, corroborating projections for the end of the 21-st century presented by Davis et al. (2017). Of the northern pyromes, we projected the WA North Cascades to be more similar to the contemporary burn probability of the OR West Cascades, while burn probability in the Olympics were projected to remain relatively low despite high proportional increases. While we observed significant variability among simulations based on 12 GCM projections and five pyromes, several key threads emerged as commonalities across the Westside, namely an increased number of fires and proportion of area burned by very large wildfires (>40,000 ha), increased burn probability and shorter fire rotation, and a longer fire season.

All pyromes had three or more simulations that resulted in at least a doubling of burn probability (+100%) by mid-century, and all pyromes had at least one simulation projecting an extreme (+600% or more) increase (Figure 3). Often, the highest future changes to burn probability were driven by GCMs that ranked in the top 50% of GCMs for contemporary performance in the PNW (Figure 3; Rupp et al., 2013). Likewise, the majority of simulations that resulted in negative or minimal changes were driven by GCMs that ranked in the lower 50% for GCM performance (Figure 3). Whether or not a GCM that performs well against contemporary climate will also more reliably project the "correct" future climate is an inherently untestable hypothesis (Rupp et al., 2013); however, here it serves a useful purpose for unpacking uncertainty and interpreting results. Using multiple GCMs is a recommended best practice for analyzing future climate projections (e.g., Mote et al., 2011 suggest 10 or more), but it may not be feasible for all studies to include more than a few. In our case, the choice to incorporate 12 GCMs with varying levels of contemporary performance provides a useful framework to assist with communicating the consequences of GCM selection; for example, if we had specifically chosen only the "best-performing" GCMs from the outset, we would likely be reporting higher average increases to fire activity. Similarly, large ranges of variability are reported in other fire simulation studies that incorporate multiple different projections of future climate to inform models (e.g., Barros et al., 2021; Dye et al., 2023; Heidari et al., 2021; McEvoy et al., 2021).

Fire rotation is projected to remain below historical levels in some pyromes but approach the estimated historical fire rotation in others. Despite large projected relative increases in burn probability in the Olympics and Puget Lowlands (+478%), the projected fire rotation for mid-century is over 1,000 years which still barely approaches historical estimates of 800 years for this region (Fahnestock & Agee, 1983). Mid-century projected fire rotations in the WA West Cascades are also longer than available historical estimates (610 vs. 465 years) from Mt. Rainier (Hemstrom & Franklin, 1982). Although the probability of large fires in these pyromes is low, the potential for very large high severity fires that occurred historically (Reilly, Zuspan, et al., 2022) still exists and has the potential to catalyze vegetation change (Crausbay et al., 2017). Historical fire rotation estimates from lower and middle elevation forests of western Oregon range from 78 to 149 years (Morrison and Swanson, 1990; Teensma, 1987), suggesting a return to the historical fire rotation for the OR West Cascades where fire has increased rapidly in recent decades. The WA North Cascades, however, have little evidence of large fires since the 1700s (Henderson et al., 1989). A future projected fire rotation of 110 years is far shorter than historical estimates for the WA North Cascades (Agee, 1993) and if realized is likely to have profound impacts on these forests. While these landscapes were resilient under fire regimes prior to Euro-American colonization, many landscapes are now dominated by young plantations, which are less resistant to

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fire than old growth under moderate fire weather conditions (Zald & Dunn, 2018). Furthermore, warming temperatures and increased water deficit are likely to continue to challenge forest resilience (Stevens-Rumann et al., 2018).

In the Olympics, WA North Cascades, and OR West Cascades, fires in the largest size class (>40,000 ha) were responsible for the greatest changes in number of fires per decade, as well as the proportion of total area burned (Figures 5 and 6). These projections are congruent with findings from McEvoy et al. (2020), which projected a doubling of mean fire size and number of fires by mid-century for a small portion of the OR West Cascades east of Portland. Although we did not find increases of the same magnitude for the number and size of fires in OR Coast Range and WA North Cascades, many individual GCMs still projected increases in the number of the largest fires; for WA North and West Cascades, nearly all of these GCMs were in the top 50% performance categories (Figures 5 and 6). Assessing changes to size and area burned for fires larger than 40,000 ha is potentially insightful for future fire severity on the Westside because fire size in this region (Reilly et al., 2017), as well as other regions (Cansler & McKenzie, 2014; Lutz et al., 2009; Miller et al., 2012) is highly correlated with size of high severity patches. The proportion of area burned at high severity has been variable in contemporary Westside fires, but the only five fires greater than 40,000 ha in the contemporary record (i.e., 2020 Labor Day fires) experienced from 50% to 70% high severity fire (Reilly, Zuspan, et al., 2022). Thus, larger fires are likely to equate to larger patches of high severity fire, which tend to have greater economic and social effects with greater suppression costs (Calkin et al., 2005). Additionally, larger patches of high severity fire have different ecological effects than smaller patches, particularly due to a larger area of interior where seeds have to travel greater distances to disperse and establish, and thus may take longer to regenerate than smaller patches (Romme et al., 1998).

In the three Cascade pyromes, our 30 km fire occurrence area (FOA) buffer extends over the Cascade crest into the adjacent Eastside forests where contemporary fires are more frequent and often larger (Figure 1); using a spatially aware fire spread model like FSim accounts for the probability and spread of Eastside fires over a topographically complex landscape, including transmission into Westside pyromes. Many of the largest fires simulated started on the Eastside and crossed the crest into the Westside, an effect that highlights spatial linkages between pyromes where greater lightning frequency and burn probabilities in the high-elevation forests east of the Cascade Crest result in increased fire activity in the WA West and North Cascades and OR West Cascades (Figure 1). In OR Coast Range, spread of large, frequent fires igniting in the part of the FOA buffer zone including the drier Siskiyou Mountains leads to higher burn probabilities in the southeast portion of the pyrome (Figure 1). The linkages we demonstrate between pyromes may play a particularly important role under east winds events when ignitions in drier landscapes have the greatest potential for spread to the Westside.

Our results suggest that seasonality of fire on the Westside will shift in the future, including a lengthening fire season window that would lead to larger and more frequent fires in the summer (especially for OR Coast Range and OR West Cascades) and the spring and autumn months (especially for the Olympics and WA North Cascades) (Figure 6). These types of trends have been observed and projected in interior and more fire-prone dry forests (Dong et al., 2022; Dye et al., 2023; Riley & Loehman, 2016), but are less well documented in moist temperate and maritime forests of the PNW (Halofsky et al., 2020). Synoptic dry east winds that drove the Labor Day 2020 fires in September and other historic large fires in the region (Morris, 1934) have a distinct late summer summer/early fall seasonality (Cramer, 1957) and are a primary concern. Wind events across the Westside are not expected to increase with climate change (Hawkins et al., 2022; Mass et al., 2022), nor did we incorporate future wind projections in our analysis. However, more fires burning into the historically windiest months could increase the likelihood of ignitions coinciding with dry east wind events. This was the case for the 2020 Beachie Creek Fire which started on August 16, as well as the more recent 2022 Cedar Creek Fire which started on August 1 on the Cascade Crest and ultimately burned >50,000 ha following an east wind event in early September (NWCC, 2023). There is currently limited historical precedent for major spring and autumn wind-driven fires in the Olympics and WA North Cascades, but this could change if these areas consistently experience more fire and fire-conducive weather during autumn.

Our update of fuel types to match post-2020 fire conditions led to substantial areas that were less burnable in FSim. This landscape configuration propagated through all of our future simulations since we retained the current landscape, limiting the potential for simulated fires in areas burned in 2020. However, moist temperate forests may be more flammable following fire until closed-canopy forest conditions reestablish (Whitlock et al., 2015) which may take four to six decades under historical conditions (Freund et al., 2014; Tepley et al., 2014). There is also precedent for early seral reburns following large high-severity fires in this region (Reilly, Zuspan, et al., 2022), but it is unknown how widespread this phenomenon was historically. Neiland (1956) found that maximum daytime summer temperatures were approximately 11°C warmer with 10% lower relative humidity in the reburns

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than in adjacent old-growth forests following a high severity fire in 1945 near Tillamook in the Oregon Coast Range. Warmer, drier conditions may increase the potential for burning in early seral landscapes where post-fire regeneration and vegetation rapidly establish in abundance. The OR West Cascades was by far the most heavily impacted pyrome in the Labor Day 2020 fires, and, since our calibration statistics included the 2020 fire season, it is possible that the lower proportional change we identified for OR West Cascades was due to its contemporary baseline period already having a set of extreme fires built in, in addition to lower burnability in areas affected by these fires, whereas other pyromes did not have a similar set of extreme fires in the historical record.

A caveat for our simulations is that we assumed the composition and structure of fuels will remain constant in the future. This assumption is plausible for a mid-century projection (Dye et al., 2023; McEvoy et al., 2020; Riley & Loehman, 2016), but vegetation is likely to change beyond that in ways that could alter ignition patterns and vegetation-climate-fire feedbacks in complex ways. For example, it is possible that instead of simply reducing fire by increasing fuel moisture, more precipitation could instead lead to greater vegetation productivity, thereby increasing the loading of fuels available to burn when droughts do occur (Ellis et al., 2021); similarly, enhanced variability of wet and dry spells could then lead to periods of high productivity followed by periods of intense drought (Swain et al., 2018). Climate change could also bring about entirely new vegetation structures (Clark et al., 2017; Kim et al., 2018) or facilitate introduction of invasive species (Tortorelli et al., 2022), both of which can alter fire regimes, and, in extreme situations, shift ignitions away from climate-limited toward fuel-limited. Some of our highest projected burn probabilities coincide with high-elevation, subalpine forests (Figure 1; see eastern reaches of WA West, North Cascades and OR West Cascades), which could exceed the capacity of these forests to handle fire and lead to vegetation conversion or loss, congruent with mechanistic models of vegetation change for the Westside that project loss of high-elevation forests in these same areas (Reilly, Zuspan, et al., 2022; Rogers et al., 2011).

Though not included in our modeling exercise, vegetation change and vegetation-fire feedbacks are also intertwined with land management and fuel treatment practices, which play a central role in development of forest structure and controls on fire spread and containment under climate change (Halofsky et al., 2020; Wimberly & Liu, 2014). Coupling vegetation change and management scenarios with fire simulation models is an important next step for future research. Additionally, we acknowledge several other interrelated environmental factors that could influence future fire regime change in unexpected ways in the future: changes in anthropogenic ignitions (Balch et al., 2017), lightning ignitions (Kalashnikov et al., 2023), microclimate conditions such as wind and solar radiation (De Frenne et al., 2021), and fire suppression and fuel treatment strategies (Pritchard et al., 2021).

5. Conclusions

Our study highlights the complexity and variability around potential future changes in fire changes in moist temperate forests of the Westside PNW. However, by assessing the effects of a suite of 12 different GCM-based climate projections on fire spread, we identified several common threads to inform expectations for future fire regime shifts on the Westside. Increases in fire are plausible in moist temperate forests, and likely based on agreement among better performing GCMs in the region - all pyromes showed the potential for extreme increases in fire relative to their current state; fire rotations are expected to shorten; very large fires could become more common across the entire Westside; and shifts to the seasonality of fire ignitions and size are likely. Each of these conclusions contributes actionable information for scientists and managers who are developing climate change adaptation strategies for Westside resources that will be affected by fire in the future. For example, managers may want to consider preparing for an increased frequency of larger fires and worst-case changes to Westside fire regimes, while also maintaining flexibility moving into a fluid and uncertain future. Building from our study, future modeling work incorporating projections of vegetation change, wind events, and socio-ecological impacts of a changing fire regime will generate valuable additional insights beyond what we have presented in this study.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Shapefiles of original pyrome boundaries for the United States can be accessed at www.fs.usda.gov/rds/archive/Catalog/RDS-2020-0020 (Short et al., 2020). The contemporary period fire occurrence database can be accessed at www.fs.usda.gov/rds/archive/catalog/RDS-2013-0009.6 (Short, 2022). Executable files for FSim, the large-fire simulator, can be obtained from www.firelab.org/project/fsim-wildfire-risk-simulation-software (FSim, 2023). All LANDFIRE data products used in creation of the landscape layers can be found here www.landfire.gov/index.php (LANDFIRE, 2020). Original downscaled GCMs for RCP8.5 emissions scenario can be found at www.nccs.nasa.gov/services/data-collections/land-based-products/nex-dcp30 (NASA, 2021). Software downloads for FireFamilyPlus version 5 software can be accessed at www.firelab.org/project/firefamilyplus (FireFamilyPlus, 2022). All maps were created in QGIS version 3.4.4 which can be downloaded at www.timdocs.qgitimdocs.qgis.org/en/site/forusers/download.html (QGIS.org, 2023). All figures were created in R version 4.2.3 which can be accessed at www.r-project.org (R Core Team, 2023). Data used to construct Table 1 can be downloaded at prism.oregonstate.edu (PRISM Climate Group, 2023). Weather data from Remote Automated Weather Stations (RAWS) used were obtained from the Western Regional Climate Center at raws.dri.edu (WRCC, 2021).

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