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REVIEW

Climate influences on future fire severity: a synthesis of climate-fire interactions and impacts on fire regimes, high-severity fire, and forests in the western United States

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Abstract

Background Increases in fire activity and changes in fire regimes have been documented in recent decades across the western United States. Climate change is expected to continue to exacerbate impacts to forested ecosystems by increasing the frequency, size, and severity of wildfires across the western United States (US). Warming temperatures and shifting precipitation patterns are altering western landscapes and making them more susceptible to high-severity fire. Increases in large patches of high-severity fire can result in significant impacts to landscape processes and ecosystem function and changes to vegetation structure and composition. In this synthesis, we examine the predicted climatic influence on fire regimes and discuss the impacts on fire severity, vegetation dynamics, and the interactions between fire, vegetation, and climate. We describe predicted changes, impacts, and risks related to fire with climate change and discuss how management options may mitigate some impacts of predicted fire severity, and moderate some impacts to forests, carbon, and vegetation changes post fire.

Results Climate change is increasing fire size, fire severity, and driving larger patches of high-severity fire. Many regions are predicted to experience an increase in fire severity where conditions are hotter and drier and changes in fire regimes are evident. Increased temperatures, drought conditions, fuels, and weather are important drivers of fire severity. Recent increases in fire severity are attributed to changes in climatic water deficit (CMD), vapor pressure deficit (VPD), evapotranspiration (ET), and fuels. Fire weather and vegetation species composition also influence fire severity. Future increases in fire severity are likely to impact forest resilience and increase the probability of forest type conversions in many ecosystems.

Conclusions Increasing warming and drying trends are likely to cause more frequent and severe disturbances in many forested ecosystems in the near future. Large patches of high-severity fire have lasting legacies on vegetation composition and structure, and impacts on tree regeneration. In some ecosystems and under certain fire-weather conditions, restoration and fuel treatments may reduce the area burned at high severity and reduce conversions from forest to non-forest conditions, increasing forest resistance and resilience to wildland fire. Thinning and prescribed fire treatments can be effective at reducing the potential for crown fire, reducing fuels, and promoting forest resilience.

Keywords Climate, Fire, Severity, Forests, Western US, Models, Forecast, Predict, Palabras clave, Clima, Fuego, Severidad, Bosques, Oeste de los EEUU, Modelos, Predicciones

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Resumen

Antecedentes Incrementos en la actividad de incendios y cambios en los regímenes de fuego han sido documentados en décadas recientes en todo el oeste de los EEUU. Se espera que el cambio climático continúe exacerbando su impacto en ecosistemas forestales del oeste de los EEUU, a través de un incremento en la frecuencia, tamaño, y severidad de los incendios. El aumento de la temperatura y cambios en los patrones de precipitación están alterando los paisajes del oeste y haciéndolos más susceptibles a incendios de alta severidad. El incremento de grandes parches ocasionados por fuegos muy severos puede resultar en impactos significativos en la estructura y composición de la vegetación. En esta síntesis, examinamos la influencia del cambio climático pronosticado, en los regímenes de fuegos y discutimos su impacto en la severidad de los incendios, en la dinámica de la vegetación, y en las interacciones entre el fuego, la vegetación y el clima. Describimos los cambios pronosticados, y el impacto y los riesgos relacionados a los incendios con el cambio climático, y discutimos como las diferentes opciones de manejo pueden mitigar algunos impactos en la severidad pronosticada, y moderar otros en el bosque, en el carbono y en otros cambios en la vegetación post fuego.

Resultados El cambio climático estaría incrementando el tamaño de los incendios, la severidad, y conduciendo a mayores parches de fuegos de alta severidad. Se pronostica a la vez, que muchas regiones donde las condiciones serán más cálidas y secas, experimentarán cambios evidentes en los regímenes de fuegos. Incrementos en las temperaturas, condiciones de sequía, combustibles, y situaciones meteorológicas predisponentes serán importantes condicionantes en la severidad de los fuegos. Incrementos recientes en la severidad de los fuegos son atribuidos a cambios en el déficit climático de humedad (CMD), en el déficit de vapor de difusión (VPD), evapotranspiración (ET), y combustibles. El Clima de fuego y la composición de especies también influencia la severidad del fuego. Incrementos futuros en la severidad del fuego podrían impactar en la resiliencia de los bosques e incrementar la probabilidad de su conversión a otros ecosistemas.

Conclusiones Las tendencias de incremento en las temperaturas y condiciones de sequía probablemente causen disturbios más frecuentes y severos en muchos ecosistemas boscosos en un futuro próximo. Grandes parches de alta severidad tienen legados duraderos en la estructura y composición de la vegetación e impactos en la regeneración de los árboles. En algunos ecosistemas proclives a incendios, y bajo ciertas condiciones atmosféricas, la restauración y tratamientos del combustible pueden reducir las áreas quemadas a alta severidad y también la conversión de bosques a condiciones de no-bosque, incrementando la resiliencia y resistencia de los bosques a los incendios de vegetación. Los raleos y tratamientos con quemas prescriptas pueden ser efectivos en reducir la probabilidad de producirse fuegos de copas, reducir la carga de combustibles, y promover la resiliencia de los bosques.

Introduction

Fire is a keystone process in many ecosystems and affects forest structure, species composition, carbon storage, soils, and wildlife habitat. Ecosystems are adapted to particular fire regimes that control the seasonality, pattern, frequency, and severity of fire within the system. Climate change is influencing fire regimes and impacting landscape processes and ecosystem functions. Fire activity is increasing globally (Bowman et al. 2011), and warming temperatures and increasing aridity are influencing patterns of fire activity across the western United States (Littell et al. 2009; Higuera et al. 2015; Abatzoglou and Williams 2016; Williams and Abatzoglou 2016; Abatzoglou et al. 2017). Higher temperatures can lead to an increase in fire ignitions and a faster rate of fire spread due to decreased fuel moisture and extreme fire weather conditions (Abatzoglou and Williams 2016; Westerling 2016). Altered fire regimes can increase the vulnerability of these systems to vegetation type conversions, invasive species, reduce carbon stocks, impact wildlife habitat and watershed health, and directly affect human infrastructure (Hurteau and Brooks 2011; Moody et al. 2013; Calkin et al. 2014; Johnstone et al. 2016; Walker et al. 2018; Stevens-Rumann et al. 2018; Coop et al. 2020).

Increases in area burned by wildland fire across the western US have been documented since the 1980s and have been linked with warmer and drier conditions (Dennison et al. 2014; Abatzoglou and Williams 2016; Westerling 2016). The total area burned and area burned at high severity has increased in forest and woodland ecosystems across the western US (Littell et al. 2009; Dillon et al. 2011; Miller and Safford 2012; Singleton et al. 2019). Furthermore, over the past several decades, there has been a well-documented increase in the number of large fires (Westerling et al. 2006; Miller et al. 2009a, b; Dennison et al. 2014; Singleton et al. 2019), and increased fire-season length (Westerling et al. 2006). An increased shift in fire activity across the western US since the year 2000 has been noted in long-term datasets that examine temporal trends in fire severity (Abatzoglou and Williams 2016; Dillon et al. 2011; Mueller et al. 2020), as well as a documented increase in high-severity fire across many regions (Singleton et al. 2019; Parks and Abatzoglou 2020; Huang et al. 2020; Mueller et al. 2020) (Fig. 1). Warming temperatures and an earlier onset of snowmelt have increased the length of fire seasons and lowered fuel moisture in many regions, allowing large extents of the western US landscape to remain dry and flammable for longer periods of time (Westerling et al. 2006; Miller et al. 2012).

Several studies have quantified the temporal trends in annual fire severity (Dillon et al. 2011; Miller and Safford 2012; Miller et al. 2012; Stevens et al. 2017; Reilly et al. 2017; Singleton et al. 2019; Parks and Abatzoglou 2020). Typically, patterns of fire behavior are driven by topography, fuels, and weather. However, over the long-term climate change is impacting plant productivity and moisture availability, and thus influencing the amount of fuels and available biomass on the landscape and changing fire regimes (Fig. 2) (Krawchuck and Moritz 2011; Parks et al. 2014; Abatzoglou et al. 2018). Examining the climatic influence on fire severity is important to understanding how wildland fire is impacting ecosystems, and how that may change with hotter and drier conditions (Abatzoglou et al. 2017; Keyser and Westerling 2017; Mueller et al. 2020). Additionally, an increase in human ignitions and values at risk is increasing, and understanding how to allocate fire resources and funds is necessary. Long-term climatic variables coupled with fire perimeter data can elucidate contemporary climate-fire interactions and model future predicted fire severity (Parks et al. 2016). Regional fuel conditions and climate conditions can lead to both increases and decreases in fire activity under future climate conditions, but less is known about the influence of climate change on fire severity.

In this synthesis, we review the relevant body of literature and discuss the forecasted impacts of climate

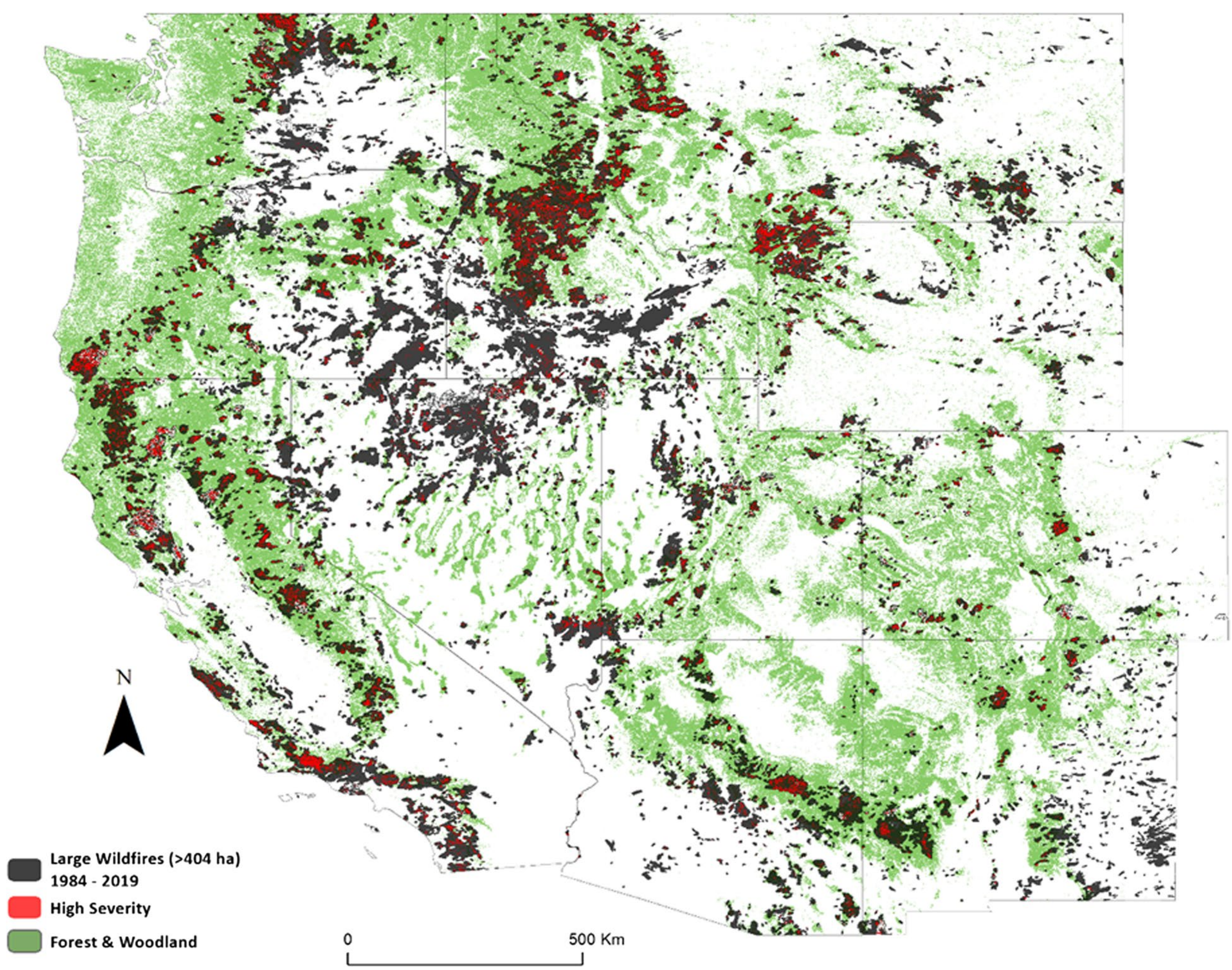

Fig. 1 Map of large fires (≥ 404 ha or 1000 acres; MTBS 2014) across western US forests and woodlands (USGS 2016) 1984–2019. Area burned at high severity is highlighted in red

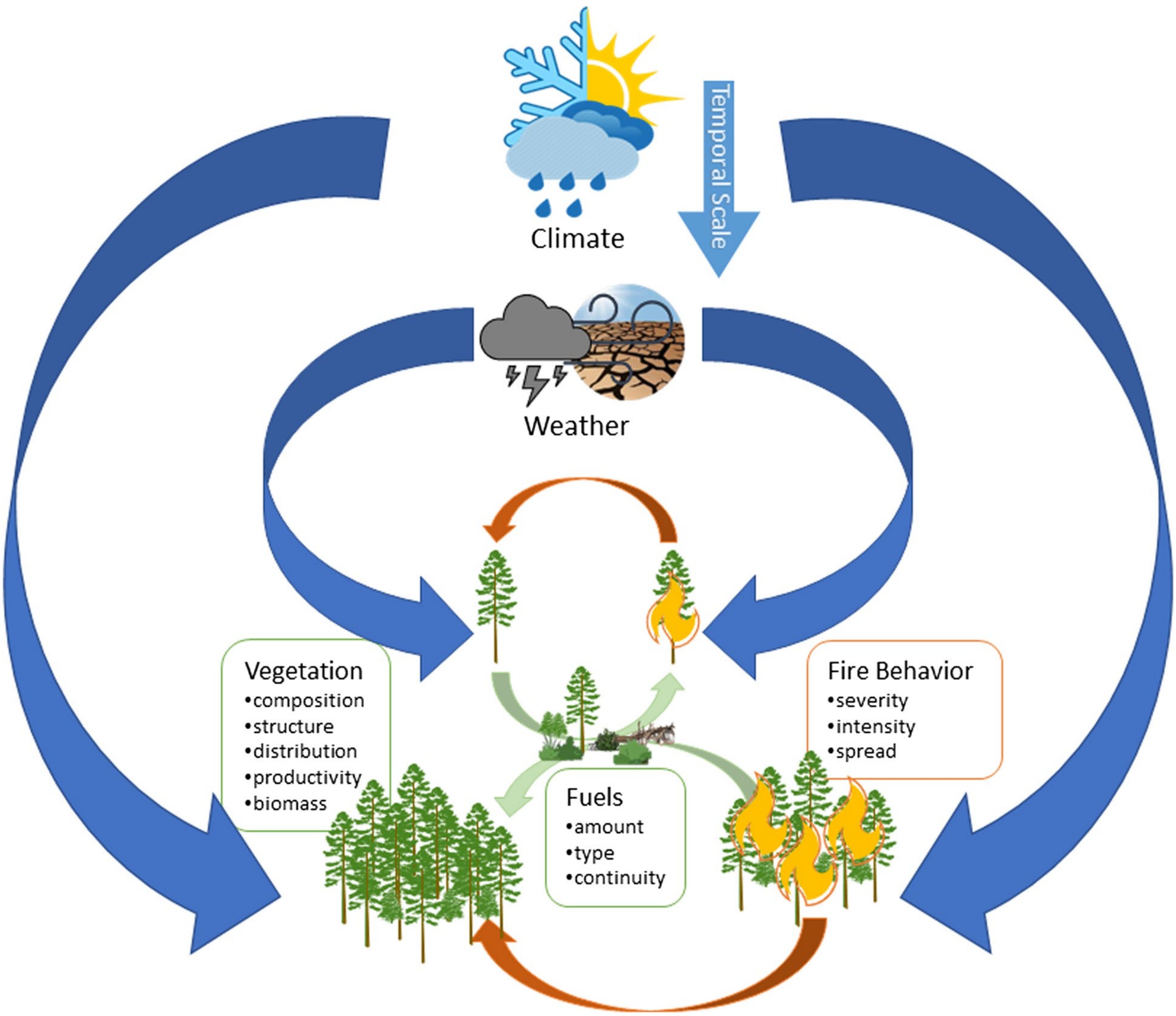

Fig. 2 Patterns of vegetation are driven by climate and fire. At long temporal scales, climate, vegetation, fuels, and weather all influence fire behavior on the landscape, including fire intensity, severity, and spread. Climate directly influences vegetation patterns and fuel characteristics across the landscape. Climate and weather drive fuel flammability, fire behavior, and fire patterns at the scale of the fire and on shorter temporal scales

change on fire severity across forests in the western US. We assessed published papers that used empirical and simulation models to project future fire severity with respect to climate change effects. These simulations explicitly model the climatic influence on fire and fire regimes across western US forests, and discuss the impacts on fire severity, vegetation dynamics, and the interactions between fire, vegetation, and climate. We describe predicted changes, impacts and risks related to fire with climate change, and discuss how management options may mitigate impacts of high-severity fire where it is not desired. We then discuss what effects fuel and restoration treatments can have on fire severity, forest resilience, and forest carbon.

Methods

We used evidence-based review protocols (Pullin and Stewart 2006; Lortie 2014) to find the relevant body of literature that exists on this subject area. Keyword search strings and multiple databases were used to identify relevant publications on climate-fire interactions and climate impacts on fire severity (Table 1). Five independent online science-based search engines were examined, (CAB Abstracts, ProQuest, BIOSIS, Web of Science, and Google Scholar), and the literature cited sections of relevant publications prior to April 2022. We required that papers included in this synthesis specifically model climate influence on fire severity were focused in western US forests and were

Table 1 Search string included in literature search

The search strings included: "climate change" OR climate-change OR "climate changes" OR "global warming" OR "climatic change" OR "climatic changes" OR "climate warming" OR "warming climate" OR "warmer climate" OR "increasing temperatures" OR "increased temperatures" OR "increasing temperature" OR "increased temperature" OR "climate effects" OR "climatic effects" OR "changing climate" AND fire OR wildfire OR fires OR wildfires AND severity OR "high severity" OR high-severity OR "low severity" OR low-severity OR "mixed severity" OR mixed-severity OR "surface severity" OR surface-severity OR "high fire severity" OR "low fire severity" OR "mixed fire severity" OR "mixed-fire severity" AND "southwestern united states" OR "western united states" OR "southwestern U.S." OR "western U.S." OR "american west" OR "american southwest" OR "southwest united states" OR "southwest U.S."OR Arizona OR "New Mexico" OR Colorado OR Utah OR Wyoming OR California OR Nevada OR Montana OR Idaho OR Oregon OR Washington OR "mountain states of USA" OR "Western states of usa" OR "southwestern states of usa" OR "pacific northwest" OR "western US" OR "southwestern US" OR "southwest US".

published in refereed journal articles. The potentially relevant publications were then screened to eliminate those that did not meet our inclusion criteria, and the remaining papers were searched to determine if all criteria were met.

We assessed the body of literature the search identified within the five science-based databases examining climatic influences on fire severity. We added additional papers not found in our search strings but were later found to be relevant subject matter. In this synthesis, we discuss how high-severity fire is measured and defined, examine the climatic influence on fire regimes, and review the types of fire-climate models. We then synthesize modeling studies of future projections of climatic influence on high-severity fire. We discuss climate-induced shifts in fire severity, climate-fire-vegetation dynamics, and discuss fuel and restoration treatment effects on fire severity and forest resilience (Table 2).

Results

Synthesis of the literature

High-severity fire

Fire severity is defined as the effect of fire on the environment, and characterizes the amount of ecosystem change caused by fire (Key and Benson 2006; Lentile et al. 2006). Fire severity is measured by the degree of fire-induced change and includes the loss of vegetation above and belowground, and soil impacts (Key and Benson 2006; Miller and Thode 2007; Keeley 2009). Soil burn severity is measured as the estimated effect of heat transfer from vegetation burning on the surface and the combustion of organic material into the soil layers (Keeley 2009). High-severity fire commonly creates large areas of overstory tree mortality, extensive soil damage, and vulnerability to extreme hydrologic events (Neary et al. 1999; Yocom-Kent et al. 2015). Fire severity can be measured via field-based metrics or satellite-derived imagery. Field-based measurements of fire severity identify total fire effects following a fire occurrence (e.g., soil organic matter loss, vegetation mortality, tree scorching) (Key and Benson 2006; De Santis and Chuvieco 2009). Satellite-derived indices are based on the relationships between remotely sensed spectral indices, where the difference between pre- and post-fire spectral characteristics is evaluated from satellite images (e.g. Landsat). These indices include the relativized burn ratio (RBR), delta normalized burn ratio (dNBR), and its relativized form (RdNBR); such indices typically quantify fire severity as the degree of fire-induced change to vegetation and soils, as inferred from changes in surface reflectance in the near-infrared and shortwave infrared portions of the electromagnetic spectrum (Key and Benson 2006; Lentile et al. 2006; Miller and Thode 2007; De Santis and Chuvieco 2009; Parks et al. 2014). Maps of wildfire burn severity show the immediate fire effects and long-term ecosystem changes and are often used to mitigate post-fire effects, are used in monitoring wildfire effects and patterns, and in future fire planning (Robichaud et al. 2007). The Monitoring Trends in Burn Severity (MTBS) is a platform that maps fire severity and extent of large fires ($\geq$404 ha, or 1000 acres) across all lands of the United States from 1984 to present and provides data to public users (Eidenshink et al. 2007; Picotte et al. 2020) (www.mtbs.gov). The Rapid Assessment of Vegetation Condition after Wildfire (RAVG) provides burn severity and vegetation conditions after large wildland fires ($\geq$404 ha, or 1000 acres)

Table 2 Studies and data used in our synthesis with geography, climate data, and model information

Study	Geography	Forest type	Forecast time period	Elevation (m)	Study extent (km)	GCMs in model	Climate scenario	Climate Variables used in model	Model Used
Cassell et al. 2019. Widespread severe wildfires under climate change lead to increased forest homogeneity in dry mixed-conifer forests	Southern Blue Mountains of central Oregon	Mixed conifer	2010–2100	719–2744	9388	Range of 20 CIMP5	Contemporary, RCP 4.5 and RCP 8.5	maximum temperature, minimum temperature, average precipitation, daily average wind speed, wind direction	LANDIS II Dynamic Fire and Fuels extension
Hansen et al. 2020. Can wildland fire management alter 21st-century subalpine fire and forests in Grand Teton National Park, Wyoming, USA?	Grand Teton NP, WY	Mixed conifer	2018–2098	1600–3400	400	CNRM-CM5, GFDL-ESM2M	RCP 4.5 and RCP 8.5	KBDI, daily temperature, precipitation, vapor pressure deficit, solar radiation	iLand
Honig and Fulé 2012. Simulating effects of climate change and ecological restoration on fire behavior in a southwestern USA ponderosa pine forest	Kaibab National Forest, AZ	P. pine	2070–2099	2067–2184	7	CSIRO:MK3 (least extreme model); MPIM:ECHAM5 (most extreme model)	A1B	temperature, relative humidity, 1-h fuel moisture, 10-h fuel moisture, 100-h fuel moisture, wind speed	ANOVA, Tukey HSD mean comparison
Hurteau 2017. Quantifying the Carbon Balance of Forest Restoration and Wildfire under Projected Climate in the Fire-Prone Southwestern US	Northern AZ, Camp Navajo	P. pine	Early (2010–2019), mid (2050–2059), and late (2090–2099) century	2164	116	Range of 41 CIMP5	RCP 8.5	Mean monthly minimum temperature, mean monthly maximum temperature, mean monthly precipitation	LANDIS II Dynamic Fire and Fuels extension

Table 2 (continued)

Study	Geography	Forest type	Forecast time period	Elevation (m)	Study extent (km)	GCMs in model	Climate scenario	Climate Variables used in model	Model Used
Krofcheck et al. 2017a. Prioritizing forest fuels treatments based on the probability of high-severity fire restores adaptive capacity in Sierran forests	Sierra Nevada, CA	Oak, p. pine, mixed conifer	1950–2100	300–3000	875	CIMP5: CCSM4, CNRM-CM5, FGOAL-g2S, GFDL, MICROC5-ESM 2	RCP 8.5	temperature, precipitation	LANDIS II Dynamic Fire and Fuels extension
Krofcheck et al. 2017b. Restoring surface fire stabilizes forest carbon under extreme fire weather in the Sierra Nevada	Sierra Nevada, CA	Mixed conifer	1980–2015 to 2100	300–3000	875	NA	contemporary, extreme	temperature, precipitation	LANDIS II Dynamic Fire and Fuels extension
Krofcheck et al. 2019. Optimizing Forest Management Stabilizes Carbon Under Projected Climate and Wildfires	Sangre De Cristo mtns, NM	PJ, P. Pine, Mixed conifer	2000–2050	1900–3700	450	CIMP5: CCSM4, CNRM-CM5, FGOAL-g2S, GFDL, MICROC5-ESM 2	RCP 8.5	temperature, precipitation	LANDIS II Dynamic Fire and Fuels extension
Liang et al. 2018. Large-scale restoration increases carbon stability under projected climate and wildfire regimes	Sierra Nevada, CA	Forested areas	2010–2100	165–4230	34,000	GFDL, CCSM3, CNRM	A2	temperature, precipitation	LANDIS II Dynamic Fire and Fuels extension
Loehman et al. 2018. Can Land Management Buffer Impacts of Climate Changes and Altered Fire Regimes on Ecosystems of the Southwestern United States?	Jemez Mountains, NM; Kaibab Plateau, AZ	Ponderosa pine; dry-mixed conifer	2015–2115	1500–3500 (Jemez), 1439–2830 (Kaibab)	1800 (Jemez), 3350 (Kaibab)	CCSM4 (warm-dry), HadGEM2ES (hot-arid)	RCP 4.5 and RCP 8.5	temperature, precipitation	LANDIS II Dynamic Fire and Fuels extension, FireBGCv2

Table 2 (continued)

Study	Geography	Forest type	Forecast time period	Elevation (m)	Study extent (km)	GCMs in model	Climate scenario	Climate Variables used in model	Model Used
Loudermilk et al. 2017. Bending the carbon curve: fire management for carbon resilience under climate change	Lake Tahoe Basin, CA, NV	Jeffrey pine and dry-mixed-conifer	2010–2110	1897–3320	850	GFDL	A2 (high), B1 (moderate)	temperature, precipitation	LANDIS II Dynamic Fire and Fuels extension
Lutz et al. 2009. Climate, lightning ignitions, and fire severity in Yosemite National Park, California, USA	Yosemite NP, CA	P. pine, dry mixed conifer	2020–2049	657–3997	30.27	HadCM3	B1	1 April SWE	Linear regression
O'Conner et al. 2020. Projected Climate-Fire Interactions Drive Forest to Shrubland Transition on an Arizona Sky Island	Sky islands. Huachuca mtns and Madrean Sky islands, AZ	Forests and woodlands	2005–2055	1199–2855	not specified — Huachuca Mountains	CanESM2, HadGEM2-CC, HadGEM2-ES	RCP 8.5	maximum temperature, minimum temperature, average precipitation	FireBGCv2
O'Donnell et al. 2018. Forest restoration as a strategy to mitigate climate impacts on wildfire, vegetation, and water in semiarid forests	Kaibab Plateau, AZ	Forests and woodlands	2010–2110	1439–2830	330	17 GCMs	RCP 4.5 and RCP 8.5	temperature, wind speed, wind direction, relative humidity, precipitation	LANDIS II Dynamic Fire and Fuels extension
Parks et al. 2016. How will climate change affect wildland fire severity in the western US?	Western US	Forested ecosystems	2040–2069	Conterminous	500km^2 hexels; 27 ecoregions	20 GCMs	RCP 8.5	Actual Evapotranspiration (AET), water deficit (WD), Annual precipitation (PPT), soil moisture (SMO), snow water equivalent (SWO)	Boosted regression trees

Table 2 (continued)

Study	Geography	Forest type	Forecast time period	Elevation (m)	Study extent (km)	GCMs in model	Climate scenario	Climate Variables used in model	Model Used
Parks et al. 2018b. Analog-based fire regime and vegetation shifts in mountainous regions of the western US	Western US	Forested ecosystems in mountainous regions	Early (2011–2040,) mid (2041–2070), late (2071–2100)	Conterminous	1km^2; 17 ecoregions	15 CMIP5 GCMs	RCP 8.5	Climatic moisture deficit (CMD) and Evapotranspiration (ET); focus on water balance	LANDFIRE data. Next Gen Fire Severity Mapping
Parks et al. 2019. Living on the edge: trailing edge forests at risk of fire-facilitated conversion to non-forest	Western US	Forested ecosytems	Mid-century 2040–2070	Conterminous	1 km pixel; 8 ecoregions	15 CMIP5 GCMs	RCP 8.5	Climatic moisture deficit (CMD) and Evapotranspiration (ET); focus on water balance	LANDFIRE data. Next Gen Fire Severity Mapping
Serra-Diaz et al. 2018. Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century	Klamath, OR and CA	Mixed conifer	2015–2100	100–2000	29,400	ACCESS 8.5 (much hotter-drier), CanESM2 (much hotter-wetter), CNRM-CM5 4.5 (hotter-wetter), MIROC5 2.6 (mild hot-wetter)	RCP 4.5 and RCP 8.5	temperature, precipitation	LANDIS II Dynamic Fire and Fuels extension

on national forests system lands only (https://burnseverity.cr.usgs.gov/ravg/).

Fire severity is scale dependent and influenced by vegetation type, fire history, accumulation of forest fuels, topography, fire weather, climate, dry fuel conditions, and past management (Dillon et al. 2011; Mallek et al. 2013; Harris and Taylor 2015; Hessburg et al. 2015; Fang et al. 2015; Parks et al. 2014, 2018a; Stevens-Rumann et al. 2016; Keyser and Westerling 2017). At a coarse scale (e.g. ecoregions), high-severity fire is associated with fuel characteristics, fire weather (Keyser and Westerling 2017; Parks et al. 2018a), vegetation management (Prichard and Kennedy 2014), topography (Dillon et al. 2011), and climatic variables (e.g. climatic moisture deficit, evapotranspiration, mean temperature) (Parks et al. 2018b). Current live vegetation on the landscape is an important driver of fire severity across many ecoregions (Parks et al. 2018a; Singleton et al. 2019), and management efforts to reduce live fuels in high-risk landscapes via fuel treatments, prescribed fire, and managed wildland fire have the potential to reduce fire severity (Prichard et al. 2020; Cansler et al. 2022). Spatial variation in fire severity is a result of fire intensity and spread across the landscape. Across the West, topography and climate interact and influence fire extent and burn severity (Taylor and Skinner 2003; Dillon et al. 2011), where topography influences the spatial distribution of vegetation and fuels, fuel moisture, and temperature (Dillon et al. 2011). Increasing areas of high-severity fire can occur when a greater area is burned at a constant proportion of high-severity fire. The mosaic of severely burned, lightly burned, and unburned forest patches drives the future configuration of forest structure and succession (Turner et al. 1997). The burn mosaic and fire severity patterns can drive ecosystem responses to fire events (Hollingsworth et al. 2013; Liu et al. 2014; Turner 2010), such as post fire vegetation, impact soil erosion, and the ability of a forested patch to remain forested. High-severity fire is a natural component of certain ecosystems; however, the increasing occurrence of large patches of high-severity fire is becoming more prevalent and can have lasting legacies on vegetation composition and tree regeneration patterns (Miller et al. 2012; Abatzoglou and Williams 2016; Westerling 2016). High-severity fire can alter the trajectory of vegetation recovery post-fire (Turner 2010; McKenzie et al. 2011; Meng et al. 2015), and with compounding climate and drought impacts the risk of vegetation type change occurring on post-fire landscape increases.

Fire behavior is influenced by vegetation type, fuel loading, terrain, and fire weather, and these factors cause heterogeneity in fire severity across a landscape during a fire event. Wildland fire often exhibits high inter-and intra-fire heterogeneity, burning with varying degrees of severity (Lentile et al. 2007) depending on fuel load, vegetation type, topography, climate, and weather (Cansler and McKenzie 2014; Harvey et al. 2016). Topography impacts vegetation type and growth, and fire behavior on different topographic features (Dillon et al. 2011; Povak et al. 2018), while the interaction among climate, weather, and fuels drives fire behavior. Topography affects the spatial distribution of fuels and local wind and weather patterns at a fine scale. Fire behavior is complex, and fire severity is difficult to predict during extreme fire years with many large fires (Dillon et al. 2011; Parks et al. 2018a).

Climate influence on fire

Climate is an important driver of variability in fire activity in the western US at annual, decadal, and centennial time scales (Swetnam and Betancourt 1990; Littell et al. 2009; Kitzberger et al. 2007; Marlon et al. 2012; Margolis et al. 2017). General circulation models (GCMs) consistently project increasing temperatures in North America through the end of the 21st century, with a greater proportion of precipitation falling as rain rather than snow and an earlier onset of snowmelt, resulting in longer fire seasons in the western US (Scholze et al. 2006; Littell et al. 2009), and global climate models predict -4.7 to +13.5% change in precipitation (Mote et al. 2014). Climate models predict an increase in temperature western-wide. By 2100, temperatures in the western US are expected to increase in the Northern Rockies (+5 °F to 12 °F) (Stocker et al. 2013), Interior Rockies (+5.5 °F to 9.5 °F) (Lukas et al. 2014), Northwest (+2°F to 5.4 °F) (Mote et al. 2014), Southwest (+5 °F to 12 °F) (Cayan et al. 2013), California Sierra Nevada (+5 °F to 10 °F) (Reich et al. 2018), and coastal California (+2 °F to 4 °F) (Pierce et al. 2018) (Fig. 3). Models agree that extreme precipitation and disturbance events will increase, and the length of time between precipitation events will increase (Mote et al. 2014; Easterling et al. 2017). These models assume temperature change and representative concentration pathways (RCP; emission scenarios) RCP 4.5 (moderate emission scenario) and RCP 8.5 (highest emission scenario) (Moss et al. 2010) using global climate model CM3.

Contemporary climate is influencing fire severity causing both increases and decreases in severity across ecoregions and varies along a moisture gradient (Parks et al. 2016). Increased climate-water deficit (CWD) and vapor pressure deficit (VPD) can increase fire frequency and decrease vegetation productivity in water-limited regions of the western US (Parks et al. 2016; Mueller et al. 2020), and can reduce the amount of biomass available on a landscape to burn, reducing fire severity. Long-term increases in minimum temperature and climate-water

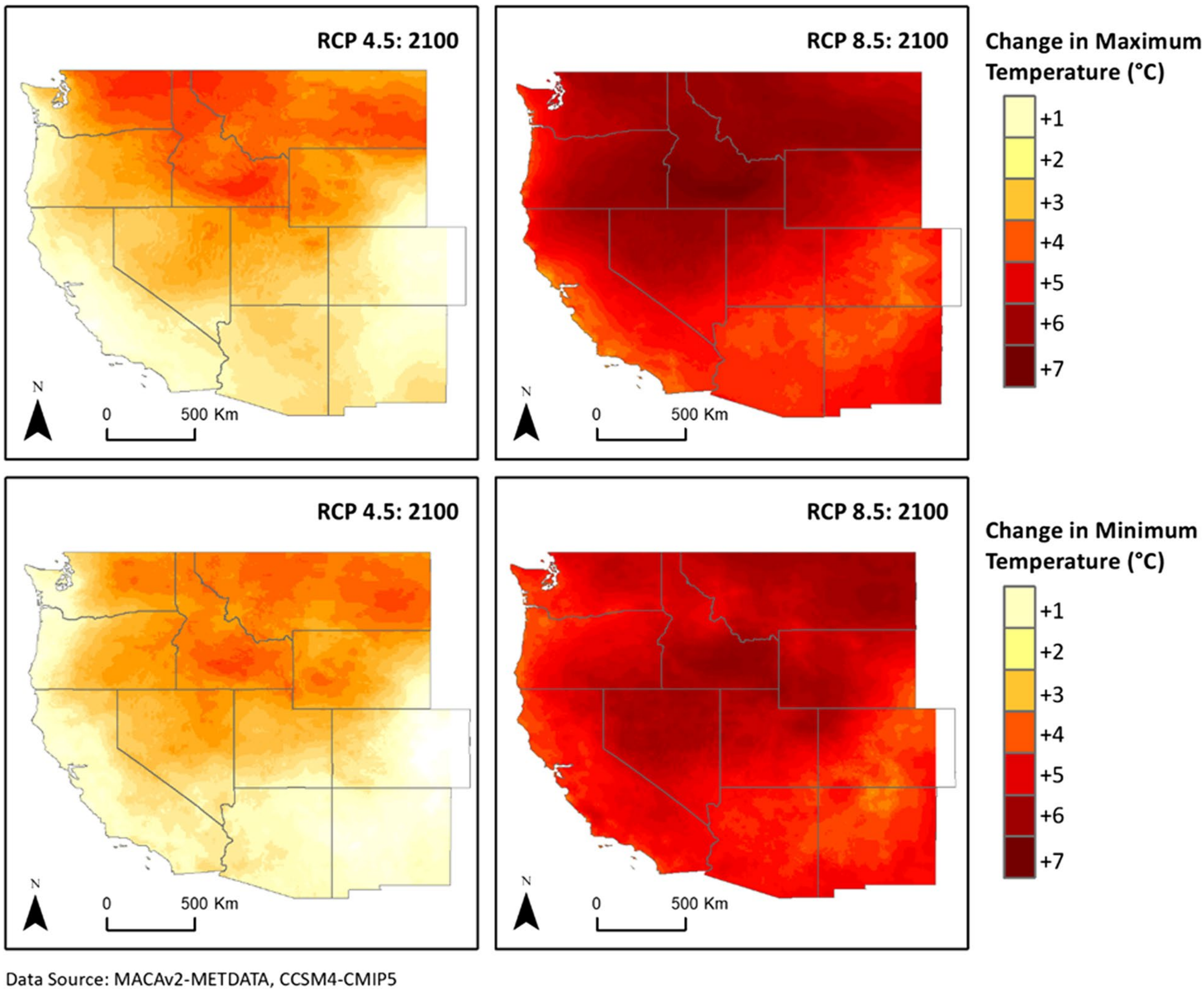

Fig. 3 Forecasted change relative to the historical aggregated mean (1995–2005) in maximum and minimum temperature (°C) for the western US in 2100. This data used climate model CCSM4, representative concentration pathways RCP 4.5 (moderate) and RCP 8.5 (high), within the CMIP5 experimental framework (data provided by google earth engine, University of California Merced, and University of Idaho)

deficit have been found to drive the increased percentage of area burned at high severity, and areas that burned had a higher climatic water deficit and lower fuel moisture (Huang et al. 2020). Annual area burned by wildland fire across the western US is projected to increase up to five times of that observed in 1961–2004 by the year 2039 (Kitzberger et al. 2017), and fire seasons have become 2–3 months longer when compared to previous decades (Jolly et al. 2015).

Forest fuels on the landscape are an important component of fire severity and are influenced by precipitation and temperature. Increased temperatures and low precipitation drive forest fuel availability, fuel moisture, and fuel flammability, and is an important component to fire regimes and fire severity (Krawchuck and Moritz 2011; Pausas and Paula 2012). Fuel moisture is driven by long-term climate coupled with low precipitation and higher temperatures that dry out fuels on the landscape. Leaf water content (normalized difference moisture index, NDMI) has been found to be a driver of fire severity (Estes et al. 2017; Parks et al. 2014). Climate drivers interact with fuel amount and continuity across the landscape and are often confounded by interannual climate variability (Abatzoglou et al. 2018). Decades of fire exclusion, logging activity, grazing, and management practices have promoted a build-up of fuels and high tree densities in many areas, increasing their susceptibility to large-scale, high-severity fire (Hagmann et al. 2014; Hessburg et al. 2015). Vegetation management activities (Thompson et al. 2007; Prichard and Kennedy 2014) and the presence of previous fire (Parks et al. 2014; Stevens-Rumann et al. 2016) have been shown to reduce fire severity.

Drivers of fire severity in the western US include temperature, water deficit, drought conditions, fire weather and relative humidity, and seasonal precipitation. Temperature is often correlated with fire extent and severity in the western US (Westerling et al. 2006) and relative humidity controls fuel moisture and consequently fire behavior (Brown et al. 2004; Westerling et al. 2011). Fire severity can vary with short-term weather, temperature extremes, and can be exacerbated by drought conditions. High temperature and precipitation extremes intensify droughts and the climate moisture deficit (Diffenbaugh et al. 2015), which can increase burn severity (Crockett and Westerling 2018). The relationship between drought and fire is complex, and the frequency and intensity of drought events impact fuel flammability and fire behavior. Fire size and area of high-severity fire were found to be greater during drought events than moderate or wet periods across the western US (Crockett and Westerling 2018). However, a wet spring followed by a period of dry months can bring abundant fuels and understory conditions that then rapidly dry out, leading to larger fires. Wetter conditions may promote the production of fine fuels that can promote fire during subsequent drought years (Jin et al. 2014). Alternatively, prolonged drought conditions and lack of precipitation can reduce the availability of forest fuels, thus limiting fire occurrence and leading to less severe fire in ecosystems that then become fuel and biomass limited. Long-term drought conditions have delayed effects on forest conditions and fuels and can intensify fire risk and fire severity (van Mantgem et al. 2013). The interaction of drought and fire also impacts vegetation recovery post fire. Regional and global circulation patterns (e.g., El Nino Southern Oscillation (ENSO), Pacific decadal oscillation (PDO)) drive drought severity and extent, while local factors like topography control drought impacts at a particular location (McCabe et al. 2004).

There are significant interactions and feedbacks between climate, fire, and vegetation. Climate change and human influence have shifted fire regimes, which consequently impacts the vegetation and fuels on the landscape (Westerling et al. 2006; Westerling 2016; Abatzoglou and Williams 2016; McKenzie and Littell 2017) (Fig. 2). Climate variables such as precipitation and temperature drive the local and regional water-balance, which affects fire occurrence, spread, and severity via effects on fuel moisture, abundance, and distribution (Mueller et al. 2020). Climate directly influences fire regimes by influencing fire season length and fuel moisture (Pausas and Paula 2012; Jolly et al. 2015; Holden et al. 2018), and via its influence on vegetation productivity (Krawchuk et al. 2009). Fire modifies vegetation composition and structure, including effects on fuel type and amount, connectivity of fuels, and fuel moisture (Krawchuk et al. 2009; Holden et al. 2018). These factors then shape the spread and severity of subsequent fires (Westerling 2016; Parks and Abatzoglou 2020). The strength of fire-vegetation feedbacks is influenced by climate and can be either positive or negative. A severe fire can convert a forested landscape into drier shrub-dominated landscapes that have continuous fuels (Tepley et al. 2017). This post-fire vegetation is easily burned in a subsequent fire, thus driving a positive feedback where non-forest conditions persist. Alternatively, severe fire can convert forests to early-seral vegetation that is less flammable, reducing the risk for a subsequent severe fire (Tepley et al. 2017; Coop et al. 2020). The strength of the feedback is driven by climate and drought. Warmer and drier climate conditions may reduce vegetation growth with less vegetation and fuels available to burn, and these areas then become biomass limited, and fire risk decreases (Parks et al. 2016). Warming and drying trends can delay forest recovery and tree seedling establishment and growth, and via the unavailability of seed sources in large patches of high-severity fire (Chambers et al. 2016; Stevens-Rumann and Morgan 2019).

The effects of climate on forest dynamics and fire regimes have the potential to cause large shifts in tree species distribution and vegetation composition (Liang et al. 2017; Mathys et al. 2016; Serra-Diaz et al. 2018; Cassell et al. 2019). Wildland fire and drought can cause shifts towards altered vegetative communities (Parks et al. 2018a), and forested ecosystems may often experience lagged responses to climate change (Bertrand et al. 2011; Liang et al. 2016). The interaction of climate, fuels, topography, vegetation, and weather is complex and can impact fire severity in multiple ways. Higher temperatures cause extensive drying of forest fuels, making western ecosystems more flammable during extended fire season lengths (Abatzoglou and Williams 2016). High spring and summer temperatures combined with previous-year or current year drought conditions can drive regional variations in large fire occurrence and extent, driven by the drying of forest fuels (Westerling et al. 2006; Heyerdahl et al. 2008; Littell et al. 2009; Westerling 2016). Projected hotter and drier conditions across some areas in the western US may directly increase fire severity by drying out fuels and vegetation, with dry years experiencing higher burn severity than wet years.

Understanding annual trends in area burned and area burned at high severity can aid in understanding patterns and drivers, and identify refugia. Few west-wide analyses exist, and responses vary by ecoregion. Parks and Abatzoglou (2020) quantified the annual area burned and annual area burned at high severity from 1985–2017. They examined four ecoregions (Northern mountains, Western mountains, Southwest, and California Coast) and found that all ecoregions except the California Coast experienced an increasing positive trend in annual area burned and annual area burned at high severity. This trend was substantial across western US forests, where the area burned at high severity increased by 184,000 ha (454,674 acres). By ecoregion, mean annual area burned at high severity increased by at least 35,000 ha (86,487 acres) from 1984 to 2017. Annual mean fire severity and the annual proportion of area burned at high severity increased in both the Northern mountains and Southwest ecoregion. These trends in increasing high-severity area were positively correlated with mean maximum vapor pressure deficit, mean maximum temperature, and climatic water deficit. Warmer and drier conditions were evident from 1985 to 2017 in the CA Coast, Northern mountains, and Western mountains regions, as well as the broader western US These warmer and drier fire seasons corresponded to more high-severity fire across the western US (Parks and Abatzoglou 2020).

Fire-climate models

Fire-climate models are used to predict future fire severity with climate change variables. These models help elucidate the potential effects of changing climatic conditions, vegetation dynamics, fire weather, and landscape conditions on future fire frequency and fire severity. Satellite-derived fire severity data such as MTBS, other platforms (e.g. RAVG, LANDFIRE) and other derived data products (e.g. Parks et al. 2018b) are common post-fire data products used in models. Empirical models use the statistical relationship between observed historical climate and historical area burned during the recent past (the last 100 years) to predict future area burned and area burned at high severity. Predicted future area burned and fire severity are based on modeled projections of precipitation and temperature from global climate models or regionally downscaled models. Some of these models account for previous fires or changes in vegetation post-fire. Machine learning statistical models can be used to model how fine-scale environmental variables control the spatial and temporal patterns of fire severity. Models can also identify the relative importance of key drivers of fire severity and how they may change under changing wet and dry conditions. Mechanistic models include the interactions of vegetation, climate, and fuels under changing and novel future climate conditions. These models are complex and link climate, weather, and fuel patterns to fire frequency and area burned. Some mechanistic models that simulate fire include dynamic global vegetation models, such as LANDFIRE NextGen (Parks et al. 2014, 2018b), LANDIS-II (Scheller and Mladenoff 2008), FireBioGeoChemical (Fire-BGCv2; Keane et al. 2011), and Individual-based Forest Landscape and Disturbance Model (iLand) (Seidl et al. 2012, Seidl and Rammer 2019).

Future projections of wildland fire with climatic influence: impacts on fire severity, fire regime, and vegetation dynamics

Models help elucidate potential changes in fire severity under predicted changing climate. Notably, fire-climate models often aim to project future fire severity and impacts on the landscape processes, including vegetation, carbon dynamics, and forest resilience. In this review, we focused on models that predicted fire-climate interactions in western US forests and their impacts on fire severity. Models of future projections of fire-climate interactions include climate-induced shifts in fire severity, changes in vegetation and forest dynamics, climate-fire impacts on biomass and carbon, how fuels and restoration treatments can be used to mitigate climate-fire effects, and changes in hydrology. There were few studies addressing large-scale western-wide climate-severity interactions (e.g., Parks et al. 2016, 2018a, b, 2019), and most studies were based on smaller forested landscapes (Table 2). These studies examined the probability of future fire severity and drivers of high-severity fire (Parks et al. 2016), and climate-fire-vegetation effects (Parks et al. 2018b, 2019).

Climate-induced shifts in fire severity Projecting future changes in fire severity as a function of climate can help us understand how future climate conditions will affect fire regimes and forest fuel loads. A climate-induced increase in fire activity is predicted in many forests in the western US, and an increase in fire frequency, increased area burned, and increased fire severity is predicted in the Rocky Mountains of Wyoming (Hansen et al. 2020), Sierra-Nevada mountains California (Krofcheck et al. 2017a; Serra-Diaz et al. 2018), central Oregon mountains (Cassell et al. 2019), and the southwestern US (Hurteau 2017; Loehman et al. 2018; O'Donnell et al. 2018; Krofcheck et al. 2019; O'Conner et al. 2020). These studies predict major shifts in species composition and post-fire vegetation. Climate directly influences fuel moisture, vegetation productivity and biomass, and fire season length (Krawchuk et al. 2009; Pausas and Paula 2012; Jolly et al. 2015; Holden et al. 2018). Precipitation and temperature affect moisture availability (wet vs dry), and fuel moisture, abundance, and distribution (Parks et al. 2014; Mueller et al. 2020). The results of models predicting climate impacts on fire regimes and fire severity are not easily parsed by forest type, ecoregion, or climate, and vary by scale. Each large-scale western-wide study should be evaluated individually, as data inputs, climate models, ecoregion delineations, and metrics used to evaluate impacts differ.

At broad temporal scales, the indirect influence of climate on fire severity in the western US may be driven by changes in annual precipitation and an increased water deficit that can increase water stress and decrease vegetative productivity (Parks et al. 2016). Cooler and wetter forested regions (Pacific Northwest, Northern Rocky Mountains, and Southern Rocky Mountains) can have a higher probability of higher fire severity, while over time fire severity is predicted to decrease in the Southwestern US (Arizona, New Mexico) (Parks et al. 2016). The broad potential decrease in future fire severity in the southwestern US is attributed to a warmer and drier climate, where less vegetation and fuels over time result in less burnable biomass available on the landscape (Parks et al. 2016). This is due to a higher water deficit, lower vegetative productivity, and less biomass available if vegetation and fuels track changes with climate in equilibrium (Parks et al. 2016). This study is based on using climate as a proxy for vegetation and fuels, and more broad-scale studies are needed to elucidate trends over ecoregions and large spatial extents and understand the uncertainty.

Alternatively, when vegetation is explicitly used in the models, the results can conflict with models that don't account for climate and vegetation interactions directly. For example, Parks et al. (2018b) examined climate-induced shifts in fire regime and vegetation over ecoregions in the western US. The mean fire return interval and probability of stand-replacing fire vary along a climate moisture deficit gradient. Under extreme conditions when climate moisture deficit is high, the mean fire return interval and probability of stand-replacing fire are also high. Regions with cooler and wetter climates are predicted to have a shorter mean fire return interval (increased fire frequency) and therefore a decreased fire severity over time, whereas warmer and drier regions are predicted to have longer mean fire return interval (decreased fire frequency) and increased fire severity over time. In wet regions where there is a low climate moisture deficit, mean fire return interval and probability of stand-replacing fire are predicted to decrease, which indicates higher fire frequency and lower fire severity (Parks et al. 2018b).

Climate-fire-vegetation dynamics Incorporating the interaction of climate, vegetation, and fire is important in understanding complex ecosystem dynamics, and climate-induced shifts in fire regimes will have a significant impact on vegetation responses. Parks et al. (2018b) predicted future vegetation distributions associated with interactions between future climate conditions and fire. Cold forest is predicted to be highly impacted, where 16% of reference period cold forest will remain cold forest in 2085, 19% will become a mesic forest, 51% is predicted to change to dry forest, and 14% is predicted to become shrubland/grassland. This corresponds to a decrease in mean fire return interval (higher fire frequency) but a decrease in fire severity, due to a decrease in productivity and overall biomass. Mesic forest is predicted to remain stable, where 59% of mesic forest remains mesic under a future climate (2085) and is not expected to change vegetation class; however, 36% of current mesic forest is expected to shift to dry forest. In dry forests, the mean fire return interval (FRI) and percent of replacement severity fire (PRS) (Rollins 2009; www.landfire.gov) are expected to increase, especially along the ecotone between forest and shrubland/grassland ecosystems, suggesting a future transition from forest to non-forest. About 52% of dry forest is expected to stay as dry forest however, 41% of dry forest may shift to shrubland/grassland (Parks et al. 2018b). This study assumes fire regimes and vegetation will keep pace with climate change and does not implicitly allow for the lag in vegetation response to climate.

Vegetation change and probability of stand-replacing fire across the interior western US were modeled using fire severity datasets (NextGen; 1 km resolution) (Parks et al. 2019). This study used gridded climate data and gridded vegetation data to examine future forest cover (1 km resolution) under future climate and the differences between current and mid-21st century distribution of forest to evaluate potential climate-induced change in forest extent and distribution. Under future predicted climate conditions, 35.8% of current forested area is predicted to become climatically unsuitable for forests by mid-century as conditions generally become warmer and drier. Across the Intermountain West, 32,000 km^2 of these future climatically unsuitable forested areas are predicted to be susceptible to stand-replacing fire. Under average weather conditions 15.1% of UT-WY Rockies, 10% of the Southern Rockies, and 3.7% of the Arizona and New Mexico mountains is predicted to experience stand-replacing fire by the mid-21st century. Under extreme weather conditions, 30% of current forested areas in the Colorado Plateau, Arizona and New Mexico Mountains, and the Apache Highlands are predicted to be susceptible to stand-replacing fire (Parks et al. 2019).

The LANDIS II model was used to simulate forest and fire dynamics under future climate scenarios using downscaled climate projections and representative concentration pathways (RCP; emission scenarios) RCP4.5 and RCP 8.5 (2010–2100) (Moss et al. 2010) in a mixed conifer forest in the southern Blue Mountains of central Oregon (Cassell et al. 2019). Increases in fire severity, frequency, and area burned were predicted under future projected climate, where 20.4–22.4% of the forested landscape is expected to be burned by a high-severity fire at least once over the simulation period compared to 12.2% under contemporary climate. A 20% increase in extreme fire years, defined as years with at least 40,000 ha (98,842 acres) burned, is projected to drive a shift in species composition with a decline in sub-alpine species (*Abies lasiocarpa, Picea engelmannii, Pinus albicaulis*) and increases in lower elevation species (*Pinus ponderosa, Abies grandis*).

Serra-Diaz et al. (2018) used LANDIS II to predict potential shifts in vegetation and forest dynamics due to changes in fire severity under four climate change scenarios over early (2015–2042), mid (2043–2070), and late century (2071–2100) in the Klamath forest of northern California and southwest Oregon. The data included four GCMs and RCPs that cover the range of climate change conditions predicted for the study area (hotter and drier, hotter and wetter, slightly hotter and slightly wetter, slightly hotter and slightly drier). Climate change is predicted to increase fire size and severity and drive larger patches of high-severity fire (> 50 ha, 124 acres). This increase is more pronounced in the late century (2071–2100) under the warmest climate change scenarios (climate scenarios ACCESS 8.5 (much hotter-drier) and CanESM2 (much hotter-wetter RCP 8.5)) (IPCC 2013; Flato et al. 2013), where mega fires (200,000 ha and 500,000 ha; 494,000–1.24 million acres) were more common. Simulations of both contemporary baseline and future climate change conditions predicted a large shift in dominant vegetation, where 31% conifer forest is predicted to become shrubland-hardwood by 2100. This vegetation shift is particularly evident where conditions are drier and high fire activity is predicted. Overall, there was a predicted reduction in the fire rotation period, an increase in fire size and total area burned at high severity, a reduction in forest growth, and a shift in the annual establishment probability of conifers due to low soil moisture and higher temperatures (Serra-Diaz et al. 2018).

Hansen et al. (2020) used the iLand model to predict the influence of climate change on future fire in subalpine forests of Greater Grand Teton National Park, Wyoming. Two climate scenarios using GCMs (CNRM-CM5 and GFDL-ESM2M; RCP 8.5 and 4.5) were modeled. Large, high-severity fires are predicted to increase by 2050, and the annual number of fires, area burned, and area-weighted mean fire size increased after 2050. Annual area burned 2018–2099 was 1,700% greater than it was 1989–2017 under the CNRM-CM5 RCP 8.5 climate scenario. By 2098, only 65% of the current forest area remained forested due to increased fire activity during the mid-21st century dry period. Vegetation shifts were also projected, where the area dominated by lodgepole pine and spruce-fir forests declined after mid-century and Douglas-fir extent increases, replacing lodgepole pine as the dominant forest type. Differences in projected future fire activity between RCP scenarios allowed more forest remaining under RCP 4.5 for both GCMs.

Fuel and restoration treatment effects on fire severity, forest resilience, and carbon

Many studies in this synthesis aimed to model climate-fire interactions to predict fire severity and quantify if fuels and restoration treatments were effective to mitigate climate-driven fire severity and vegetation dynamics under future climatic conditions and changing fire regimes. Climate change often reduced biomass, changed forest composition, and altered forest structure in many forest types by 2100. Using thinning, prescribed burning, and managed fires, managers aim to reduce the risk and spread of high-severity fire by decreasing tree density and forest fuels. Restoring historical forest structure and function can be effective in reducing the potential for high-severity fire under contemporary climate conditions (Fulé et al. 2012).

The effects of forest management on future fire severity in the southern Sierra Nevada, CA were modeled and found to be an effective tool (Krofcheck et al. 2017a, b). Management scenarios that included thinning and burning treatments lowered predicted mean fire severity under climate change relative to the no-management scenario under all scenarios modeled. Thinning and maintenance burning scenarios had a large reduction (> 25%) in mean fire severity across the landscape, decreasing the portion of the landscape that burned at high severity by an order of magnitude compared to no-management (Krofcheck et al. 2017b). Thinning alone did not reduce fire severity, as shrubs increased the continuity of fuels and contributed to increased severity (Krofcheck et al. 2017b). In a tandem study, thinning and burning treatments increased carbon stability and reduced fire severity more than no-management in both the short (20 years) and long term (100 years) (Krofcheck et al. 2017a). The highest burn severity occurred in areas dominated by ponderosa pine and pine-mixed conifer forests. In a study in the Sierra Nevada mountains, cumulative area burned by wildland fire was consistent across treatment scenarios; however, restoration treatments across the landscape gradually reduced the proportion of landscape burned by high-severity fire, with an increasingly greater proportion of the landscape burned by low-severity surface fires relative to the control (Liang et al. 2018). In the Tahoe basin, when wildland fire intersected fuel treatments, overall fire severity was reduced, and consequently, less carbon was volatilized (Loudermilk et al. 2017).

On the Kaibab Plateau in AZ, the projected mean area burned at high severity declined when forest restoration treatments were applied under all climate scenarios. High restoration rate (20-yr prescribed burning rotation) was the most beneficial in terms of reducing high-severity fire, slowing forest composition change, and reducing sediment yield (O'Donnell et al. 2018). Climate change initiated the loss of higher-elevation mixed conifer, aspen, and spruce–fir forest types driven by fire mortality and regeneration failure. Restoration treatments maintained a higher percentage of these species on the landscape and mediated the effects of climate-driven changes in vegetation (O'Donnell et al. 2018). Honig and Fulé (2012) used empirical modeling to simulate future fire activity (2070–2099) with climate change and predicted fire weather in southwestern ponderosa pine forests in northern AZ. Simulated restoration treatments decreased fire severity under future climate scenarios, though effectiveness varied by treatment. The magnitude of change is more strongly influenced by future wind speeds and climate effects on vegetation than on altered temperatures and fuel moistures alone (Honig and Fulé 2012). A future hotter and drier climate increased fire frequency, annual area burned, and the probability of high-severity fire in the southwestern US (Loehman et al. 2018). More area is predicted to burn at high severity in episodic and large fire events in the Jemez Mountains, NM (Loehman et al. 2018). Climate-fire interactions predicted a conversion of ponderosa pine forests to shrublands and woodlands dominated by oak, pinyon pine, and juniper in the Jemez mountains. Thinning and burning treatments did not offset climate-driven vegetation reorganizations and were only partially effective at reducing fire severity (Loehman et al. 2018). On the Kaibab Plateau, fire regimes were more highly influenced by thinning and burning, and these treatments decreased the area of high-severity fire and forest compositional changes were predicted to be minimal (Loehman et al. 2018).

Fuel and restoration treatments demonstrate the potential to limit the extent and severity of fire-induced mortality along bioclimatic transition zones (i.e., ecotones). O'Conner et al. (2020) used FireBGCv2 to examine the potential for prescribed fuel treatments and restoration of historical fire frequencies to mitigate the effects of climate on forest species distributions, composition, total biomass, and fire severity in the Huachuca Mountains range in southeastern Arizona under future climate (2005–2055). Models showed that fuel treatments reduced the extent of high-severity patches for the first two decades, and second-entry treatments at year 20 extended these effects for the remaining 30 years of simulation. Fuel treatments with follow-up entries showed the potential of treatments to mitigate fire severity effects and tree mortality under projected future conditions and slow the transition from forest to shrubland in some vegetation types. However, middle-elevation forests dominated by pine and oak are projected to convert to shrublands even in the absence of fire, and upper-elevation pine and mixed conifer forests are expected to lose more than a third of their basal area and species diversity by mid-century (O'Conner et al. 2020).

Studies of restoration and fuel treatments implemented to mitigate fire behavior and the effects on forest carbon dynamics showed that management actions are effective in reducing the risk of high-severity fire and mitigating carbon loss. Krofcheck et al. (2019) used LANDIS II to model management scenarios with climate change and impacts of carbon and the probability of high-severity fire in the Santa Fe Fireshed in New Mexico. Using three scenarios (no-management, prioritized, and optimized) and five climate projections for the years 2000–2050, mean fire severity was predicted to increase with climate change. Mechanical thinning and prescribed burning in both management scenarios resulted in reductions in carbon losses due to wildland fire. Hurteau (2017) used LANDIS II to simulate carbon dynamics under early (2010–2019), mid (2050–2059), and late (2090–2099) century climate projections for a ponderosa pine forests in northern AZ, and the effect of treatments on moderating fire behavior and forest carbon loss. Fire severity was consistently higher in the untreated control area, and thinning and burning treatments substantially decreased mean fire severity. Over the 100-year simulation period, 32.8–48.9% of the control landscape was either carbon neutral or a carbon source to the atmosphere, and more than 90% of the treated landscape was a moderate carbon sink.

Conclusions and management implications

Climate change is altering fire regimes across western forests, and many regions will experience an increase in high-severity fire in forested landscapes. The western US has experienced an increase in the number of large fires, and a larger amount of total annual area burned with an increased percentage of area burned at high severity. Large patches of high-severity fire have lasting legacies on vegetation composition and structure, and impacts on tree regeneration. Increasing warming and drying trends are likely to cause more frequent and severe disturbances in many forested ecosystems in the near future (Bentz et al. 2010; Abatzoglou and Kolden 2013; Riley et al. 2019). Increasing spring and summer temperatures and earlier spring snowmelt extend the length of fire season (Jolly et al. 2015), and increasing trends in area burned by wildland fire are likely to continue in many regions throughout the remainder of the 21st century (Westerling 2016). A temporal trend of increasing frequency of fire and area burned annually with warming climate is likely to continue on the current trajectory, and in areas that are warmer and drier, fires may continue to be large and burn at high severity until they become biomass limited (Parks et al. 2016).

Climate effects on fire regimes vary along climatic and resource gradients (Krawchuk and Moritz 2011; Parks et al. 2018b). Future projections suggest that northwestern US forests in wetter climates are predicted to experience an increased fire frequency and decreased fire severity, whereas warmer and drier regions are likely to show decreased fire frequency and increases in fire severity (Parks et al. 2018b). In high-elevation sub-alpine and boreal systems that may experience greater temperature and precipitation changes, more uncharacteristic severe fire may be prevalent, and shifts in vegetation, loss of habitat, and vegetation type changes will occur (Guiterman et al. 2022). In arid and semiarid ecosystems, projected changes to vapor pressure deficit and temperature regimes are expected to significantly increase drought-induced tree mortality, alter forest species distributions, and limit tree sizes (Allen et al. 2010; Williams et al. 2010, 2013; McDowell et al. 2011, 2016). From 1984 to 2012, cooler and wetter forested areas such as the Pacific Northwest, Northern Rocky Mountains, Southern Rockies have experienced more high-severity fire compared to warmer and drier regions of Arizona and New Mexico mountains (Parks et al. 2016). Recent increases in fire severity are attributed to changes in climatic water deficit, vapor pressure deficit, evapotranspiration, and fuels.

While forests of the western US show a range of adaptations to fire, fire activity is likely to exceed the historical range of variability observed over the last two centuries (Westerling et al. 2011; Kelly et al. 2013; Kitzberger et al. 2017; Higuera et al. 2021). Intensifying drought, combined with abundant fuel loads will allow for more high-severity fire. Alternatively, some models predict increases in fire activity and imply that less biomass will be able to accumulate between fires, meaning there will be less biomass available to burn on a landscape post fire and over time (Parks et al. 2016). A predicted increase in water deficit could result in a decrease in biomass in water-limited systems (Chen et al. 2010; Williams et al. 2013) causing a reduction in fire severity.

Climate change and high-severity fire will drive changes in forest composition and structure, trigger declines in biomass, and increase the probability of type change conversions in future forests (Turner 2010; Coop et al. 2020). However, studies modeling the impacts of restoration and fuels treatments and their effects on fire behavior suggest that management actions can be effective in reducing the risk of high-severity fire (Krofcheck et al. 2017a, 2017b, 2019; Loehman et al. 2018; O'Conner et al. 2020). In some ecosystems and certain weather conditions, restoration and fuel treatments may reduce the area burned in high-severity fires and reduce conversions from forest to non-forest conditions, thus increasing resistance and resilience to fire events. Thinning and prescribed fire treatments can be effective at reducing the potential for crown fire, reducing fuels, and promoting forest resilience. However, the efficacy of these treatments depends on the extent and intensity of the treatment, stochastic weather events, terrain, and forest structure and composition. Restoration treatments can delay vegetation change, and slow biomass declines due to fire-climate interactions and provide opportunities for uphill movement of lower-elevation species (O'Donnell et al. 2018). Fuel treatments can mitigate fire severity impacts in systems that may become fuel-limited; however, the pace and scale of implementation is outpaced by wildfire activity across western US forest. Restoration and fuel treatments may be less effective in systems where the effects of future fire are more heavily influenced by climate variables than by fuels on the landscape do (Littell et al. 2009; Loehman et al. 2018).

Climate-induced changes in fire regimes will drive changes in fuel loads and fuel moisture conditions, drive fire severity, and impact future species composition in western US forests (Parks et al. 2016, 2018a, b; Westerling 2016; Abatzoglou and Williams 2016; Cassell et al. 2019; Coop et al. 2020). Forested ecosystems often experience lagged responses to climate change or climatic debts (Bertrand et al. 2011; Liang et al. 2018) which occurs when tree species do not completely track changes in their climatically suitable environment. This climate-vegetation disequilibrium makes predicting the timing or magnitude of forest community shifts with climate change difficult. In addition, some lagged changes in vegetation may be driven by stochastic mortality events.

This synthesis may be used to increase the knowledge of what the regional and place-based models predict in terms of future climate-driven changes in fire severity and the associated vegetation changes. Management and adaptation strategies are needed to mitigate the effects of climate-induced extreme fire events in many ecosystems. Addressing fire risk across many regions involves fuel reduction and restoration programs, fire risk evaluations, smoke tolerance, funding, work force, and social and economic buy-in. Recent research has shown that fuel and restoration treatments burned at lower severity than untreated controls, and prescribed fire is an effective treatment to reduce fire severity (Cansler et al. 2022). Restoration and fuel treatments may help bridge the gap between climate and vegetation lags (Millar et al. 2007; Stephens et al. 2010), if the pace and scale of implementation can increase to meet the pace of wildland fire.

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Authors' contributions
This paper was conceived by T.N. Wasserman. Both authors conducted literature reviews and combined results. T.N. Wasserman was the primary author and S.E. Mueller is the secondary author. S.E. Mueller made Figures 1 and 3. Both authors made Figure 2. Tzeidle Wasserman made Tables 1 and 2. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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