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Contemporary wildfires are more severe compared to the historical reference period in western US dry conifer forests

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A R T I C L E I N F O

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A B S T R A C T

Dry conifer forests in the western US historically experienced frequent fire prior to European American colonization. Mean fire return interval ranged from about 5–35 years, with the majority of fires burning at low-to-moderate severity. The arrival of European Americans initiated notable reductions in fire frequency through the cessation of Indigenous burning, livestock grazing, and fire suppression. These activities effectively excluded fire from most dry conifer forests, thereby allowing live and dead fuels to accumulate. There are concerns that this fuel accumulation is causing contemporary fires (since 1985) to burn more severely compared to pre-colonization time periods, thereby increasing potential for enduring fire-catalyzed conversions to non-forest. Here, we used satellite-derived fire severity data to characterize the prevalence of contemporary (1985–2020) stand-replacing fire in dry conifer forests within four broad ecoregions for all fires, non-wilderness fires, wilderness fires, and prescribed fires. Our results indicate, that as a proportion of area burned, contemporary fires experienced 2.9 to 13.6 times more stand-replacing fire (depending on the ecoregion) compared to the pre-colonization period. Non-wilderness areas exhibit somewhat higher prevalence of stand-replacing fire, relative to the historical fire regime, than wilderness areas (where logging is prohibited). The relatively small difference between non-wilderness and wilderness suggests that fuel accumulation resulting from fire exclusion has played a larger role than historical logging activities on the prevalence of contemporary stand-replacing fire. Prescribed fires do not exhibit a higher prevalence of stand-replacing fire compared to the historical fire regime. We conducted a parallel analysis in the Gila Wilderness in New Mexico, USA, is it is arguably the best example of an unrestrained fire regime (many fires are not suppressed) in western US dry conifer forests. The Gila Wilderness proportionally experienced only 1.8 times more stand-replacing fire compared to the historical reference period; in contrast, the southwest ecoregion experienced 5.9 times more stand-replacing fire. Fire will inevitably burn a given forest no matter how much money and personnel we commit to fire prevention and suppression, and because of the high prevalence of stand-replacing fire, the long-term persistence of dry conifer forests is jeopardized. Unless forest managers are provided the social license and enabling conditions to substantially accelerate efforts to restore conditions resistant to stand-replacing fire, we anticipate that the extent of dry conifer forests will continue to erode as fire-catalyzed conversions increasingly unfold across the western US.

1. Introduction

Dry conifer forests in the western US, defined as those dominated by ponderosa pine, sugar pine, western larch, Douglas fir, and other fire-resistant tree species in dry settings, historically experienced frequent fire prior to widespread European American colonization (Taylor and Skinner, 2003, Heyerdahl et al., 2008). Research suggests that the mean fire return interval in these dry conifer forests generally ranged from about 5–35 years (Taylor and Skinner, 1998, Veblen et al., 2000, Heyerdahl et al., 2001, Fulé et al., 2003, Margolis and Balmat, 2009).

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Prior to European American colonization, fires in these forests were ignited by both lightning and Indigenous peoples (Agee, 1996, Taylor et al., 2016), with the majority of fires burning at low-to-moderate severity as evidenced by surviving trees that recorded fire scars (Kellogg et al., 2008, Falk et al., 2011, Miller and Safford, 2017). However, the arrival of European Americans resulted in a notable reduction in fire frequency and area burned starting in the mid- to late-1800′s through the cessation of Indigenous burning, livestock grazing that reduced fine fuels, and the direct suppression of fire (Savage and Swetnam, 1990, Allen et al., 2002, Lake et al., 2017, Hessburg et al., 2019). These activities effectively excluded fire in western US dry conifer forests for over a century, resulting in a substantial 'fire deficit' (Marlon et al., 2012).

As a result of this fire exclusion, as well as timber harvesting practices that removed large, fire-tolerant trees, the composition and structure of most dry conifer forests in the western US have been substantially altered (Stephens et al., 2015, Hagmann et al., 2021). Increases in the prevalence of shade-tolerant, fire-sensitive trees, an increase in landscape homogeneity, and an overall increase in tree density are at least partly attributable to practices and policies that have excluded fire (Naficy et al., 2010, North et al., 2015, Hessburg et al., 2019). These changes to dry conifer forests have triggered concerns that contemporary fires are burning in an uncharacteristic manner (i.e. more severely than expected under unaltered conditions) (Hessburg et al., 2005, Calkin et al., 2015). Evidence from dry conifer forests in California, Oregon, and Washington, USA, indicate that this is the case: greater proportions of contemporary fires are burning at stand-replacing severities (i.e. a fire that kills all or most trees) compared to historical reference conditions that were prevalent prior to widespread European American colonization (Mallek et al., 2013, Haugo et al., 2019, Williams et al., 2023). Similar evaluations of stand-replacing fire across a broader spatial extent and among different land and fire management strategies (e.g. designated wilderness) could complement these previous studies and provide additional information as to whether these findings are unique to California and the Pacific Northwest or are ubiquitous across the western US.

Dry conifer forests in the western US (Fig. 1) evolved with and were adapted to frequent, low-to-moderate severity fire (Keeley, 2012). For example, ponderosa pine has thick bark, tall crowns, and flammable litter, allowing this species to survive low- to moderate-severity fire and even facilitate fire spread (Stevens et al., 2020). Consequently, any increase in the prevalence of stand-replacing fire (Williams et al., 2023) is heightening concerns among managers, scientists, and the general public about the resilience and sustainability of dry conifer forests. Of particular concern is that recovery back to a forested state following stand-replacing fire is becoming less likely with changes to fire regimes and climate, effectively resulting in conversions from forest to non-forest (Stephens et al., 2013, Coop et al., 2020). The reasoning is that seedling establishment is generally limited when distance to a live, seed-bearing tree exceeds ~150 m (Chambers et al., 2016, Stevens-Rumann et al., 2018). Additionally, post-fire climate conditions must be conducive to the establishment and survival of seedlings (Davis et al., 2019, Littlefield et al., 2020). Finally, microclimates are often more extreme and unsuitable for regeneration following stand-replacing fire relative to pre-fire microclimate conditions (Wolf et al., 2021). All of these factors are exacerbated by ongoing and projected changes to climate and fire regimes (Harvey et al., 2016b, Stevens-Rumann et al., 2018, Singleton et al., 2019, Davis et al., 2019, Parks and Abatzoglou, 2020, Rank et al., 2022).

Lands designated as wilderness offer the highest level of protection in the US. How this land management designation affects the prevalence of stand-replacing fire in dry conifer forests, particularly in comparison to historical reference conditions, remains unknown. It could be argued that, because most wilderness lands were never harvested, dry conifer forests in wilderness should have large, fire-resistant trees, thereby resulting in lower severity fires in wilderness (cf. Larson et al., 2013). Conversely, as increased levels of live and dead biomass contribute to higher severity fire (cf. Birch et al., 2015), it could be argued that the lack of logging in wilderness could contribute to higher severity fire in wilderness. We are not aware of any studies that quantify the observed prevalence of stand-replacing fire in relation to historical fire regimes in wilderness. Such an evaluation, particularly when compared to non-wilderness, could expand our understanding of the relative influence of fire exclusion vs. historical harvesting practices on the observed prevalence of stand-replacing fire.

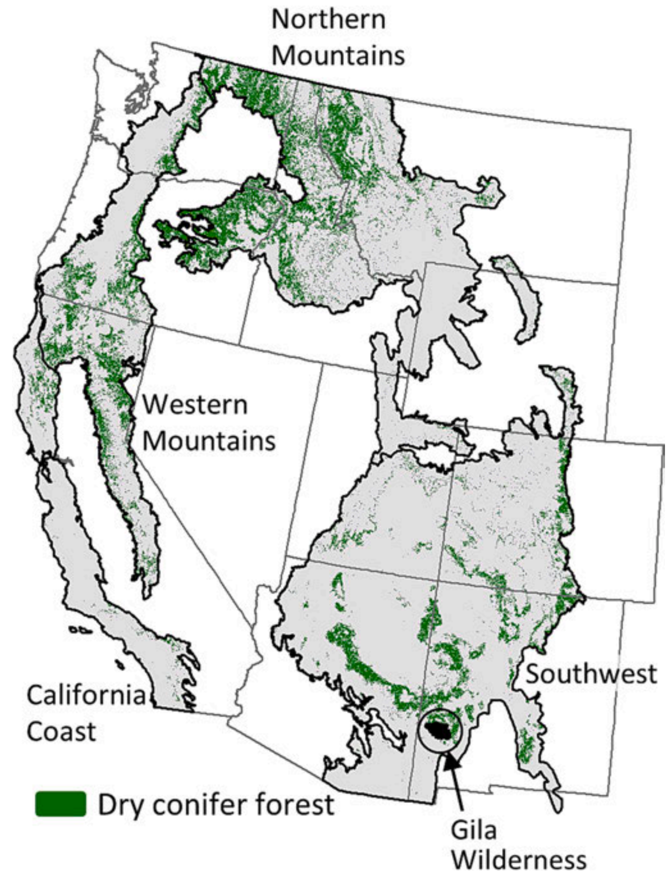

Fig. 1. Map shows the four ecoregions in which we compare observed and historical replacement severity fire (i.e. stand-replacing fire).

In recent decades, scientists have increasingly stressed the importance of allowing fires to play a more prominent role by choosing not to suppress lightning-ignited fires that pose minimal threat to human infrastructure and lives and to expand the use of prescribed burning (North et al., 2015). The rationale is that fuel loads and vegetation types in landscapes with less altered fire regimes are maintained by frequent fire and are therefore less likely to experience undesirable fire effects (i.e. Collins et al., 2007, Parks et al., 2014, Meyer, 2015). The Gila Wilderness in New Mexico has had an active fire use program (i.e. fires are often allowed to burn in the absence of fire suppression) for decades and is arguably the best example of an unrestrained (freely burning) fire regime in dry conifer forests in the western US (Hunter et al., 2014). As such, the Gila Wilderness can serve as an important case study for which to compare to other lands where fire is aggressively suppressed. As calls for 'coexisting with fire' increase (Moritz et al., 2014, McWethy et al., 2019), lessons learned from the Gila Wilderness can potentially be used to inform fire management across broader landscapes dominated by dry conifer forest.

Our primary objective is to quantify, for all lands, non-wilderness lands, and for designated wilderness, the contemporary prevalence of stand-replacing fire in dry conifer forests of the western US in comparison to the historical prevalence of stand-replacing fire. We use satellite-derived fire severity data to characterize the prevalence of contemporary (1985–2020) stand-replacing fire (calculated as a percent of area burned) in dry conifer forests within four broad ecoregions in the western US (Fig. 1). We then compare the observed prevalence of stand-replacing fire to that which we expect occurred under the historical fire regime (prior to ~1875 in most of the western US) that included ignitions from Indigenous peoples and lightning (as characterized by the LANDFIRE program; Rollins, 2009, Blankenship et al., 2021). We also conducted a parallel analysis for prescribed fires. Although prescribed fires in dry conifer forests generally don't exhibit extensive stand-replacing fire (by design), this parallel analysis provides a qualitative assessment of our methods, in that we expect that the prevalence of stand-replacing fire to more or less mimic that which occurred under the historical reference period. Lastly, we conducted a parallel analysis for the Gila Wilderness, as it is arguably the best example of an unrestrained (freely burning) fire regime in dry conifer forests in the western US (Hunter et al., 2014). We focused our study on dry conifer forests because we have greater confidence in estimates of historical stand-replacing fire relative to other forest types. Dominant conifer species in dry forests are long lived, relatively fire resistant (Stevens et al., 2020), and capable of fire scarring. Consequently, they are excellent recorders of fire history and provide comparatively more information than other forest types in the western US (Margolis et al., 2022). Dry conifer forests are also considered the most departed from reference conditions in the western US as a result of 20th century logging and ongoing fire suppression (Mallek et al., 2013).

2. Methods

We compared observed (1985–2020) and historical (prior to ~1875) stand-replacing fire in each of four large ecoregions in the western US (Fig. 1). We limited our analysis to conifer savannas, woodlands, and forests generally located at the lower elevational range of forest vegetation and within drier climatic settings (labeled 'dry conifer forests'). We used the LANDFIRE Biophysical Settings (BpS) geospatial dataset (resolution = 30 m) to identify these dry conifer forests (Table S1), which are dominated by tree species such as ponderosa pine, Jeffrey pine, sugar pine, Douglas fir, and western larch. The LANDFIRE BpS depicts vegetation classes expected under a fire regime that included ignitions from humans and lightning, or in other words, the vegetation types that existed prior to European American colonization (Rollins, 2009).

2.1. Observed replacement severity fire

Observed fires are those ≥400 ha that occurred from 1985 to 2020 as represented by a geospatial dataset of fire perimeters produced and distributed by the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al., 2007; https://www.mtbs.gov). For these fires, we produced raster datasets (resolution = 30 m) characterizing modeled composite burn index (CBI) using Google Earth Engine (Gorelick et al., 2017) and the model developed by Parks et al. (2019b). This procedure maps the predicted CBI using a Random Forest (Breiman, 2001) model developed using field-derived CBI data from >250 fires across North America; explanatory variables in this model include Landsat spectral indices, latitude, and 1981–2010 annual average climatic water deficit (CWD). We used the bias-corrected CBI described by Parks et al. (2019b). The field-based CBI was developed as a composite measure of fire severity that rates >20 individual factors such as duff consumption, char height, and canopy mortality (Key and Benson, 2006). Modeled CBI therefore represents our best attempt to replicate this field-based measure of fire severity and allows for improved ecological interpretations of fire effects compared to non-standardized indices such as the delta normalized burn ratio (dNBR).

For the observed fires, each burned pixel was then converted from its CBI prediction to a binary fire severity categorization of 'replacement severity' or 'other'. Replacement severity fire (i.e. stand-replacing fire) was based on a CBI threshold (CBI ≥ 2.05) that corresponds to 75% overstory mortality (Fig. 2), thereby matching LANDFIRE's definition of stand-replacing fire (described below) (Miller et al., 2009, Parks and Abatzoglou, 2020).

2.2. Historical replacement severity fire

For the historical reference period, each LANDFIRE BpS pixel is attributed with 'percent replacement severity'. Percent replacement severity indicates the percent that each BpS type experienced replacement severity fire under a historical fire regime (prior to ~1875) that included ignitions by both lightning and Indigenous peoples. Percent replacement severity is based on LANDFIRE vegetation dynamics models developed for each BpS type based on available literature and expert judgment and subject to multiple rounds of peer review (Blankenship et al., 2021). According to LANDFIRE, 'replacement severity' (i.e. stand-replacing) is defined as a fire that kills ≥75% of the overstory trees. For example, if the overstory canopy cover of a given dry forest patch was 40% prior to a fire, the post-fire overstory canopy cover must be 10% or less for that fire to be considered a replacement severity fire. Percent replacement severity represents a long-term (i.e. multi-century) estimate of mean fire severity applicable to broad geographic areas and recognizes that there was variability in the prevalence of replacement severity fire across space and time.

In contrast to current fire severity, historical fire severity cannot be directly measured. However, historical fire severity in dry conifer forests can be inferred from species functional traits (Stevens et al., 2020), dendrochronology records (including stand and fire history reconstructions) (Greenberg and Collins, 2021), archival accounts, reference forests (Safford and Stevens, 2017, Miller and Safford, 2017), early aerial photographs (Hessburg et al., 2007), vegetation plots, stand inventories, and timber surveys (Hagmann et al., 2019). LANDFIRE instructed vegetation dynamics model developers to use these sources,

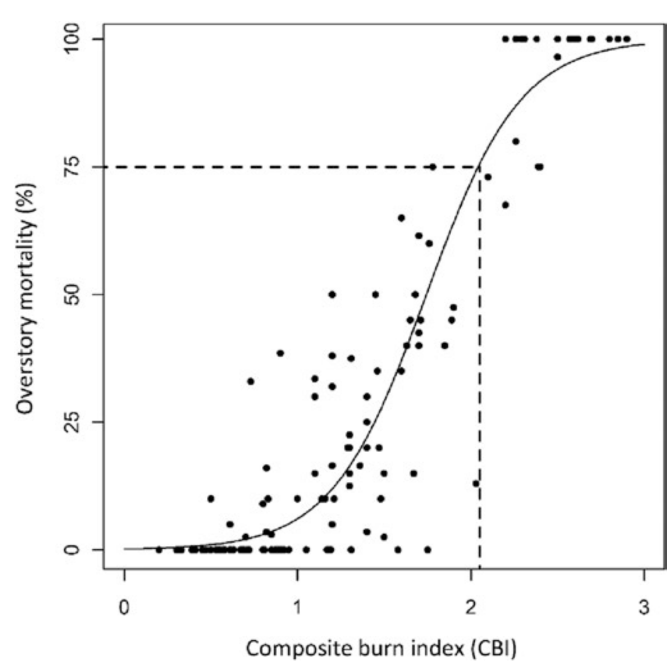

Fig. 2. Relationship between overstory tree mortality and the composite burn index (CBI). CBI data were collected in the 2011 Miller Fire (92 plots; Gila Wilderness) and the 2011 Hammer Creek fire (50 plots; Bob Marshall Wilderness). Overstory tree mortality represents the average mortality of 'intermediate trees' (subcanopy) and 'big trees' (upper canopy) as represented by the CBI protocol. As shown, 75% overstory mortality is achieved when CBI ≥ 2.05. We use this threshold to define replacement severity fire, thereby matching the definition that is used by LANDFIRE.

literature, and local data to inform model development and specifically estimates of percent replacement severity. Consistent with a large body of literature, LANDFIRE models show strong agreement that dry conifer forests were characterized by a predominantly low and mixed severity fire regime and that replacement severity fire was relatively rare historically (Hessburg et al., 2005, Safford and Stevens, 2017, Merschel et al., 2021).

2.3. Analyses

Given that dry conifer forests as defined by LANDFIRE BpS may not currently be in a forested state as a result of land-use change or prior disturbance such as stand-replacing fire, we further restricted our analysis. Following Dillon et al. (2020), we only included pixels identified as forest, woodland, or savanna from a combination of landscape level vegetation products that include LANDFIRE's (Rollins, 2009) Existing Vegetation Cover (EVC), Environmental Site Potential (ESP), and the Landsat Time Series Stacks-Vegetation Change Tracker (LTSS-VCT) (Huang et al., 2010). Following Parks and Abatzoglou (2020), we also excluded all pixels with a pre-fire normalized differenced vegetation index (NDVI) < 0.35, thereby eliminating low productivity sites that might be misclassified as forest or are considered non-forest due to a previous stand-replacing fire. Pre-fire NDVI represents the mean NDVI from one year before the fire using the same Landsat spectral imagery used to produce the CBI predictions (Parks et al., 2019b).

Percent replacement severity was then averaged across all pixels that burned from 1985 to 2020 in dry conifer forests for all lands, non-wilderness lands, and wilderness lands in each ecoregion, resulting in historical percent replacement severity (hereafter 'historical PRS'). The observed binary representation of fire severity (replacement severity $=$ 1; other severity $=$ 0) from 1985 to 2020 was then averaged across dry conifer forests for all lands, non-wilderness lands, and wilderness lands in each ecoregion, resulting in observed percent replacement severity (hereafter 'observed PRS'). For each of the four ecoregions, we divided the observed mean PRS by the historical mean PRS, resulting in the PRS_{ratio}. The PRS_{ratio} therefore represents the overall difference in observed PRS in relation to historical PRS. For example, $PRS_{ratio} = 4$ indicates that observed stand-replacing fire is 4 times more prevalent in an ecoregion compared to what would have occurred if the same areas burned during the historical reference period. Previous studies have used a similar approach to characterize observed vs. historical stand-replacing fire (Mallek et al., 2013, Haugo et al., 2019).

We conducted parallel analyses (comparing observed and historical PRS in dry conifer forest) in each of the four ecoregions for prescribed fires. To do so, we selected fires in the MTBS dataset identified as 'prescribed fire'. Lastly, we compared observed and historical PRS in dry conifer forest in the Gila Wilderness (as a case study) to provide additional insight about the consequences of allowing fire to play a more prominent role in dry conifer forests.

For all analyses, we used a bootstrapping procedure to measure uncertainty in our estimates of the observed prevalence of stand-replacing fire compared to the historical prevalence of stand replacing fire, or PRS_{ratio}. To do so, we took 1000 random observations using a sampling rate of 0.1% each for each bootstrap sample and then calculated and report the interquartile range (IQR) for PRS_{ratio} for each of our results.

3. Results

In dry conifer forests in the western US, stand-replacing fire (observed PRS) comprised 25–56% of the area burned from 1985 to 2020, depending on the ecoregion (Table 1). These values represent a stark departure from the historical reference period (i.e. prior to European American colonization) in which stand-replacing fire (historical PRS) was estimated to comprise only 4–11% of area burned (depending on the ecoregion). Consequently, stand replacing fire, as reported as the ratio between observed and historical PRS (PRS_{ratio}), was 2.9–13.6 times more prevalent from 1985 to 2020 compared to the historical reference period, depending on the ecoregion (Table 1).

In non-wilderness, stand-replacing fire comprised 27–58% of total area burned in dry conifer forests from 1985 to 2020 (observed PRS), depending on the ecoregion (Table 1). We found that stand-replacing fire was 2.8–14.5 times more prevalent from 1985 to 2020 compared to the historical reference period (PRS_{ratio}) on non-wilderness lands. In wilderness, stand-replacing fire from 1985 to 2020 was lower compared to the historical reference period, both in terms of observed PRS and PRS_{ratio}, than in non-wilderness in all ecoregions except the Northern Mountains, where the observed prevalence of stand-replacing fire showed little difference between non-wilderness and wilderness (Table 1). Although the prevalence of stand replacing fire (both observed PRS and PRS_{ratio}) is lower or unchanged when constrained to wilderness (vs. non-wilderness), stand-replacing fire was still 2.9–10.3 times more prevalent than the historical reference period, depending on the ecoregion (Table 1).

When looking only at prescribed fires, the prevalence of stand-replacing fire comprised only 2–6% of the area burned from 1985 to 2020, depending on the ecoregion (Table 1). Stand-replacing fire was less prevalent from 1985 to 2020 compared to the historical reference period (as reported PRS_{ratio}) in all ecoregions except the California

Table 1
For dry conifer forests in each ecoregion, we calculated the ratio (PRS_{ratio}) between observed and historical percent replacement severity (PRS) (i.e. stand-replacing fire) for all fires, non-wilderness, fires, wilderness fires, and prescribed fires. We also provide the interquartile range (IQR) for a bootstrapped sample of the PRS_{ratio} (see Methods).

Ecoregion	Fire location or type	Observed PRS	Historical PRS	PRS_{ratio}	IQR for PRS_{ratio}	Area burned in dry forest (km^2)
California Coast	All fires	56.3	4.1	13.6	13.0–14.1	193
	Non-wilderness fires	58.0	4.0	14.6	14.0–15.3	153
	Wilderness fires	49.7	4.8	10.3	9.3–11.4	40
	Prescribed fires	3.3	3.2	1.0	NA*	1
Western Mountains	All fires	45.8	6.5	7.1	6.9–7.3	827
	Non-wilderness fires	47.1	6.6	7.2	7.0–7.4	726
	Fires in wilderness	36.5	5.9	6.2	5.7–6.8	101
	Prescribed fires	6.2	9.7	0.6	0.0–0.9	12
Northern Mountains	All fires	31.5	11.0	2.9	2.8–2.9	1174
	Non-wilderness fires	31.9	11.3	2.8	2.7–2.9	897
	Fires in wilderness	30.0	10.2	2.9	2.8–3.1	277
	Prescribed fires	4.2	10.0	0.4	0.0–0.6	20
Southwest	All fires	25.1	4.2	5.9	5.7–6.2	901
	Non-wilderness fires	26.6	4.0	6.6	6.3–6.8	764
	Wilderness fires	16.9	5.3	3.2	2.8–3.5	137
	Prescribed fires	1.7	3.1	0.6	0.3–0.8	84
	Gila Wilderness	7.3	4.1	1.8	1.3–2.3	74

* Sample size too small to conduct bootstrapping procedure.

Coast, where the historical and observed prevalence was about equal ($PRS_{ratio} = 1.0$). It is worth noting that the area burned by prescribed fire, as recorded in the MTBS fire history dataset, was fairly low as a percent of total area burned in dry conifer forests, ranging from < 1% (California Coast) to 9% (Southwest) (Table 1).

A comparison of observed and historical stand-replacing fire in the Gila Wilderness, which serves as a case study, provides an interesting contrast to the broader Southwest ecoregion. From 1985 to 2020, stand-replacing fire in dry conifer forests in the Gila Wilderness comprised 7.3% of the area burned. This contrasts sharply with the dry conifer forests of the Southwest ecoregion (the Gila Wilderness is located in this ecoregion; Fig. 1), in which stand-replacing fire, under the contemporary regime, comprised 25.1% of the area burned. Similarly, the departures in stand-replacing fire, as the ratio between the percent of

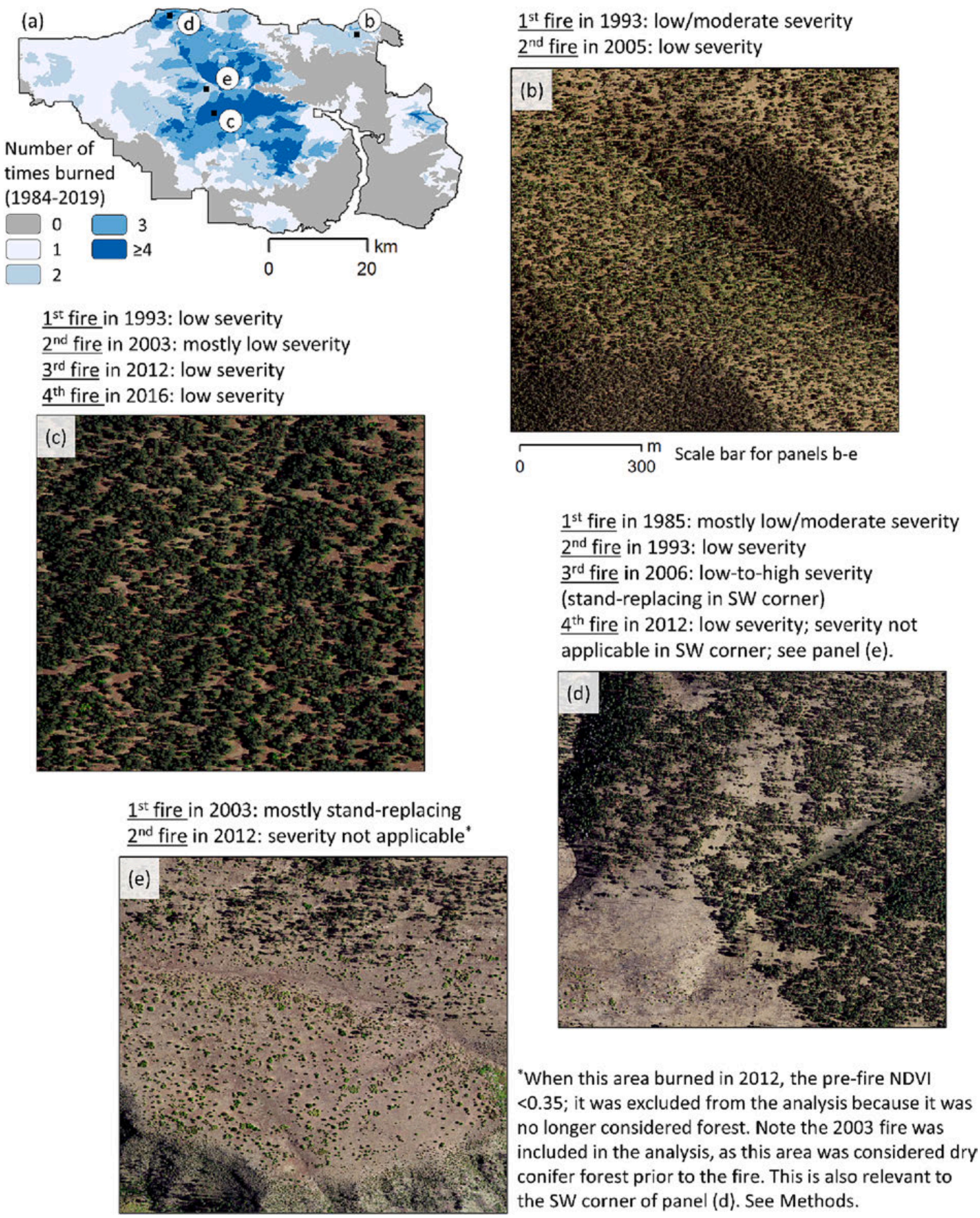

Fig. 3. Map shows the Gila Wilderness (a) with the number of times burned and four bounding boxes showing the extents of each inset (b-e). Each map inset (b-e) shows aerial imagery from circa 2019 and therefore reflects the cumulative effects of the fires that occurred at each site. For each map inset, we also provide a narrative of the severity for each fire. Open, low-density dry conifer forest generally remains extant at these sites even after repeated burning (except panel [e]).

observed and historical area burned at replacement severity (PRS_{ratio}), was much less pronounced in the Gila Wilderness compared to the Southwest ecoregion. Stand-replacing fire from 1985 to 2020 in dry conifer forests was 1.8 times more prevalent compared to the historical reference period in the Gila Wilderness but 5.9 times more prevalent in the broader southwest ecoregion (Table 1). The relatively small departure in observed vs. historical stand-replacing fire in the Gila Wilderness, as quantified by PRS_{ratio}, is corroborated by a visual assessment of recent aerial imagery (Figs. 3 & 4). Although stand-replacing fire in the dry conifer forest of the Gila Wilderness has occurred (Fig. 3e & 4f), the departure between observed and historical stand-replacing fire was much less than in the broader Southwest ecoregion.

4. Discussion

Area burned by wildland fire has increased over the last few decades in the western US (Dennison et al., 2014, Abatzoglou and Williams, 2016), sparking concerns about changing fire regimes. Area burned, however, is an imperfect measure of the impacts of fire, particularly in fire-adapted dry conifer forests, and consequently, many studies are now explicitly considering patterns and trends in *fire severity* because they better characterize the ecological consequences of fire (Dillon et al., 2011, Harvey et al., 2016b, Reilly et al., 2017, Stevens et al., 2017, Parks and Abatzoglou, 2020, Cova et al., 2023). As a proportion of area burned, fires that occurred from 1985 to 2020 have 2.9 to 13.6 times more stand-replacing fire compared to the historical reference period (i.e. prior to ~1875) in western US dry conifer forests, depending on the ecoregion. We recognize that there is inherent uncertainty in comparing a satellite-derived contemporary measure of stand-replacing fire to historical reconstructions represented in the BpS data. However, our findings are likely indicative of the direction and general magnitude of change and convincingly demonstrate that contemporary fire regimes are highly departed from historical conditions (cf. Hagmann et al., 2021).

It has been argued that fires burn with lower severity in wilderness and similarly protected lands because of the lack of widespread historical logging and forest management practices that are more prevalent on unprotected lands (cf. Larson et al., 2013). The rationale is that historical logging practices generally removed large, fire-resistant trees, but where these large tree shave been retained (e.g. wilderness), forests should be more resilient to fire and exhibit lower fire severity (Brown et al., 2004, Merschel et al., 2021). It has also been suggested, because fires are sometimes allowed to burn in wilderness with less aggressive fire suppression ('managed fire'), that they may burn under less extreme weather conditions (Miller and Aplet, 2016) and exhibit lower severity fire overall. We found that stand-replacing fire is 2.9 to 10.3 times more prevalent from 1985 to 2020 (as a proportion of area burned) compared to the historical reference period in wilderness, depending on the

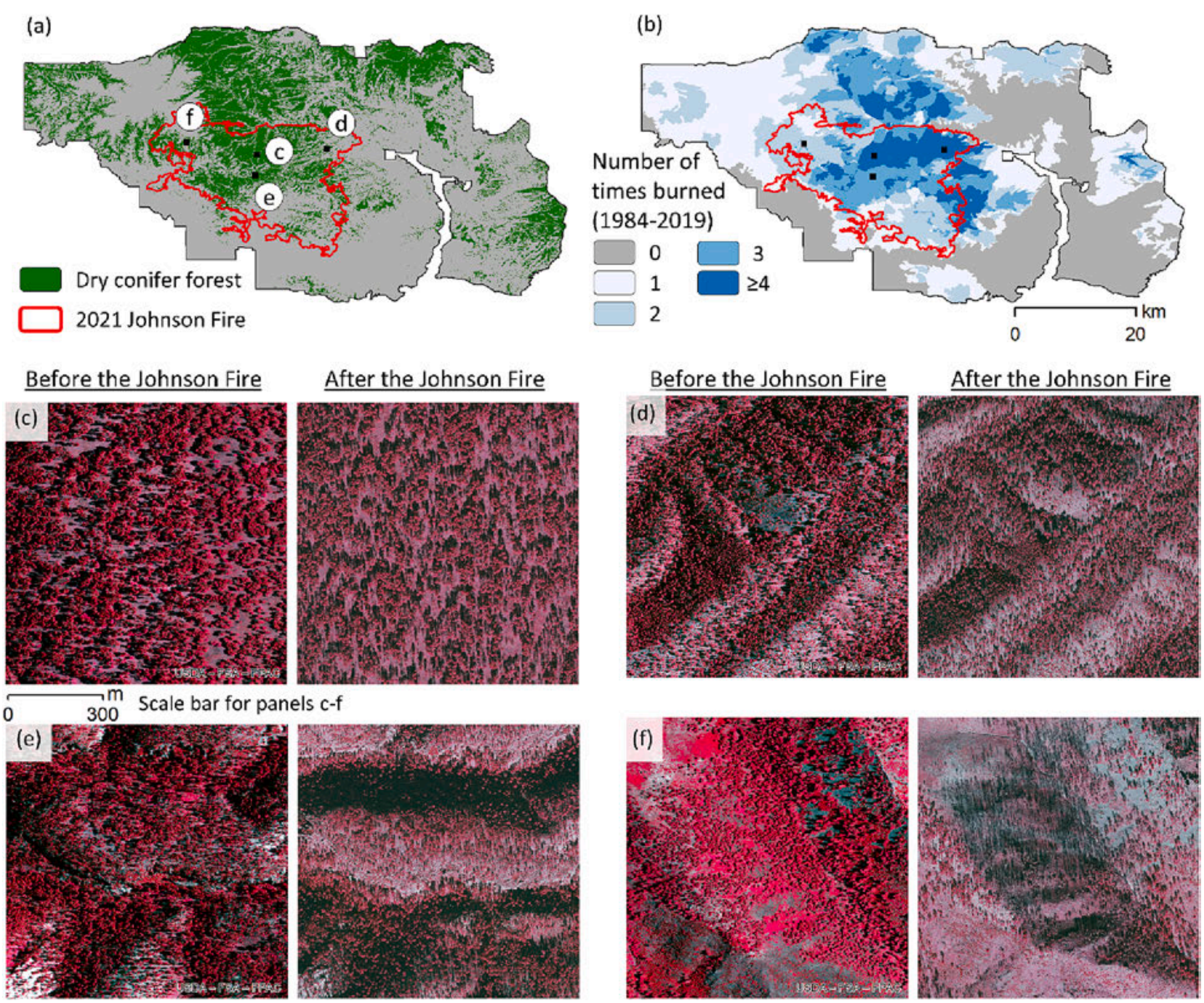

Fig. 4. In 2021, the Johnson Fire burned about 38,000 ha in the Gila Wilderness, including large swaths of dry conifer forest (a) and previously burned areas (b). Based on aerial imagery, nearly all areas that had live conifer trees prior to the Johnson Fire had live conifer trees after the fire (c-e). There were only limited instances of stand-replacing fire (f).

ecoregion. Consequently, the observed prevalence of stand-replacing fire in dry conifer forests in wilderness is marginally lower than that of observed in non-wilderness (see Table 1). An important caveat, however, is that although wilderness exhibits somewhat lower severity fire compared to unprotected lands, the severity is still much higher than the historical reference period. This important finding suggests that fuel accumulation resulting from fire exclusion has played a larger role than historical logging practices on the prevalence of contemporary stand-replacing fire. This finding also suggests that returning lightning-ignited fire to fire-excluded wilderness without explicitly considering uncharacteristic fuels loads may result in undesirable outcomes (Prichard et al., 2021) and may even provide rationale for increasing the use of prescribed fire in wilderness (Parsons, 2000).

Prescribed fires, particularly in combination with other treatments, are one of the most effective means to treat fuels and restore fire-adapted landscapes (Ryan et al., 2013, Prichard et al., 2021). We found that, in contrast to our analyses that pertained to all fires, non-wilderness fires, and wilderness fires, prescribed fires did not exhibit more stand-replacing fire compared to the historical reference period (see Table 1). Although this is not necessarily surprising given that prescribed fires are carefully controlled and are only implemented under predetermined fuels and weather conditions, it does provide evidence that prescribed fire can be used to more or less mimic historical fire regimes. Our prescribed fire findings also indicate that our methods are

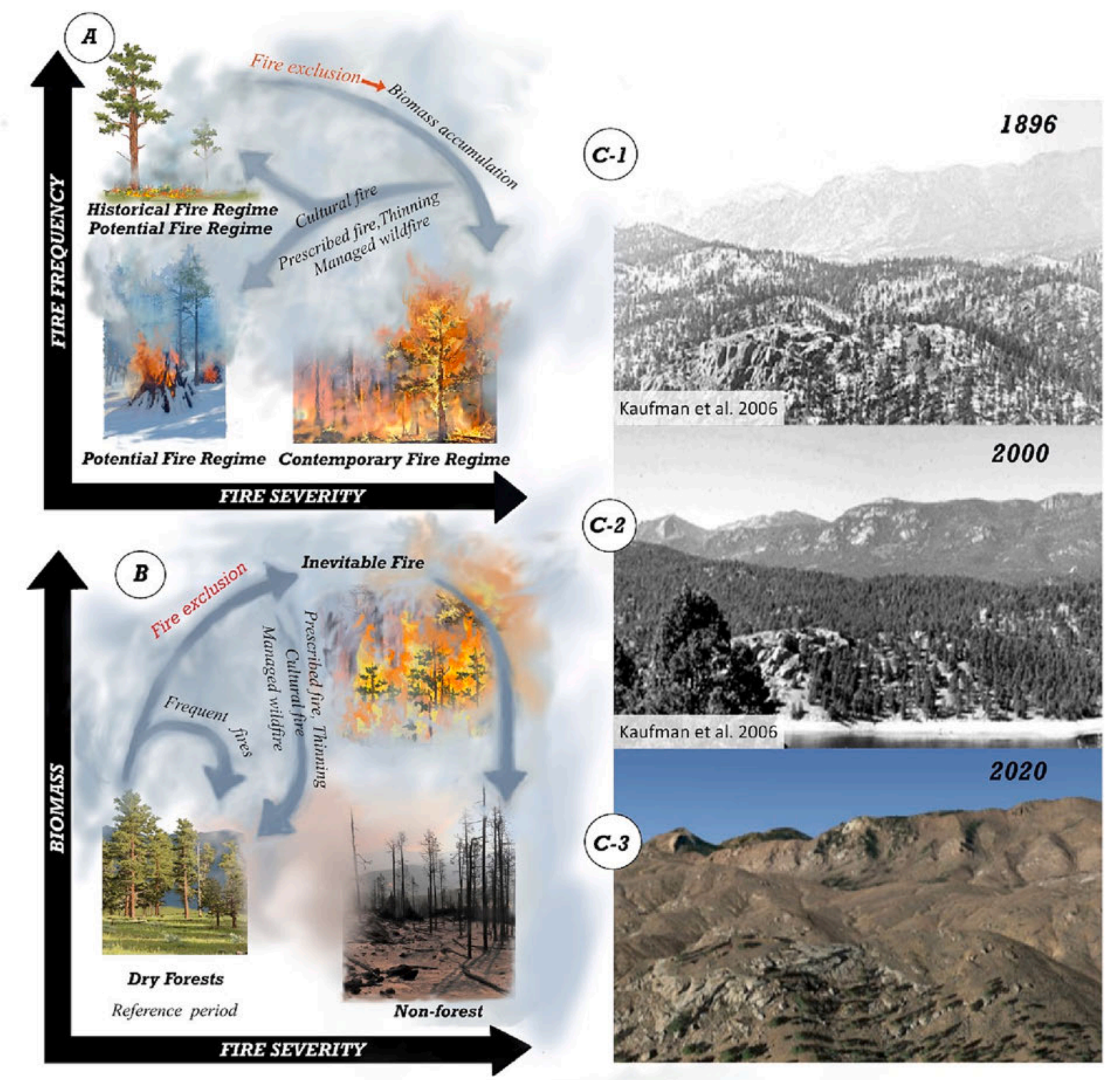

Fig. 5. Conceptual model depicts the consequence of altered fire regimes in dry conifer forests of the western US and a path forward to restore these forests. Historically, dry conifer forests experienced frequent but low- to moderate-severity fire (a), and as a result, tree density and biomass remained relatively low (b; c-1). Because of fire exclusion, dry conifer forests have now transitioned from a historical fire regime characterized by frequent, low- to moderate-severity fire to a 'contemporary fire regime' characterized by infrequent, stand-replacing fire (a). As a consequence of these changes to the fire regime in dry conifer forests, tree density and biomass have increased (b; compare panel c-2 to panel c-1). Therefore, when the inevitable fire occurs, there is an increased probability of stand-replacing fire and conversion to non-forest (b; c-3). Acknowledging that it is not always possible or practical to return dry conifer forests to a 'historical fire regime', we offer that several strategies can be used to reduce tree density and biomass across these landscapes (see Discussion), thereby resulting in dry conifer forests that are more resistant to stand-replacing fire (i.e. 'the potential fire regime'). Here, the potential fire regime can span a range of fire frequencies: fire can be frequent in the form of prescribed, cultural, or managed fire, but if fire is not frequent, other treatments such as thinning are necessary to reduce fuel loads. The Hayman fire (i.e. the inevitable fire [b]) burned the site of this photo series in 2002 (c).

sound and do not grossly overestimate the departures in stand-replacing fire reported elsewhere in this paper. Lastly, as prescribed fires have also been shown to reduce the severity of the inevitable wildfire (Prichard and Kennedy, 2014, McKinney et al., 2022), they provide a critical tool for managers to decrease uncharacteristic fuel loads, reduce fire risk to communities, and to restore ecological function to dry conifer forests in the western US (Kolden, 2019).

The tree-ring fire scar record indicates that fire was fairly frequent in dry conifer forests in the western US prior to European American colonization, burning a given site every 5–35 years (Heyerdahl et al., 2008, Margolis and Malevich, 2016, Taylor et al., 2016, Margolis et al., 2022). Fire exclusion has resulted in a substantial reduction in fire frequency (Swetnam and Baisan, 2003, Beaty and Taylor, 2008) and an overall increase in tree density and biomass (Keane et al., 2002, Hagmann et al., 2021). The inevitable outcome of these changes is an increased probability of stand-replacing fire in dry conifer forests, as supported by our findings (see Fig. 5 for conceptual model) and those of similar studies (Mallek et al., 2013, Haugo et al., 2019, Williams et al., 2023). Consequently, dry conifer forests, even in wilderness, have experienced an overall shift from a fire regime characterized by frequent, low severity fire to a fire regime characterized by less frequent fire and an increased prevalence of stand-replacing fire (Fig. 5). This fire regime shift has serious consequences: fire-catalyzed shifts from dry conifer forest to non-forest are increasingly being realized across the western US (Coop et al., 2020, Steel et al., 2023, Coop, 2023) and are expected to compound as a result of ongoing climate change (Parks et al., 2019a, Davis et al., 2020, Davis et al., 2023). Stand-replacing fire and subsequent conversions to non-forest can negatively impact ecosystems and human well-being by increasing erosion potential (Moody et al., 2013), reducing carbon stocks (Hurteau and Brooks, 2011, Liang et al., 2018), reducing habitat for forest-dwelling species (Jones et al., 2021, Steel et al., 2023), and jeopardizing human safety, infrastructure, and communities (Safford et al., 2009, Calkin et al., 2014).

4.1. Lessons from the Gila wilderness

In a handful of large and remote wilderness areas, fire has sometimes been allowed to burn in the absence of aggressive fire suppression over the last few decades (Berkey et al., 2021), thereby providing ample opportunities to improve knowledge about the causes and consequences of fire (Kreider et al., 2023). One of these areas, the Gila Wilderness in New Mexico, is arguably the best example of an unrestrained fire regime in dry conifer forests in the western US (Hunter et al., 2014). Fire is common in the Gila Wilderness, with some areas burning 4+ times since 1985 (Fig. 3). Because fire is so common, the Gila Wilderness has frequently been used as a natural laboratory to study the effects of an unrestrained fire regime (e.g. Holden et al., 2007; Rollins et al., 2002). Studies conducted in the Gila Wilderness have concluded that low-severity fire begets low-severity fire (Holden et al., 2010, Parks et al., 2014), a phenomenon that has also been observed in other regions such as the US northern Rocky Mountains (Harvey et al., 2016a), the Sierra Nevada (Harris and Taylor, 2017), and northeastern Washington (Cansler et al., 2022). The unrestrained fire regime in the Gila Wilderness sharply contrasts with that of the ecoregion in which it is embedded in terms of the ratio between contemporary and historical percent replacement severity fire (PRS_{ratio}). Dry conifer forests in the Gila Wilderness have proportionally experienced 1.8 times more stand-replacing fire compared to 5.8 times more stand replacing fire within its broader ecoregion (Table 1).

The unrestrained fire regime of the Gila Wilderness, particularly when compared to other dry conifer forests in the Southwest ecoregion, offers valuable lessons that are applicable to other remote forested regions. For example, our results reinforce the notion that low-severity fire begets low-severity fire in dry conifer forests (Harvey et al., 2016a; Parks et al., 2014) and highlight that frequent, low-severity fire is possible even as our climate has become warmer and drier over the last few decades. Our Gila Wilderness findings are roughly similar to a study of a mixed-severity fire regime in the Sierra Nevada, where fire severity was generally lower in Yosemite National Park (which also has a long-standing policy that allows fires to burn to meet management objectives) compared to surrounding lands (Miller et al., 2012). The decades-long policy of allowing fire to burn in the Gila Wilderness demonstrates the benefit of allowing fire to fulfill its ecological role, thereby serving as a roadmap to restore resilience to dry conifer forests in the western US. This said, we recognize that restoring frequent, low-severity fire (as observed in the Gila Wilderness) is not likely across the full extent of dry conifer forests in the western US (Fig. 1), even in wilderness. In moving forward, however, a greater appreciation for unrestrained fire regimes (and regimes that include managed wildfire) can help us better understand factors that result in low-severity fire and the benefits of moving towards a ‘potential fire regime’ in which dry conifer forests are resistant to stand-replacing fire (Fig. 5a).

4.2. Caveats and other considerations

We recognize that historical reference conditions do not necessarily represent contemporary target conditions, particularly under a warming climate, but they do provide critical historical and evolutionary context to guide management of dry conifer forests into the future. Furthermore, while tree ring fire scars provide widely accepted estimates of fire frequency in western dry conifer forests, there is more uncertainty associated with estimating historical fire severity. Quantifying historical fire severity is complex because individual sites burn at multiple severities over space and time, and fire severity must be inferred from limited, indirect evidence. In addition, there is no standard methodology for measuring historical fire severity, some methods have been the subject of considerable scientific debate (Hagmann et al., 2021 and references therein), and definitions of fire severity classes are inconsistent between studies. Even similar evidence may be interpreted differently among studies. For example, the presence of even-aged cohorts is sometimes used as an indicator of high severity fire even though these cohorts can also result from insects, disease, drought, and other disturbances. For example, Brown and Wu (2005) conclude that even-aged cohorts are more likely the result of episodic recruitment during periods of favorable climate conditions in southwest Colorado ponderosa pine forest, and Safford and Stevens (2017) state that there is little evidence that even-aged cohorts were common following high severity fire in dry conifer forests of California. Differences in methods, definitions, and interpretation make it difficult to compare results between studies. Despite these challenges, there is substantial evidence that dry conifer forests in the western US were shaped by multiple low severity fires as evidenced by the many trees that recorded and survived repeated fires over hundreds of years (Margolis et al., 2022). It is also worth noting that there is some uncertainty in our contemporary estimates of fire severity, but the effects of such are likely negligible given that there is no systematic bias in terms of under- or over-predicting fire severity (Parks et al., 2019b).

Warmer and drier fire seasons exhibit more stand-replacing fire, both in terms of area burned and as a proportion of total area burned (i.e. observed PRS) (Reilly et al., 2017, Parks and Abatzoglou, 2020, Whitman et al., 2022), suggesting that climate change has an influence on the prevalence of stand replacing fire. In fact, there is evidence that climate change has resulted in more high severity fire (as a proportion of total area burned) in the southwestern US (Dillon et al., 2011, Singleton et al., 2019, Parks and Abatzoglou, 2020). Admittedly, we did not analyze fire-season climate or climate change in this study. However, partitioning the relative influence of fuel accumulation resulting from fire exclusion vs. climate change in driving departures in stand-replacing fire would make a valuable contribution to the literature.

5. Moving forward (Conclusions)

It is becoming increasingly clear that 1) fire will inevitably burn a given forest no matter how much money and personnel we commit to fire prevention (Moritz et al., 2014, North et al., 2015) and 2) these fires threaten the long-term persistence of dry conifer forests because they often burn under extreme weather and fuel conditions (Fig. 5) (Hagmann et al., 2022; Higuera and Abatzoglou, 2021). As land managers and other interested parties grapple with these realizations, it is critical to understand that the only viable solution for restoring dry conifer forests to conditions resistant to stand-replacing fire is by reducing fuels, tree density, and overall biomass across these landscapes. This can be achieved through different strategies depending on biophysical conditions and management constraints. For example, prescribed fire can reduce fuels and the probability of a subsequent stand-replacing fire (Fernandes, 2015, Hunter and Robles, 2020), and it is increasingly recognized that other social, spiritual, and ecological benefits can be achieved with a greater appreciation and application of cultural burning (Lake et al., 2017, Long et al., 2021). However, because many dry conifer forests are currently too dense to safely implement prescribed or cultural fire in isolation, a combination of thinning and prescribed burning can effectively mitigate the potential for stand-replacing fire (Kalies and Yocom Kent, 2016, Prichard et al., 2021); once implemented, these treatments can then be maintained over time with prescribed and cultural fire (Battaglia et al., 2008, Wynecoop et al., 2019). Managers can also reduce fuel loads by choosing not to suppress a fire under appropriate weather and fuels conditions (i.e. 'managed wildfire') (Kolden et al., 2010, Fillmore et al., 2021), as demonstrated in the Gila Wilderness (Figs. 3 & 4). It is also worth noting that, although it may be contentious, prescribed fire is allowed in wilderness according to the policies of all agencies that manage wilderness; this could be an option where fuel conditions make managed wildfire too risky or unpredictable. Combinations of all of these strategies (thinning, prescribed fire, cultural fire, and managed wildfire) have also been proposed (Hessburg et al., 2021, North et al., 2021) (Fig. 5). It has been pointed out, however, that the current pace and scale of current treatment efforts are inadequate to restore dry conifer forests (North et al., 2012, Haugo et al., 2015, Prichard et al., 2021). This said, initiatives have recently been unveiled that aim to increase efforts to improve forest resilience to the inevitable fire. For example, the state of California has an ambitious plan to build a culture of beneficial fire by increasing the use of prescribed fire, cultural fire, and managed wildfire to the tune of 160,000 ha/year by 2025 (California Wildfire & Forest Resilience Taskforce, 2022). The USDA Forest Service has also released a new strategy to protect communities and improve forest resilience through thinning and prescribed burning across millions of acres (USDA Forest Service, 2022). Nevertheless, unless enabling conditions are established that allow forest managers to substantially accelerate efforts to restore conditions resistant to stand-replacing fire (cf. Stoddard et al., 2021), the extent of dry conifer forests will continue to erode as fire-catalyzed conversions to non-forest unfold across the western US (Woolman et al., 2022, Coop, 2023).

CRediT authorship contribution statement

Sean A. Parks: Conceptualization, Methodology, Formal analysis, Writing – original draft. **Lisa M. Holsinger:** Conceptualization, Methodology, Writing – review & editing. **Kori Blankenship:** Conceptualization, Validation, Writing – review & editing. **Gregory K. Dillon:** Conceptualization, Writing – review & editing. **Sara A. Goeking:** Formal analysis, Writing – review & editing. **Randy Swaty:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The Google Earth Engine code used to produce the fire severity data is available on request

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Appendix A. Supplementary data

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