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Does conserving roadless wildland increase wildfire activity in western US national forests?

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Abstract

National forests in the western United States are divided roughly in half between lands without roads managed for wilderness characteristics and lands with an extensive road system managed for multiple uses including resource extraction. We investigated the influence of these land use designations on fire ignitions, fire extent, and fire severity over the last three decades. Although roadless areas experienced fewer fire ignitions and are generally cooler, moister, and higher elevation landscapes less conducive to fire, wildfire extent was far greater in these areas than in roaded areas. An area equivalent to approximately one-third of roadless areas burned in the last three decades, while an area equivalent to less than one-fifth of roaded areas experienced fire. Most of the largest fires that have burned on national forest land in recent years began in roadless areas. Despite greater fire extent in roadless areas, there was no significant difference in fire severity between roadless areas and roaded areas after accounting for biophysical differences between these management regimes. Although fire patterns in roadless areas may pose challenges to land managers, the available evidence suggests that the greater extent of fire in roadless areas may confer resilience to these landscapes in the face of climate change.

1. Introduction

The number and size of wildfires in the western United States has increased dramatically over the last three decades, with significant social, economic, and ecological consequences (e.g. Calkin *et al* 2015, Sankey *et al* 2017, Bladon 2018). Understanding the drivers of fire activity is important to help society adapt to the new fire reality, particularly in the context of anthropogenic climate change (North *et al* 2015, Dunn *et al* 2020). Numerous studies have investigated the influence of fuel dynamics, topography, and climate change on fire in the Anthropocene (e.g. Parks *et al* 2014a, Keyser and Westerling 2017, Meddens *et al* 2018). This study examines the influence of public policy on wildfire, specifically the influence of different land use designations on fire ignitions, fire extent, and fire severity on national forest land managed by the US Forest Service (USFS).

The USFS manages 20% of forestland in the United States (1.5% of the global forestland total), most of which is found in the 11 western states (figure 1). For much of the agency's 115 year history, US Congressional legislation emphasized development of natural resources, e.g. the Multiple Use Sustained Yield Act and the National Forest Management Act (Clary 1986). In the last 60 years, protection of landscapes from development has received increasing attention from policy makers. In particular, the Wilderness Act of 1964 provided for the creation of wilderness areas to 'preserve natural conditions'. The Wilderness Act required the USFS to inventory roadless areas not designated as wilderness pending future Congressional action (Roth 1984, Booth 1991).

Inventoried roadless areas not released for development in the 1970s and early 1980s served as an ad hoc administrative extension of the wilderness system until 2001, when the Roadless Area Conservation Rule ('Roadless Rule') generally prohibited road construction and commercial timber harvest in these areas (USDA (US Department of Agriculture) 1972, 1979, Loucks *et al* 2003, Voicu 2010; see also Wyoming Outdoor Coordinating Council v. Butz, 484 F.2d 1244 (10th Cir.1973)).

Decisions to protect roadless wildlands from development have thus created two strongly contrasting management regimes: an actively managed landscape with an extensive road system and a legacy of resource extraction, and a passively managed landscape with no roads and little or no history of resource extraction (figure 1, table 1). Actively managed roaded landscapes have been in the past and continue to be subject to a wide variety of anthropogenic modifications including but not limited to timber harvest, road construction and maintenance, and a wide variety of recreational developments. These activities have been largely absent within roadless areas. Passive management of roadless landscapes is largely a matter of decisions about suppression of natural disturbances like wildfire.

Examining the influence of different management regimes on wildfire is timely. Recent Congressional legislation such as the Healthy Forest Restoration Act of 2003, revisions to the National Forest Management Act planning regulations in 2012, and agency policy initiatives like the Collaborative Forest Landscape Restoration Program emphasize restoration of the natural fire regime to which different landscapes are adapted (Schultz *et al* 2012, Feldman and Reimer 2019). Wildfire is a key disturbance process that shapes the structure, composition, and function of forests, and a better understanding of the influence of passive vs active management on fire patterns is critical for evaluating the ability of USFS managers to meet forest restoration objectives (Johnstone *et al* 2016, Thompson *et al* 2018, Schultz *et al* 2019). In this study we used USFS databases and satellite data to determine if there are important differences in (a) fire ignitions, (b) fire escape from initial suppression efforts, (c) fire extent, and (d) fire severity between passively managed wilderness and inventoried roadless areas ('roadless areas') and the roaded portion of national forest lands actively managed for multiple uses ('roaded areas').

In this paper we report results from a complete census of the extent and severity of wildfire based on satellite data encompassing all USFS roadless and roaded areas. However, simple summaries of ignitions, fire escape, fire extent, and fire severity between roadless and roaded areas may be an inadequate basis for evaluating the influence of passive vs active management because land use decisions that created different management regimes were not made at random. Many national forest wilderness and inventoried roadless areas were originally designated in large part because these lands are generally rugged, high-elevation landscapes that are difficult to develop (DeVelice and Martin 2001, Hjerpe *et al* 2017). Although roadless areas include extensive dry and fire-prone forests, at the broad spatial scales we consider, the history of wilderness and inventoried roadless area designations means that these lands are likely to be moister, cooler, and hence less conducive to fire ignition and fire spread (Agee 1996, O'Connor *et al* 2017).

We contextualized our comparison of fire activity across management regimes in several ways. First, we characterized differences in annual precipitation and maximum temperature between roadless and roaded areas. These interannual climate variables are good surrogates for differences in fuel abundance, site productivity, and vegetation type that exert a strong indirect control on the burning environment (Dwyer *et al* 2000, Westerling 2008, Krawchuk *et al* 2009). Second, we compared area burned between roadless and roaded areas within different western US ecoregions with distinctive climates and vegetation communities. Finally, we built statistical models that estimated the influence of management regime on fire probability and severity after accounting for temperature, precipitation, slope, elevation, vegetation type, and a wide range of other biophysical variables that potentially influence the fire environment.

2. Data and methods

2.1. Study area and data acquisition

We investigated the influence of management regime on fire ignitions, extent, and severity within national forests in the 11 conterminous western US states (WA, ID, MT, OR, CO, CA, NV, UT, CO, AZ, NM; figure 1). We limited our study to this geographic scope because the vast majority of national forest lands (82%) are found within these states and because the USFS has adopted lower size thresholds for protecting roadless areas and wilderness areas in the eastern states. Also, many eastern US national forests consist of formerly intensively managed private lands acquired by the federal government, which complicates inference about the effects of management regime on fire pattern. Most USFS lands in the west have remained in the public domain since Euro-American colonization (Bramwell 2012). We delineated national forest lands using USFS spatial data layers and divided them into two categories: roadless and roaded areas (figure 1, table 1). Roadless areas fall within the administrative boundaries of lands protected by the Wilderness Act or inventoried roadless areas protected by the Roadless Rule. Roaded areas include the remainder of the national forest lands managed for multiple use objectives.

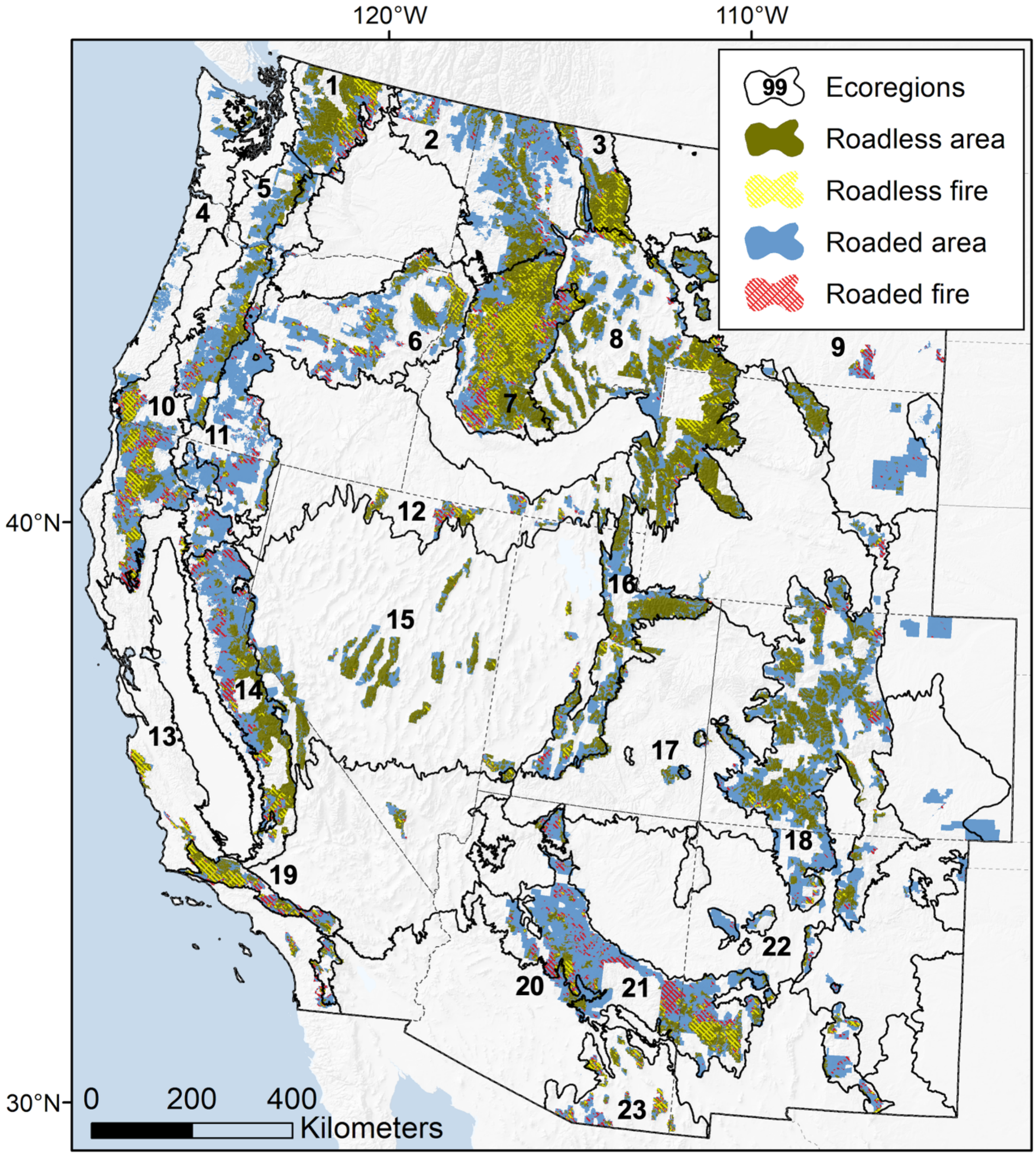

Figure 1. Map of the western states national forest study area showing ecoregions, roadless and roaded portions of USFS lands, and 1984–2018 fire perimeters. Only federal lands managed by the USFS are shown. Numbers correspond to Environmental Protection Agency (EPA) level III ecoregions: 1 = North Cascades; 2 = Northern Rockies; 3 = Canadian Rockies; 4 = Coast Range; 5 = Cascades; 6 = Blue Mountains; 7 = Idaho Batholith; 8 = Middle Rockies; 9 = Northwestern Great Plains; 10 = Klamath Mountains/California High North Coast Range; 11 = Eastern Cascades Slopes and Foothills; 12 = Northern Basin and Range; 13 = Central California Foothills and Coastal Mountains; 14 = Sierra Nevada; 15 = Central Basin and Range; 16 = Wasatch and Uinta Mountains; 17 = Colorado Plateaus; 18 = Southern Rockies; 19 = Southern California Mountains; 20 = Sonoran Basin and Range; 21 = Arizona/New Mexico Mountains; 22 = Arizona/New Mexico Plateaus; 23 = Madrean Archipelago.

Table 1. Descriptive statistics for western states national forest (NF) study area. All fire extent statistics reported in this paper are from the period 1984 to 2018 and reflect the sum of fire extent in areas that have burned more than once. All fire severity (RdNBR) statistics are calculated from 1985 to 2017, corresponding with the MTBS database and available pre- and post-fire Landsat imagery.

NF management regime	Area (ha)	Percent of total NF area	Burned area (ha)	Percent of burned area burned more than once	Percent of management regime burned	Fire severity (mean RdNBR weighted by fire extent)
Roadless	28 578 665	44%	8433 241	32%	30%	484
Roaded	36 230 885	56%	6597 273	24%	18%	430
Totals	64 809 550	100%	15 030 514	—	—	—

We evaluated the influence of roadless management on fire ignitions and probability of those ignitions escaping initial suppression efforts using the Fire Occurrence Database (FOD) maintained by USFS fire management staff. We defined escaped fires as those ignitions that grew to be larger than 121 ha, a size at which the USFS generally expects wildfire to exceed initial attack capabilities (Fried and Fried 1996, Calkin *et al* 2005). At the time of our analysis the FOD included information about fire ignition location and ultimate fire size for ∼2 million ignitions in the United States between 1992 and 2017 (Short 2017). Although other data sources, including the Monitoring Trends in Burn Severity (MTBS) program (see below), contain information about fires prior to 1992 we used the FOD because 90% of area burned in the study area occurred after 1991 and because the FOD contains detailed information about the spatial and temporal origin of fires (including fires that did not grow to the minimum size mapped by other data sources) essential for evaluating the influence of land use and biophysical variables on the fate of wildfire ignitions.

To evaluate the influence of management regime on fire extent we downloaded fire perimeter data from the MTBS program (www.mtbs.gov), which at the time of our analysis mapped all large (>405 ha) fires in the United States between 1984 and 2017 (Eidenshink *et al* 2007, Finco *et al* 2012). We added fire perimeter data compiled by the Geospatial Multi-Agency Coordination (GeoMAC; www.geomac.gov) to extend our fire extent data through the year 2018. We excluded GeoMAC fire perimeter data for fires less than 405 ha for consistency with MTBS fire perimeter data.

To evaluate fire severity we created seamless maps of the relative differenced normalized burn ratio (RdNBR) at 30 m resolution using Landsat satellite time-series within each MTBS fire perimeter (Kennedy *et al* 2018). RdNBR is an objective measure of fire-induced changes in vegetation (i.e. tree mortality) and soil reflectance that accounts for differences in vegetation across different regions (Miller and Thode 2007). We provide a detailed account of our fire severity mapping methods as supplementary materials (see supplementary materials S1 (available online at stacks.iop.org/ERL/16/084040/mmedia)).

2.2. Data analysis

We summarized the total number of ignitions documented in the FOD across both roadless and roaded portions of the western states national forest study area. Then we estimated the influence of biophysical variability and management regime on the probability of fire escape using generalized additive models (GAMs) with a binomial distribution implemented with the mgcv package in the R statistical environment (Wood 2004, 2006, R Core Team 2018). Many of the ignitions on national forest lands catalogued in the FOD that occurred between 1992 and 2017 were close together in time and space and may be temporally and/or spatially autocorrelated. We included individual national forest and year of fire as random effects in models, reasoning that variability in escape probability could be explained in part by the resources available to individual administrative units of the national forest system and the year in which ignitions occurred.

We summarized fire extent across roadless and roaded portions of the study area using the complete inventory of area burned within our western states study area provided by MTBS/GeoMAC data. To better understand variability in fire extent across national forest lands, we summarized total area burned in roadless and roaded areas within each of 23 different level III ecoregions delineated by the US Environmental Protection Agency located within the study area (Omernik 1987). We do not report results from 12 ecoregions that are composed of less than 2% national forest land or in which fire burned less than 1000 ha during the study period.

To account for environmental differences between roadless and roaded areas that potentially influenced fire extent, we analyzed 100 000 points randomly located across the study area. We constrained random location procedures so that points were at least 500 m apart, a distance that the literature suggests avoids spatial autocorrelation in fire effects that could bias coefficient estimates (van Mantgem and Schwilk 2009, Lanorte *et al* 2013, Kane *et al* 2015). We examined autocorrelation function plots and performed Moran's I tests to ensure that there was no significant autocorrelation among points. We estimated the influence of management regime (roadless or roaded) and a wide variety of biophysical variables (table 2) on the probability that these points would fall within a 1984–2018 fire perimeter using a GAM with a binomial distribution. We graphed the probability of fire along 30 year average precipitation and maximum temperature gradients because these climate variables are key indirect controls of natural fire regimes and good surrogates for environmental variability at the broad spatial scales we considered (Westerling 2008, Guyette *et al* 2012, Liu *et al* 2013, Whitman *et al* 2015).

To evaluate differences in fire severity attributable to management regime, we summarized mean RdNBR for the roadless and roaded portions of fire perimeters between 1985 and 2017, leveraging pre- and post-fire Landsat imagery spanning 1984–2018. Like our summaries of fire extent, our summary of fire severity represents a comprehensive census of fire across the study area. To account for environmental differences between roadless and roaded areas that potentially influence fire severity, we modeled the influence of biophysical variability and management regime on RdNBR with a

Table 2. Variables used as explanatory terms in models for fire escape, fire probability, and fire severity.

Variable	Description	Source
Fire year	Year during which fire burned	MTBS (www.mtbs.gov)
Fire type	One of five fire classifications: wildfire, wildland fire use, prescribed fire, complex, unknown	MTBS
Discovery	Date (month and day converted to continuous variable) in which fire was first detected	FOD
Latitude	*y*-coordinate in decimal degrees (North American Datum 1983 projection)	Calculated in GIS
Elevation	Height above sea level (m)	Digital elevation model (DEM)
Slope	Steepness of slope (%)	Calculated in GIS from DEM
Maximum temperature	Thirty year average summer maximum temperature (°C)	PRISM Climate Group (www.prism.oregonstate.edu)
Precipitation	Thirty year average annual precipitation (mm)	PRISM Climate Group
Maximum summer vapor pressure deficit	Thirty year average difference between actual vapor pressure and saturation vapor pressure at the same temperature (hPa)	PRISM Climate Group
Topographic roughness index	Focal pixel height above minimum elevation at different (100–500 m) distances	Calculated from DEM using methods described in Tagil and Jenness (2008).
Topographic wetness index	Topographical control on hydrological process calculated from upslope contributing area and slope	Calculated from DEM using methods described in Sørensen *et al* (2006).
National forest	One of 76 national forests	USFS Geodata Clearinghouse (https://data.fs.usda.gov/geodata/)
Management regime	One of two classifications: roadless (inventoried roadless areas and wilderness areas) or roaded (all other national forest lands)	USFS Geodata Clearinghouse
Ecoregion	One of 35 EPA level III ecoregions	EPA (www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states)
Biophysical setting	One of 149 vegetation classifications	LANDFIRE (www.landfire.gov)
Existing Vegetation Type	One of 432 vegetation classifications	LANDFIRE
US National Vegetation Classification	One of 23 vegetation classifications	LANDFIRE
Forested	Binary variable indicating forested or unforested	Hansen *et al* (2013)

GAM using the subset of the 100 000 random points (20% of points) that fell within 1985–2017 MTBS fire perimeters.

Our goal with statistical models was to determine if management regime had a significant influence on fire escape, fire extent, and fire severity given environmental variables that influence fire. All continuous variables were modeled as smoothed functions in order to capture non-linear relationships between the fire response and environmental gradients. All categorical variables, including management regime, were modeled as parametric variables. We tested a variety of different vegetation classifications in wide use as predictor variables in models (table 2) and used the vegetation classification that explained the most variability in the response. We report the influence of management regime to be significant when confidence intervals (alpha = 0.05) for the effect of roadless and roaded management on the fire response examined do not overlap.

A number of the continuous environmental variables that we tested as explanatory variables for fire escape, fire extent, and fire severity responses were correlated. For instance, maximum temperature was strongly correlated with elevation and latitude. We evaluated full models that included all biophysical variables and parsimonious models created using forwards and backwards model selection procedures that maximized deviance explained and minimized Akaike Information Criterion while eliminating terms with concurvity indexes that exceeded 0.60. Previous research suggests that this threshold provides a conservative approach to eliminating variables that describe similar environmental gradients (Johnston *et al* 2019). Because there was little difference in the estimated effect of management regime between full and parsimonious models, we report results from parsimonious models to improve interpretability. Model specifications and a detailed summary of our statistical methods are

Table 3. Summary of fire ignitions from the FOD.

	Total ignitions	Escaped ignitions	Mean fire size (all fires) (ha)	Mean fire size (escaped fires) (ha)	Maximum fire size (ha)
Roadless	48 577	1925	38	3638	217 741
Roaded	145 574	1977	146	2690	103 428

found in supplementary materials (see supplementary materials S2).

3. Results

3.1. Roadless and wilderness designations are associated with fewer ignitions but more escaped fires

Of the 194 151 total ignitions within the western US national forest study area currently documented in the FOD, 3902 (2% of the total) escaped initial suppression efforts and grew to be >121 ha. The majority of ignitions (74% of the total) occurred within the roaded portion of the national forest landscape, but an almost equal number of fire ignitions (1925) escaped initial control efforts within roadless areas as escaped within roaded areas (1977). Of fire ignitions in roadless areas, 4% escaped control compared to 1.4% of ignitions in roaded areas. GAM models indicated that management regime exerted a significant influence on probability of fire escape even after accounting for topographic ruggedness, slope steepness, vegetation type and other factors that influence the ability of managers to suppress fires. Escaped fires that began in roadless areas grew to be one-third larger than escaped fires that began in roaded areas (table 3). Of the 20 largest fires on national forest land from 1984 to 2018, more than three-quarters began within roadless areas, which account for slightly less than half of the total area of western US national forests (table 4).

3.2. Roadless and wilderness designations are associated with greater fire extent

Roadless areas were associated with a far greater extent of fire relative to roaded areas. Between 1984 and 2018, an area equivalent to 30% of the total area of roadless lands experienced fire, whereas an area equivalent to 18% of roaded areas experienced fire (table 1). This difference is striking because roadless areas within the western states national forest study area contained a larger proportion of cooler and moister environments than roaded areas (figure 2). Management regime exerted a strong influence on the probability of fire even after accounting for vegetation type and biophysical variables. The general shape of the fire probability response while holding other vegetation and biophysical variables constant was similar across climate gradients in roadless and roaded areas (figure 3). In both roadless and roaded landscapes, probability of fire was lowest in very cool and moist settings where climate is less conducive to fire and in very hot and dry settings where fuel is sparse. Probability of fire was highest in areas with precipitation sufficient for fuel to accumulate and dry conditions suitable for fire spread (Krawchuk *et al* 2009, Pausas and Ribeiro 2013, Whitman *et al* 2015). However, the probability of fire was significantly higher in roadless areas across these gradients. There was little overlap in confidence intervals for estimates of probability of fire in roadless and roaded areas except within temperature and moisture regimes where fire was relatively rare (figure 3).

Although roadless areas were associated with a substantially greater extent of fire than roaded areas, there was enormous variability in the extent of fire within different ecoregions (figure 4). Some ecoregions with extensive national forest land such as the Northern Rockies and Wasatch and Uinta Mountains have experienced relatively little fire, with fire evenly distributed between roadless and roaded areas. Other ecoregions with extensive national forest land such as the Idaho Batholith and Arizona/New Mexico Mountains have experienced extensive fire and a notably greater extent of fire in roadless areas. Several ecoregions stand out for the dramatic extent of fire in roadless areas, particularly when including multiple overlapping fires (i.e. reburn). An area equivalent to 86% of the large (1090 342 ha) national forest area managed as roadless wilderness in the Klamath Mountains/California High North Coast Range ecoregion burned between 1984 and 2018, while only 40% of the roaded portion of this ecoregion experienced fire during the same period. Similarly, an area equivalent to 100% of the relatively small (280 782 ha) roadless national forest land in the Central California Foothills and Coastal Mountains ecoregion burned during the same time period compared to 67% of the remaining roaded lands. Approximately 15% of total fire extent across the western states study area between 1984 and 2018 occurred within the roadless portion of the Idaho Batholith ecoregion. We provide a detailed summary of fire extent and severity in different ecoregions as supplementary materials (supplementary materials table S3.1).

3.3. Roadless and wilderness designations do not influence fire severity

Management regime had no influence on fire severity in any of the statistical models we tested. The difference in mean RdNBR between roadless and

Table 4. Largest fires in the western states national forest study area over the period 1984–2018 in terms of national forest land burned (statistics exclude private and other public land burned). State is the state where largest area burned occurred. Fires without fire origin had multiple origins found within USFS roaded and roadless areas, or an origin on other public or private ownership. The mean RdNBR of the roaded portion of the Lake Creek Fire (RdNBR = 6) was excluded from the table and calculations of mean because of the very small area of roaded land that was burned in that fire. None of the grand mean statistics reported in the lower row are weighted by fire extent. RdNBR weighted for fire extent was 481 and 394 for roadless and roaded portions of these fire perimeters, respectively. Data are from the FOD and MTBS/GeoMAC (see text).

Fire name	State	Fire year	Fire origin	Total NF area burned (ha)	NF roadless area burned (ha)	NF roaded area burned (ha)	% roadless fire	Mean roadless RdNBR	Mean roaded RdNBR
Wallow	AZ	2011	Roadless	217 123	23 802	193 321	11%	210	242
Biscuit Complex	OR	2002	Roadless	196 604	154 971	41 633	79%	550	507
Mustang Complex	ID	2012	Roadless	152 820	109 128	43 692	71%	405	411
Rim	CA	2013	Roadless	133 108	71 549	61 559	54%	504	511
East Zone Complex (Raines)	ID	2007	Roadless	128 979	104 195	24 784	81%	494	390
Cascade Complex (Monumental)	ID	2007	Roadless	128 345	101 049	27 295	79%	615	577
Whitewater-Baldy	NM	2012	Roadless	124 205	104 500	19 705	84%	165	157
Diamond Complex (Diamond Peak)	ID	2000	Roadless	109 814	107 440	2373	98%	571	364
Lake Creek	WY	1988	—	95 498	95 476	22	100%	402	—
Zaca	CA	2007	—	93 582	87 993	5589	94%	685	495
Cave Creek Complex	AZ	2005	—	93 195	13 050	80 145	14%	160	232
Hayman	CO	2002	Roaded	91 249	51 913	39 335	57%	787	780
Horseshoe 2	AZ	2011	Roadless	80 768	51 539	29 230	64%	294	287
King	CA	2014	Roaded	77 940	39 945	37 996	51%	587	581
Halstead	ID	2012	Roadless	76 950	62 831	14 119	82%	633	560
Pioneer	ID	2016	Roaded	76 724	32 654	44 071	43%	280	300
Foothills	ID	1992	Roadless	74 201	29 717	44 484	40%	128	101
Rodeo	AZ	2002	—	73 751	0	73 751	0%	—	630
Rough	CA	2015	Roadless	72 987	55 330	17 658	76%	436	523
Chetco Bar	OR	2017	Roadless	71 519	44 828	26 691	63%	561	567
Mean	—	—	—	108 468	67 095	41 373	62%	446	432

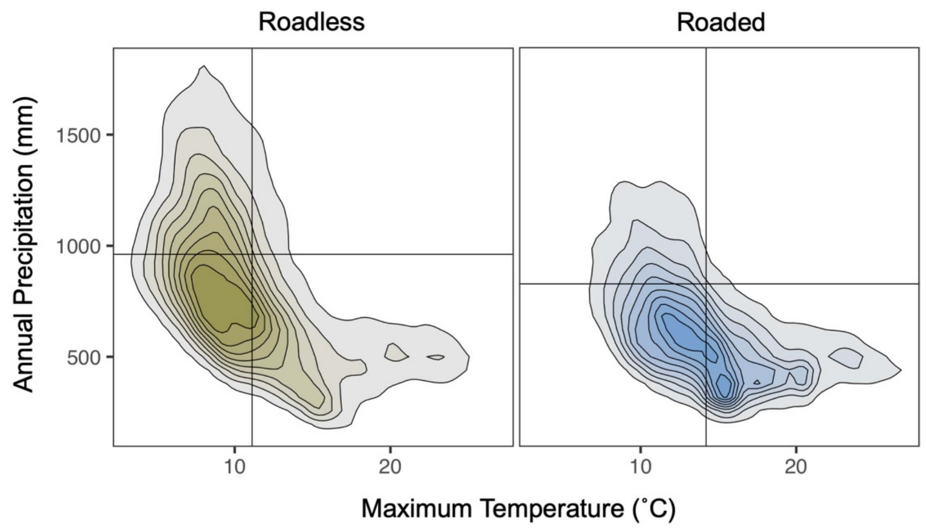

Figure 2. Area of roadless and roaded western states national forest lands along two axes: annual precipitation and maximum temperature. Denser areas correspond to a greater proportion of the landscape located within that precipitation and temperature range. Vertical and horizonal lines represent mean annual precipitation and mean maximum temperature of roadless and roaded areas. Roadless areas are generally cooler and moister and hence less conducive to fire than roaded areas.

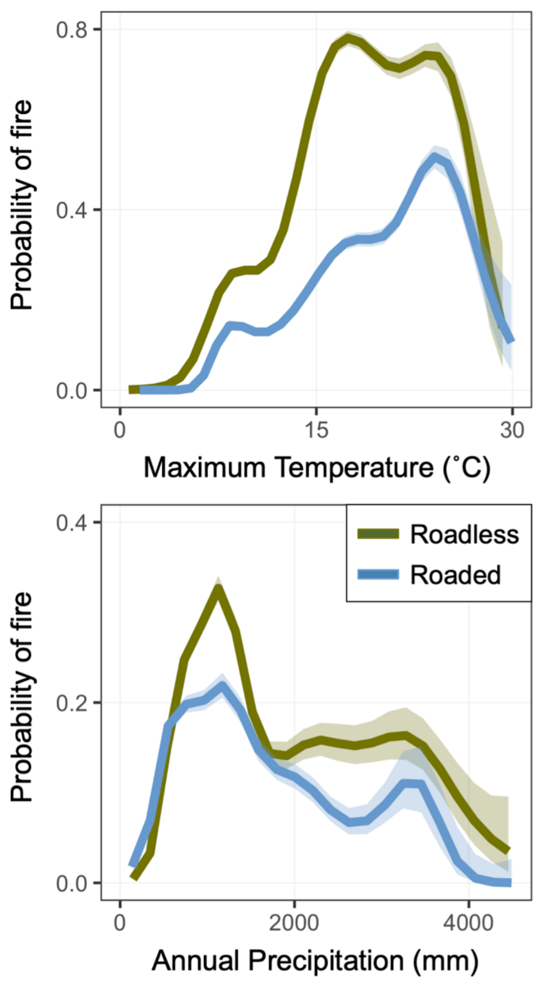

Figure 3. Probability of fire at randomly located points across western US national forests along temperature and precipitation gradients in roadless and roaded areas. Thick line shows estimated probability of fire and transparent areas around the line show confidence intervals (alpha = 0.05) for the estimate. Probability of fire in roadless areas is higher across the maximum summer temperature gradient and peaks within cooler landscape settings than in roaded areas. Probability of fire is the same or higher in roadless areas across the annual precipitation gradient.

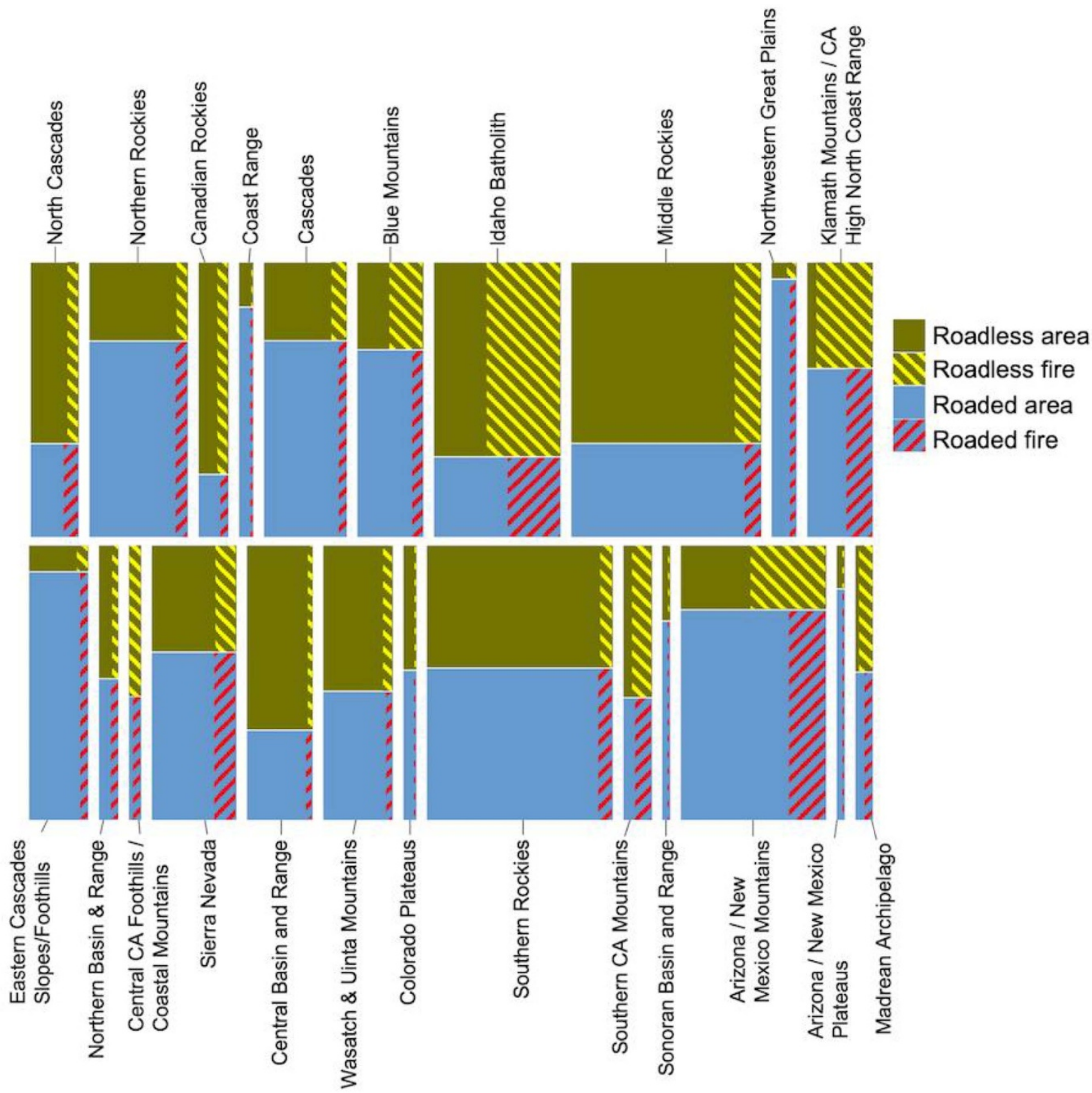

Figure 4. Relative area burned of roadless and roaded portions of USFS lands by ecoregion. The size of each tile is the area of roadless or roaded national forest land in each ecoregion relative to the total area of national forest in the study area. Each management regime in each ecoregion is divided between area burned and area not burned. Calculation of burned area is cumulative, i.e. the total area burned by fire from 1984 to 2018. Unburned area is calculated as total area of each roadless and roaded portion of each ecoregion minus burned area. Figure does not show ecoregions consisting of less than 2% national forest land or in which fire burned less than 1000 ha since 1984.

roaded areas was negligible given the wide range of RdNBR values in our dataset (figure 5, table 1). Vegetation type and biophysical variables that influence the distribution and abundance of vegetation including elevation, annual precipitation, and maximum summer temperature explained as much as 17% of the variance in the severity response compared to approximately 1% of the variance explained by management regime. Confidence intervals for the estimated effect of management regime on RdNBR overlapped zero in all models we tested that included both vegetation and biophysical variables. There were no consistent differences in fire severity between roadless and roaded areas at the scale of individual ecoregions (see supplementary materials table S3.1).

4. Discussion

4.1. The influence of management regime and biophysical variability on fire

The greater incidence of fire ignitions in roaded areas but the greater extent of fire in roadless areas that are generally less conducive to fire is most likely related to three factors. First, proximity to developed areas is associated with more ignitions (Balch *et al* 2017). Second, a lack of road access limits deployment of the full range of suppression tools available to managers to control fires in roadless areas when they are small (Dunn *et al* 2017). Third, large remote landscapes allow managers flexibility to allow fires to burn when these fires are compatible with resource management objectives or when suppression

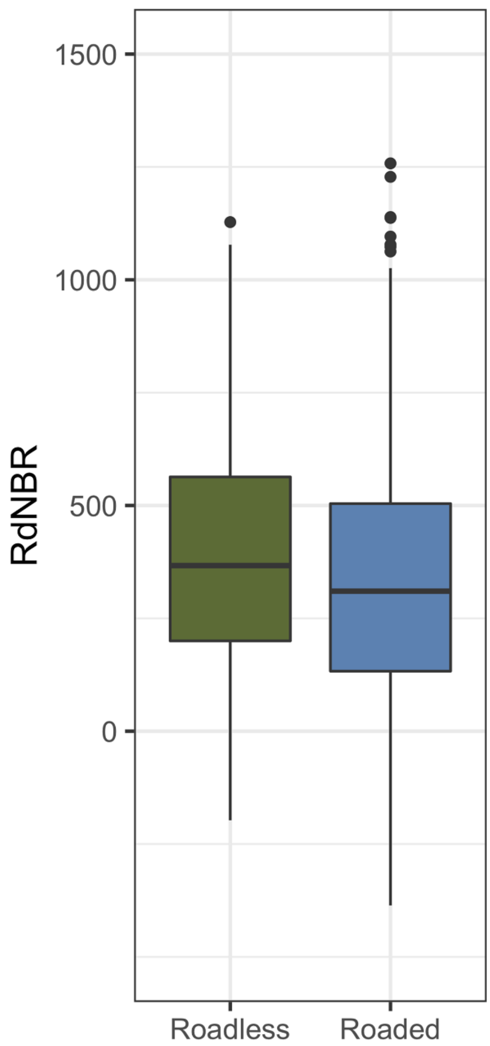

Figure 5. Fire severity as measured with RdNBR (a remotely sensed spectral index of vegetation and surface change due to fire) across all fire perimeters within the western states national forest landscape from 1985 to 2017. Some observations well above or below the mean were omitted for ease of visual observations. RdNBR reported in this figure was calculated for 30 m pixels within all fire perimeters. A random subsample of RdNBR pixels was used in statistical analysis of fire severity between roadless and roaded areas—see data and methods.

resources are strained by numerous large fire events (van Wagtendonk 2007, Haire *et al* 2013, Thompson *et al* 2017). Both human infrastructure and human ignitions are increasing rapidly within the wildland urban interface (Mietkiewicz *et al* 2020). These trends, in conjunction with spiraling fire suppression costs, may ultimately result in divergent fire regimes, with fires in roaded areas influenced primarily by the exigencies of suppression efforts while fire extent and severity in roadless areas become increasingly self-organized (Riley *et al* 2018).

Although differences in fire escape and fire extent are strongly associated with management regime, our statistical analyses demonstrate that the primary drivers of fire severity across the national forest landscape are differences in the fire environment and not land use designations per se. The small difference observed in fire severity between roadless and roaded areas (figure 5, tables 1 and S3.1) likely reflects differences in the abundance of different tree species between these management regimes. Trees growing in roadless sites with generally greater moisture availability and lower temperatures are less fire tolerant and more susceptible to mortality from fire than species found in drier, lower-elevation landscape settings (Dunn and Bailey 2016, Johnston *et al* 2019, Stevens *et al* 2020). Even without accounting for differences in mortality attributable to differences in species composition and the fire environment, the difference in fire severity between roadless and roaded areas is minor. For example, one study that calibrated Landsat-derived RdNBR with plot-based fire severity data in the Pacific Northwest found that the mean fire RdNBR values for roadless vs roaded areas across our study corresponded to 58% and 52% mortality of overstory trees from fire (Reilly *et al* 2017).

4.2. Management and policy implications

Limiting smoke exposure to vulnerable populations and reducing risk to water supplies, habitat, and human infrastructure from uncontrolled 'mega-fires' are important goals of policy makers (McKenzie *et al* 2014, Vaillant and Reinhardt 2017). Mechanical fuel treatments are a commonly used tool to accomplish these objectives (Stephens *et al* 2012), but more than half of all fires, including most of the largest fires in western US national forest lands, burn primarily in roadless areas where mechanical treatments are generally prohibited (tables 1 and 4). The extent of fire in landscapes where management options are limited drives home the need to adapt to fire rather than overcome fire in the American West (Dunn *et al* 2020).

Feedbacks between biophysical and policy systems may compound divergent trends in fire extent between roadless and roaded areas. The USFS is placing an increased emphasis on firefighter safety, which will result in fewer fire engagements in remote, complex terrain that are associated with firefighter casualties and which are more prevalent in roadless areas (Page *et al* 2019). Additionally, the greater extent of fire in roadless areas means that new fires are more likely to occur within previous fire perimeters. Suppressing these new ignitions may be extremely difficult and unsafe because of extensive patches of dead trees and difficult medical evacuation, potentially leading to a greater number of fires escaping initial suppression efforts in the future (Dunn *et al* 2019).

The disproportionate extent of fire in roadless areas may present challenges for managers depending on their objectives. For instance, roadless areas in coastal southern California are associated with large and costly fires that pose significant risk to adjacent densely populated communities (Keeley *et al* 2009). In other regions, repeated fire in dry mixed-conifer forests may result in new vegetation states with fundamentally different habitat potential (Coppoletta *et al* 2016, Serra-Diaz *et al* 2018, McCord *et al* 2020). Managers may need to adjust conservation strategies for sensitive species that rely on closed canopy forests within areas that are dominated by roadless areas given the extent of fire associated with this management regime (Spies *et al* 2006). For instance, in the Klamath ecoregion, a network of late-successional reserves designed to protect and restore habitat for the northern spotted owl (*Strix occidentalis caurina*) and other old-growth associates is anchored within roadless areas (Reilly *et al* 2018, Spies *et al* 2019). The extent of fire in these areas may require managers to conserve additional complex older forest within the roaded portion of the landscape or to develop a dynamic reserve system in which reserves are reallocated based on disturbance-mediated changes to habitat (Spies *et al* 2018).

Despite these challenges, in many areas throughout the western states, fire associated with management for roadless and wilderness characteristics has the potential to confer resilience in the context of climate change. Fire suppression has sharply reduced wildfire activity on national forest lands over the last 100–150 years, and most western forests are in a 'fire deficit' relative to the natural fire regime (Marlon *et al* 2012, Parks *et al* 2015). Lack of fire has resulted in increased forest density, shifts in species composition, and loss of resiliency to fire, drought, and insect outbreaks (Hessburg *et al* 2005, Stephens and Fulé 2005, Collins *et al* 2011). A number of recent studies have shown that forests in wilderness and roadless areas that have experienced multiple fires are less likely to experience stand-replacing fire and are recovering structural and compositional characteristics that were prevalent prior to Euro-American colonization (Larson *et al* 2013, Parks *et al* 2014b, Coop *et al* 2016). Climate change will increase flammability of most forests in the American West, and recent fire occurrence has a strong potential to moderate future fire effects and promote more diverse landscapes (Parks *et al* 2016, Hurteau *et al* 2019).

5. Conclusions

Decisions to conserve the wild and roadless characteristics of almost half of western US national forest lands has resulted in a landscape-scale experiment that contrasts the effects of passive and active approaches to accomplishing management objectives. A broad range of management tools, including mechanical thinning, prescribed fire, and wildland fire will continue to be employed to accomplish objectives on the roaded landscape (North *et al* 2012). Absent significant policy changes, wildland fire will continue to be the primary tool available to accomplish fuel management objectives within roadless areas (North *et al* 2015). Managers and scientists should collaborate to quantify the degree to which objectives are being accomplished within different management regimes across time and space.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.mtbs.gov.

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