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Research article

Rethinking the focus on forest fires in federal wildland fire management: Landscape patterns and trends of non-forest and forest burned area

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ABSTRACT

For most of the 20th century and beyond, national wildland fire policies concerning fire suppression and fuels management have primarily focused on forested lands. Using summary statistics and landscape metrics, wildfire spatial patterns and trends for non-forest and forest burned area over the past two decades were examined across the U.S, and federal agency jurisdictions. This study found that wildfires burned more area of non-forest lands than forest lands at the scale of the conterminous and western U.S. and the Department of Interior (DOI). In an agency comparison, 74% of DOI burned area occurred on non-forest lands and 78% of U.S. Forest Service burned area occurred on forested lands. Landscape metrics revealed key differences between forest and non-forest fire patterns and trends in total burned area, burned patch size, distribution, and aggregation over time across the western U.S. Opposite fire patterns emerged between non-forest and forest burns when analyzed at the scale of federal agency jurisdictions. In addition, a fire regime departure analysis comparing current large fire probability with historic fire trends identified certain vegetation types and locations experiencing more fire than historically. These patterns were especially pronounced for cold desert shrublands, such as sagebrush where increases in annual area burned, and fire frequency, size, and juxtaposition have resulted in substantial losses over a twenty-year period. The emerging non-forest fire patterns are primarily due to the rapid expansion of non-native invasive grasses that increase fuel connectivity and fire spread. These invasions promote uncharacteristic frequent fire and loss of native ecosystems at large-scales, accelerating the need to place greater focus on managing invasive species in wildland fire management. Results can be used to inform wildfire management and policy aimed at reducing uncharacteristic wildfire processes and patterns for both non-forest and forest ecosystems as well as identify differing management strategies needed to address the unique wildfire issues each federal agency faces.

1. Introduction

Wildland fire management has a long and varied history on public lands for most of the 20th century and beyond. National wildland fire policies concerning wildland fire management have primarily focused on forested lands dating soon after the U.S. Forest Service was established in 1905 (Pyne, 1997). Over the past century, the focus on federal wildland fire management has shaped public land policy and management leading to the creation of a large federal wildland fire management workforce across the United States with an annual budget of approximately 5.5 billion (https://crsreports.congress.gov/product/pdf/IF/IF1167; Dennison et al., 2014). While much of the legislation, resources, and management were directed at either suppressing fire or restoring fire and post-fire conditions on forested lands, non-forested landscapes such as cold and warm desert shrublands were not a large concern. Non-forested landscapes were often left out of federal wildland fire policy and direction due to infrequent large wildfire interactions in most of these regions.

From 1984 to 2020, U.S. area burned increased by five times (National Interagency Fire Center, https://www.nifc.gov/fire-information/statistics; Crist et al., *in review*). In response to this uptick in wildfires, several recent wildland fire management policies were enacted. National legislation such as the Healthy Forest Restoration Act (2003), the Collaborative Forest Landscape Restoration Program (2009), and the Farm Bill (2018) heavily invested in forest fuel reductions (mechanical and prescribed fire), community protection, and restoration of forest conditions as a means for reducing wildfire risk. In addition, direction to federal agencies concerning wildland fire management largely focused

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on forest fire and forest restoration (U.S. Executive Office of the President, 2018; USDA Forest Service, 2018; USDA-USDI, 2013; USDA Forest Service, 2012). The National Cohesive Wildland Fire Strategy (USDA-USDI, 2013) was formed as a national-scale effort to work collaboratively among all stakeholders and across all land ownerships to collectively agree to achieve three goals: resilient landscapes, fire-adapted communities, and a safe and effective wildfire response. More recently, two federal strategies broadened the vegetation scope for wildland fire management. The Department of Interior's Integrated Rangeland Fire Management Strategy (U.S. Department of the Interior, 2015) focused on addressing wildfire in sagebrush ecosystems for Greater Sage-grouse habitat conservation. And, the U.S. Forest Service's Wildfire Crisis Strategy (USDA Forest Service, 2022) includes the identification of other vegetation at a high fire risk across all agency jurisdictions but recommends forest restoration as the primary management approach for addressing risk. Despite these investments and strategies, the western U.S. continued to burn at historically higher rates over the past two decades (National Interagency Fire Center, https://www.nifc.gov/fire-information/statistics; Schoennagel et al., 2017; Dennison et al., 2014; Calkin et al., 2011).

Wildfires in many non-forested systems such as shrubland and desert ecosystems were relatively infrequent until the 1980s when changes in fire regimes due to invasive grass expansion across the western U.S. were documented (D'Antonio and Vitousek, 1992; Knapp, 1996, Esque and Schwalbe, 2002; Balch et al., 2009). Biological invasions of nonnative fire-prone grasses are changing fire regimes for shrubland and desert ecosystems that historically experienced fire relatively infrequently and transforming these ecosystems into alternative stable states of invasive grass dominance that promote frequent fire (D'Antonio and Vitousek, 1992; Grigulis et al., 2005; Brooks et al., 2004; Keeley and Brennan, 2012; McDonald and McPherson, 2013; Setterfield et al., 2013; Godfree et al., 2017). These invasive grasses affect fire regimes by colonizing the interstices between native vegetation, drying out earlier in the season compared to native grasses, and increasing the amount and continuity of fine fuels (Davies and Nafus, 2013). After fire, invasive grasses often outcompete recovering native vegetation (D'Antonio and Vitousek, 1992; Eliason and Allen, 1997; Melgoza et al., 1990). Invasive grass dominance promotes fire spread and can result in invasive annual grass-fire cycles. Invaded ecosystems, such as drier and lower elevation sagebrush, were found to burn 2–4 times more frequently than relatively uninvaded communities (Brooks et al., 2004; Balch et al., 2013; Bradley et al., 2018a). There are many introduced invasive grasses across the western U.S. that similarly alter fine fuel conditions resulting in longer fire seasons, higher fire frequency, and larger fire extents for certain shrubland and desert ecosystems, such as African Wire Grass (*Ventanata dubia*), Medusahead (*Taeniatherum caput-medusae*), Red Brome (*Bromus madritensis* subsp. *rubens*), Buffelgrass (*Pennisetum ciliare, Cenchrus ciliaris*), and South African Lehmann lovegrass (*Eragrostis lehmanniana*) (Fusco et al., 2019). These grasses also are invading forested ecosystems, increasing fire cycles and outcompeting native plant recovery for ponderosa pine (Kerns and Day, 2017; Kerns et al., 2020) and pinon/juniper (Miller and Tausch, 2001) communities in a similar manner as to what has been noted for sagebrush, but vary in terms of climatic suitability and where they occur on the landscape.

While this cycle of invasion, fire, and exclusion of native vegetation is believed to be pushing shrubland and desert ecosystems across a threshold to an undesirable state of invasive grass/fire cycle dominance, the spatiotemporal dynamics of the invasive grass/fire cycle has not been broadly mapped or incorporated into wildland fire risk assessments for federal wildland fire management agencies. Federal fire risk mapping and assessments began in the early 2000's and largely focused on forested lands. An example is the national Fire Regime Condition Class that mapped departure from historic wildfire trends, and used to track agency reported acres treated based on this departure required for the Healthy Forest Restoration Act (2003). Efforts since then expanded to produce national fire risk assessments such as the wildfire hazard potential mapping developed by the U.S. Forest Service (Dillon et al., 2015). This effort utilizes simulated large fire probability and flame length maps across the U.S. (Short et al., 2016) to assess where highly valued resources (e.g. wildland urban interface or municipal watersheds) may be at a higher risk of fire. While these efforts have been successful in identifying certain areas at a higher or lower risk of wildfire, they do not distinguish between specific vegetation types in the final products.

Given recent trends of increasing area burned over the past few decades along with large-scale expansion of nonnative invasive grasses that alter shrubland and desert fire cycles, there is a need in wildland fire management to understand current wildfire trends for these vegetation types in the United States. This information can be used to develop wildland fire management strategies that address different causes of uncharacteristic fire, such as fire deficit due to past fire suppression or fire surplus due to invasive grasses. The advent of landscape metrics allows for the quantification of landscape pattern for understanding the interaction of ecosystem processes, human use, wildlife movements, and landscape change over time (O'Neill et al., 1988; McGarigal and Marks, 1995; Gustafson, 1998; With and Crist, 1995). Landscape metrics can measure the spatial character and distribution of patches across a region or landscape (McGarigal and Marks, 1995; McGarigal and Cushman, 2005). Two types of landscape metrics, *area* and *aggregation*, can help assess potential differences of wildfire extent and pattern between forested and non-forested (shrubland, grassland, and desert) ecosystems. Area metrics can measure burned patch size of individual fires and calculate the total area of burned patches belonging to a class type (vegetation) across a landscape or region. Aggregation metrics can quantify the spatial arrangement and distribution of burned patches, whether the arrangement is clustered or distributed equally across a landscape, region, or class type, and are important for understanding how physical and ecological processes influence landscape-level burn patterns. Results of landscape metrics can therefore provide information on wildfire trends and patterns for different ecosystem types and geographic regions for management decisions and actions (Cushman et al., 2008). Metrics also are standardized measurements that help determine and prioritize management actions. While some metrics are scale-dependent, they can be quantified and compared at a variety of spatial extents and timescales (Frazier and Kedron, 2017) using a range of available spatial data (Tarbox et al., 2022). This type of information can expand current knowledge of wildfire dynamics over space and time, and help create more holistic wildland fire policy, priorities, and strategies for federal fire management agencies that manage many ecosystems with differing wildfire effects across their jurisdictions.

Recent advances in remote sensing have made it possible to map invasive grass-dominated communities at ecoregional extents of the western U.S., and these maps have provided snapshots of invasive grass expansion over space and time (Boyte and Wylie, 2016; Germino et al., 2016; Bradley et al., 2018a; Peterson, 2005; Allred et al., 2021; Maestas et al., 2020; Jones et al., 2021). Increases in fire frequency for non-forested ecosystems, especially sagebrush ecosystems, also have been mapped at large spatiotemporal scales (Brooks et al., 2004; Fusco et al., 2019; Smith et al., 2021). Recent advancements made in remote sensing and spatiotemporal analyses of invasive grasses along with advances in mapping past wildfire occurrence and extents (i.e. fire perimeters) make it possible to examine and map altered fire cycles for all ecosystem types across the U.S. This information can be used to identify geographically where certain ecosystems may be experiencing increased fire frequencies and contributing to the overall increase of wildfire activity across the western U.S. as well as distinguish between areas at a higher fire risk due to increased fire cycles. The spatial data can be added to fire risk assessments and wildfire monitoring programs to gain a broader understanding of management needs to either reduce or increase fire frequency.

This study was conducted to quantify and compare wildfire trends for non-forested and forested lands over the past two decades across all western lands, and specific federal agency jurisdictions including the Department of Interior (DOI), The U.S. Forest Service (FS) and the Bureau of Land Management (BLM). Since BLM jurisdictions are under the DOI along with National Park Service, the U.S. Fish and Wildlife Service and the Bureau of Indian Affairs, BLM was included with the DOI analyses. BLM was also analyzed separately since the BLM and FS manage more federal land and experience more area burned than other federal agencies. Objectives included: 1) summarize and compare area burned for forested and non-forested lands across the conterminous United States and among federal land management agency jurisdictions, specifically the DOI, FS, and BLM; 2) use landscape metrics to quantify differences in landscape-level wildfire patterns between forest and non-forest lands across the entire western U.S. and by federal land management jurisdictions; and 3) conduct a fire regime departure analysis to identify geographically where non-forested and forested areas may be experiencing higher fire frequencies compared to historic trends. Results provided a quantitative assessment of fire patterns in the western U.S. and identified key differences among forest and non-forest fire patterns and trends. Results can be used to better focus wildland fire and fuels management strategies where they are most needed on public lands.

2. Methods

2.1. Study area

The study area used to summarize non-forested and forested acres burned was the conterminous U.S. and eleven western U.S. states where wildfire has played a dominant role: California, Oregon, Washington, Idaho, Nevada, Arizona, New Mexico, Utah, Colorado, Wyoming, and Montana. For the spatial and temporal pattern and the fire departure analyses, the study area is limited to those eleven western U.S. states, and federal agency jurisdictions: the FS, DOI, and BLM (Fig. 1).

2.2. Summarizing non-forested and forested area burned

A geospatial time-series analysis was used to summarize and compare area burned between non-forest (shrubland, grassland and desert communities) and forest (tree-dominated) lands across the conterminous U.S. from 2000 through 2020. Fire records from 2000 through 2019 were obtained from GeoMAC (https://wildfire.usgs.gov/geomac/GeoMACTransition.shtml), which is a compilation spatial database of federal, state, and local wildfires and excludes agricultural fires and prescribed fire. GeoMAC's wildfire perimeter database was selected over MTBS (Monitoring Trends in Burn Severity) because MTBS lags 2 years behind GeoMAC in fire perimeter collection and processing. The GeoMAC database contains wildfire perimeters with attributes such as fire year, fire size, and an identifier. Since GeoMAC ended in 2019, fire records for 2020 were obtained from Department of Interior Wildland Fire Decision Support System using the same methodology as GeoMAC.

To compare area burned on non-forest and forest lands over time, LANDFIRE's (https://landfire.gov) Existing Vegetation Type (EVT) life-form categories (EVT_ORDER) depicting "tree-dominated", "shrub", and "herbaceous" raster datasets at the 30 m scale were used to differentiate between non-forested and forested vegetation types. Using only these three life-form categories removed water, rock, and urban developed areas represented by the no dominate life-forms, and non-vegetated categories in the dataset. The selected life-form categories were masked out annually from the LANDFIRE life-form raster datasets using GeoMAC fire perimeters that correspond with the timeframe of the LANDFIRE EVT dataset release dates. Because LANDFIRE updates EVT datasets every few years, one EVT dataset would be masked with the annual fire perimeter datasets occurring at and after that EVT timestamp up till the next released version. Given this time interval selection, this process likely captured some reburns where the life-form category had changed (e.g. tree-dominated to shrub/herbaceous dominated). This reburn life-form change likely occurred more with the shrubland, herbaceous categories than the tree-dominated.

To analyze differences in burned area across federal agencies, jurisdictional boundary GIS layers for the FS, DOI, and BLM boundaries from BLM's National Surface Management Agency Layer (https://gbp-blm-egis.hub.arcgis.com/datasets/blm-national-surface-management-agency-area-polygons-national-geospatial-data-asset-ngda/about) were used to mask out the burned life-form categories by agency jurisdiction. All datasets (fire perimeters, LANDFIRE EVT, federal agency jurisdictions) were transformed to the same projection prior to the analyses.

A total of eighty attribute tables from the resulting eighty final grids representing two decades of burned area by life-form across the conterminous U.S. (all lands including private, state, federal, etc), and the DOI, FS, and BLM jurisdictions were imported into Microsoft excel to summarize, compare, and graph results of area burned for non-forest and forest lands. The categories shrub and herbaceous were combined to represent all non-forest lands, removing the reburn life-form changes described earlier, and were compared with the category tree-dominated, which represents forest lands in the burned area summaries. This process retained a few reburns where "tree" was converted to "shrub/herbaceous", but at the scale of analysis were likely minimal. From 2000 to 2020, total area burned annually was summarized for non-forest and forest burned area separately for the conterminous U.S. Fire perimeter data tend to overestimate actual area burned for a fire (e.g. due to the inclusion of unburned patches within the perimeter or mistakes in delineations) but still offer a reliable estimate. Temporal trend lines were graphed using linear regression to see general patterns of area burned increases and decreases over time.

2.3. Quantifying landscape patterns for non-forested and forested area burned

FRAGSTATS software (version 4.2; McGarigal et al., 2012) is a computer program designed to compute a wide variety of landscape metrics for categorical map patterns (McGarigal and Marks, 1995). FRAGSTATS was used to compute 12 landscape metrics that calculate area and aggregation metric statistics on forest and non-forest burned patches from the derived geospatial datasets clipped to the western states described under objective one. Landscape metrics selected for the analysis are described in Table 1. Geospatial datasets depicting area burned for the selected three life form categories ("tree-dominated", "shrub-dominated", and "herbaceous-dominated") were combined into two classes: class 1 was non-forest (shrub and herbaceous dominated categories combined), and class 2 was forest (tree dominated category). Due to computational limitations of FRAGSTATS, each grid was upscaled to 90 m grid cell size using the Resample tool and majority technique in ArcGIS. To limit the influence of scale on the results of the analysis, landscape metrics were computed across all land ownerships (private, state, federal, etc.) for the eleven western states study area. The same metrics were computed across the study area for each federal jurisdictional boundaries: the FS, DOI, and BLM. Metric results were imported into Microsoft excel spreadsheets and then summarized, compared, and graphed for the time-period 2000 to 2020. Temporal trend lines were graphed using linear regression. The statistical measure Welch's *t*-test was used to test for differences among metrics between non-forest and forest classes across all lands of the western U.S. and then for each agency jurisdiction. The sample size was 20 (years of data) for each non-forest and forest class. Box and whisker plots were produced for comparisons between non-forest and forest area burned for the western U.S. and each agency's jurisdiction.

2.4. Areas experiencing a wildfire surplus compared to historic trends

The fire regime departure analysis compared current wildfire intervals to historic intervals to determine where vegetation communities may have departed from their historic fire trends. Two datasets were

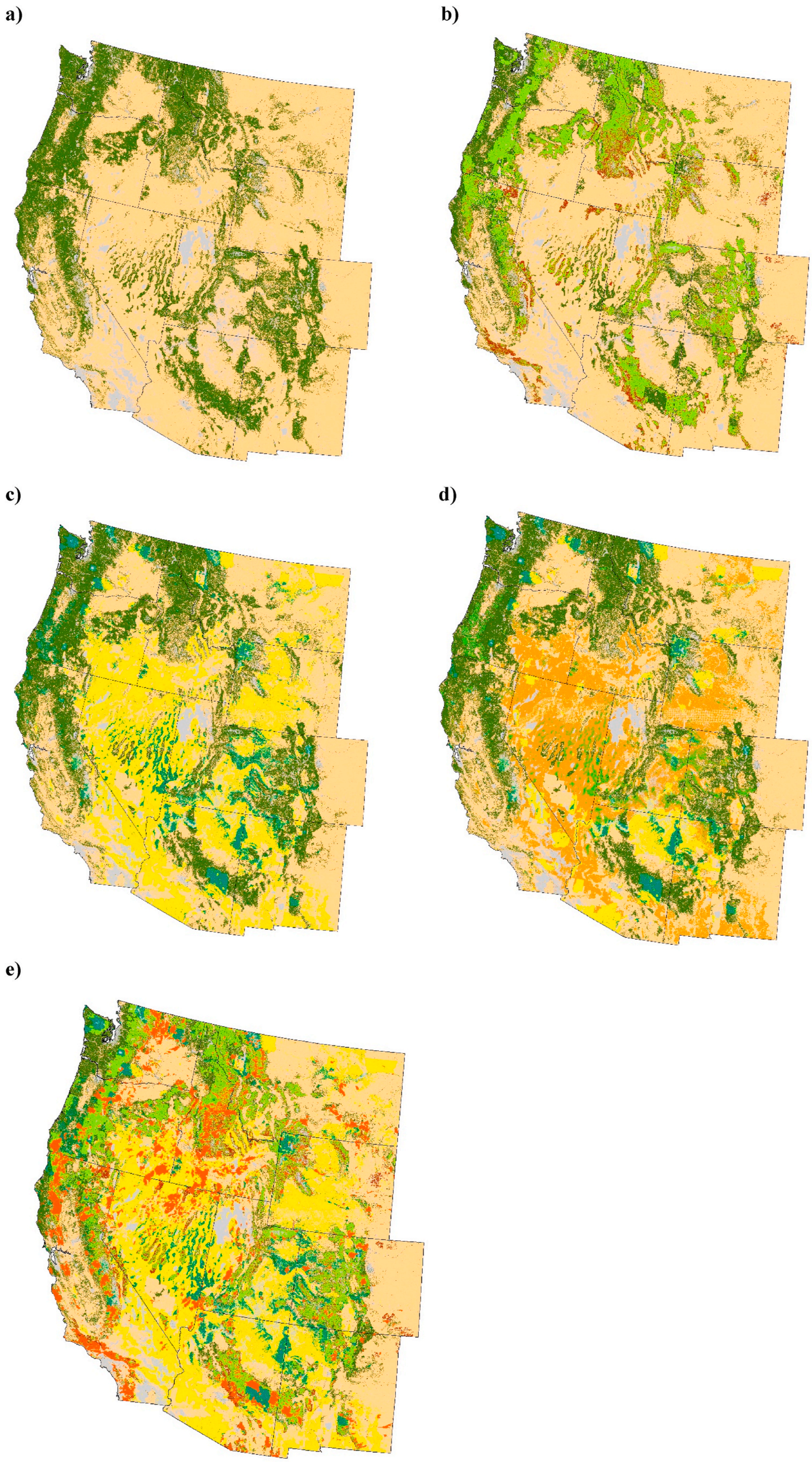


Fig. 1. Five maps depicting the study area for the quantitative assessment for spatial and temporal trends of area burned for forest and non-forest lands across the western U.S. and three federal agencies (the U.S. Forest Service (FS), Department of Interior (DOI), and Bureau of Land Management (BLM)). **a)** Western U.S. (California, Oregon, Washington, Arizona, Nevada, Idaho, New Mexico, Utah, Colorado, Montana, and Wyoming) with forest lands in dark green, non-forest lands in tan, and other (rock, water, urban) in gray. **b)** FS jurisdictions overlaid on the western U.S. map. FS forest lands are lime green, and FS non-forest lands are dark umber. **c)** DOI jurisdictions including the National Park Service, U.S. Fish and Wildlife Service, Bureau of Indian Affairs, Bureau of Land Management overlaid on the western U.S. map. DOI forest lands are teal and DOI non-forest lands are yellow. **d)** BLM jurisdictions overlaid with DOI. BLM forest lands are lime green and non-forest lands are orange. DOI forest lands are teal and DOI non-forest lands are yellow. **e)** Historic fire perimeters from 2000 to 2021 shown in red for the western U.S. Perimeters are overlaid with the western U.S. map (forest lands are dark green and non-forest lands are tan), DOI (forest lands in teal and non-forest in yellow) and FS (forest lands in lime green and non-forest lands in dark umber. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Landscape metrics used in a landscape pattern analysis of burned non-forest and forest patches. Metrics were derived from FRAGSTATS (version 4.2).

Metric	Definition
Area	
class area (CA)	The sum of the area of all patches of the corresponding patch type (hectares).
percent landscape (PLAND)	The sum of the area of all patches divided by total area of the landscape and multiplied by 100 (percent).
mean patch area (AREA_MN)	The sum, across all patches of the corresponding patch type, of the corresponding patch metric values, divided by the number of patches of the same type (hectares).
area weighted mean patch area (AREA_AM)	The sum, across all patches in the landscape, of the corresponding patch metric value multiplied by the proportional abundance of the patch (i.e., patch area divided by the sum of patch areas) (hectares).
largest patch index (LPI)	LPI equals the area of the largest patch of the corresponding patch type divided by total landscape area, multiplied by 100 (percent). LPI equals the percentage of the landscape comprised by the largest patch.
Aggregation	
number of patches (NP)	The total number of patches of the corresponding patch type.
patch density (PD)	The number of patches of the corresponding patch type (NP) divided by total landscape area and multiplied by 100 (percent).
mean nearest neighbor (ENN_AM)	The sum of the distance (m) to the nearest neighboring patch of the same type, based on nearest edge-to-edge distance, for each patch of the corresponding patch type, divided by the number of patches of the same type.
area weighted mean nearest neighbor (ENN_AM)	The sum of the distance (m) to the nearest neighboring patch of the same type, based on nearest edge-to-edge distance, of the corresponding patch type, multiplied by the proportional abundance of the patch (i.e patch area divided by the sum of patch areas).
clumpy (CLUMPY)	The proportional deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution. CLUMPY equals 0 when the focal patch type is distributed randomly and approaches 1 when the patch type is maximally aggregated.
percentage of like adjacencies (PLADJ)	The number of like adjacencies involving the focal class, divided by the total number of cell adjacencies involving the focal class; multiplied by 100 (percent). The percentage of cell adjacencies involving the corresponding patch type that are like adjacencies.
interspersion and juxtaposition (IJI)	Minus the sum of the length (m) of each unique edge type involving the corresponding patch type divided by the total length (m) of edge (m) involving the same type, multiplied by the logarithm of the same quantity, summed over each unique edge type; divided by the logarithm of the number of patch types minus 1; multiplied by 100 (percent). The observed interspersion over the maximum possible interspersion for the given number of patch types. IJI = 100 when the corresponding patch type is equally adjacent to all other patch types (i.e., maximally interspersed and juxtaposed to other patch types).

used in the analysis. 1) Large Fire Probability (Short et al., 2016), which represents modeled current annual large fire probability across the conterminous U.S. at a 270 m resolution. Large fires were defined as >60 ha for forest lands, and >120 ha for non-forest lands. 2) historic mean fire return interval point estimates from LANDFIRE's Bio Physical Settings (BPS) models (2014) and descriptions (spreadsheets are available for download at https://www.landfire.gov/national_veg_models_op2.php). The historic mean fire return interval point estimate (MFRI) was converted to an annual probability of historic fire return interval and assigned to the attribute table of the LANDFIRE raster grid based on a common identifier available in LANDFIRE. The historic fire return interval grid was upscaled from a 30 m to a 90 m resolution and the large fire probability dataset was downscaled from a 270 m to a 90 m resolution using the Resample tool and majority technique in ArcGIS. To determine departure from the historic fire return interval, a ratio was calculated by dividing the annual fire return interval by the annual burn probability. Values close to 1.0 indicate similar historic and current burn probabilities, with more difference the farther away from 1.0. To identify areas experiencing more fire compared to historic trends, all raster cells greater than 2.0 (2 times higher than the annual historic mean) were selected to show where fire frequency was higher than historic trends and then mapped across the western U.S. Using GIS overlays, vegetation communities from LANDFIRE 2014 Existing Vegetation Types (EVT) were overlayed with the fire departure, selected, and then ranked by area. All analyses were conducted in ArcGIS.

There are caveats concerning the use of this dataset. First, results are based on a departure from a mean point estimate fire return interval and do not consider if the current fire probability is within the range of historical variation around the mean. Second, depending on the vegetation type, the BPS mean fire return point estimates can be based on limited empirical data and expert opinion. Lastly, because the large fire probability source dataset (Short et al., 2016) represents the probability of large fires, the analysis does not represent small fires in ecosystems, thus potentially underestimating fire frequency where small fires are common. However, even in those areas, small fires likely make up a small total portion of the landscape, so this may be negligible. With these caveats in mind, results here represent a potential departure trend, and more information/science on historical fire regimes is needed to determine absolute departure.

3. Results

3.1. Summaries and comparisons of area burned

Annual summaries and graphed trends show that wildfire burned as much area on non-forest lands as on forest lands over the past two decades. This trend was found across all land ownerships and jurisdictions for the conterminous and the western U.S., as well as federal agency lands (DOI, FS, BLM). For both classes, burned area increased over the 20-year time-period (Fig. 2), and annual burned area was higher on non-forest lands than forest lands for 14 out of the past 21 years across the conterminous U.S. Total burned area in non-forest was 18,412,462 ha and for forest was 15,536,655 ha.

For the western U.S. total burned area in non-forest was 15,593,237 ha and for forest was 14,011,578 ha (Table 2). From 2000 to 2020, 46% of burned area on western federal lands (DOI and FS) occurred in non-forest types, whereas, across all western lands, burned area in non-forest class accounted for 53% (Table 2). Approximately 74% of the burned area on DOI lands occurred in the non-forest class and 78% of the burned area on FS lands occurred in the forest class. Comparisons of forest and non-forest burned area by jurisdiction using box and whisker plots (Fig. 3) depicted different results between the FS and the DOI and the BLM separately. For DOI, plots show that burned area on non-forest lands was substantially higher than on forest lands, and the opposite trend occurred for the FS. Plots for the DOI and BLM were similar indicating that burned area in the non-forest class occurred primarily on BLM lands. BLM burned area comprised 85% of DOI non-forest burned area and 40% of forest burned area.

3.2. Quantifying wildfire trends using landscape metrics

3.2.1. Landscape metric comparison between non-forest and forest burned areas

For the western U.S., 12 landscape metric results were used to quantify and compare total area burned and the spatial land patterns of non-forested and forested wildfires over the past two decades. T-tests

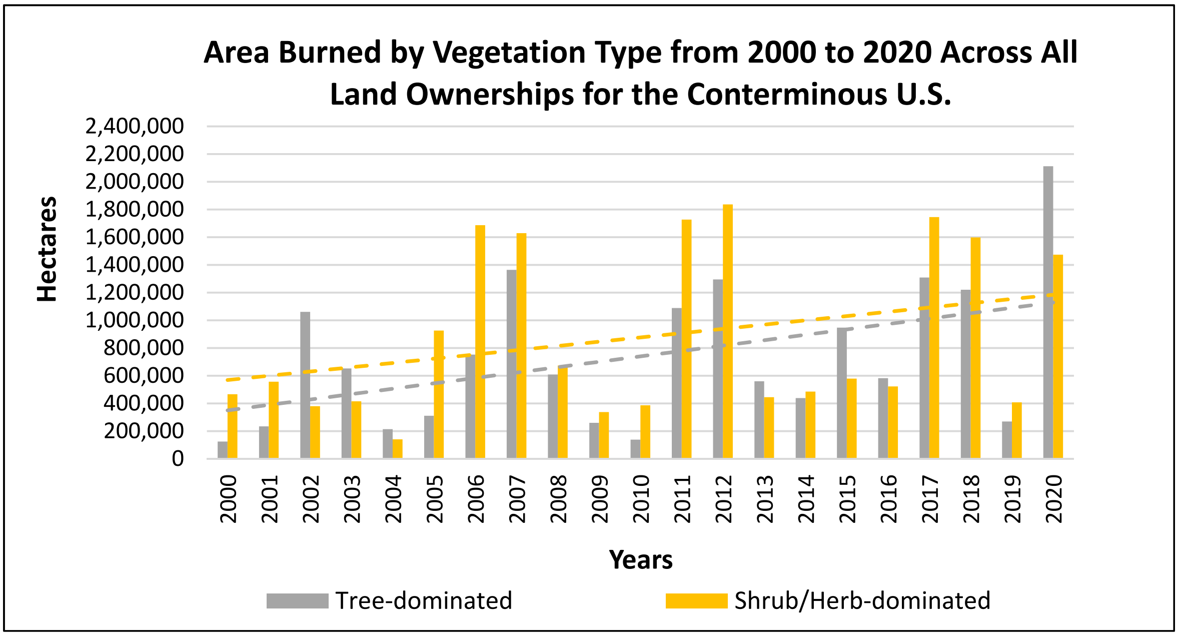


Fig. 2. Area burned for two vegetative class types: non-forested (shrub and herbaceous dominated; yellow) and forested (tree dominated; gray) over the past two decades across all land ownerships for the conterminous U.S. Total area burned for forested lands was 15,536,655 ha and for non-forested lands was 18,413,462 ha. The mean area burned for forested lands was 739,841 ha (+427,384 ha S.D.) and 876,784 ha (+533,778 ha, S.D.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

comparing the results of the landscape metrics were not significant indicating that there was no difference in area burned between the non-forest and forest classes (Table 2). Results of area and aggregation metrics in Table 2 showed that the non-forest class was burning more area (CA), experienced larger fire sizes (LPI and AREA_AM), and had a higher number of burned patches (NP) compared to the forest class.

Temporal trends for each metric depicted increases and decreases over time for both burned non-forest and forest classes (Fig. 4). Temporal trends for the AREA_MN indicated that the mean patch size decreased for the non-forest class and increased for the forest class, despite area-weighted patch size (AREA_AM) becoming larger over time for both classes. While summaries depicted more burned area in the non-forest class compared to the forest class, a comparison of the trendlines showed both are increasing over time with a higher increase in the forest class (steeper slope in the trendline; Fig. 4). The only two significant metrics (PD and IJI) indicated different spatial and temporal patterns between forest and non-forest classes. Yet, their temporal trends depicted some similarities where forest and non-forest burned patches were spatially distributed further apart at the scale of the western U.S. but occurring closer in proximity at a regional scale (supported by increasing trendlines in IJI). Trendlines for the area-weighted nearest neighbor (ENN_AM) indicated that larger burned forest burned patches were occurring closer together over time, whereas the opposite trend is depicted for burned non-forest patches. The metrics PLADJ and CLUMPY showed that for both non-forest and forest classes, a large percentage of burned area within the fire perimeters was dominated by either non-forest or forest types and this trend did not change over time despite the increase in size of area-weighted patch size (AREA_AM; Table 2; Fig. 4).

Comparisons of burned non-forest and forest classes for each agency showed different spatial and temporal patterns for each jurisdiction. Metric results for each agency (FS, DOI, BLM) differed significantly between the burned forest and non-forest classes (Table 2). Out of the 12 metrics, the DOI had 8 significant metrics, BLM had 11 significant metrics and the FS had 10 significant metrics (Table 2). The higher number of significant metrics for the BLM and the FS is likely due to each agency's non-forest and forest class composition (e.g. BLM is approx. 70% non-forested while the FS is approx. 70% forested in the western US). For the DOI and BLM, the metric CA, total burned area, was significantly higher for the non-forest class compared to the forest class (Table 2). In addition, the LPI and AREA_AM had significantly larger burned patch sizes for the non-forest class. For the FS, metric results depicted total burned area (CA) was significantly higher in the forest class, and large patch sizes (AREA_AM, LPI) also were comparably larger. Interestingly, the number of burned patches (NP) was significantly higher for the forest class for the DOI and BLM, and significantly higher in the non-forest class for the FS. Number of patches (NP) analyzed with the mean burned patch size (AREA_MN) indicate many small, burned patches occurred in these classes (forest class for DOI and BLM, and non-forest class for FS). Aggregation metrics (PD, IJI, PLADJ, CLUMPY and Nearest Neighbor) also depicted opposite spatial patterns between the non-forest and forest classes for each agency. The DOI and BLM non-forested burned patches had a higher spatial distribution and are less aggregated in the non-forested class, while the FS had similar results for the forested class.

Temporal patterns for each agency depicted opposite patterns between non-forest and forest burned area (Fig. 5). The BLM and DOI had relatively similar temporal trends and spatial patterns likely due to DOI being largely composed of BLM lands (Fig. 5a and b, respectively). Results were relatively similar for the non-forest class but depending on the metric differed for the forest class. For the BLM and DOI, the metrics PLAND (percent class burned) and LPI (large patch index) indicated increasing trends in burned area and large patch sizes for the non-forest class and decreasing trends for the forested class (Fig. 5a and b). Metric results for Interspersion and juxtaposition (IJI) and the area-weighted mean nearest neighbor (ENN_AM) show that the spatial distribution of non-forest and forest burned patches increased over time for the BLM and DOI, and patch density (PD) decreased slightly or had a relatively flat trendline (Fig. 5a and b). Aggregation metrics indicate that non-forest wildfires were increasing in their spatial distribution across the western U.S.

For the FS, temporal trends in the burned forest class depicted a much higher increase in burned area (CA, PLAND) and mean patch size (AREA_MN) over time when compared with the non-forest and forest

Table 2
Landscape metric summary statistics for the area (ha) burned from 2000 through 2020 on non-forest and forest patches across the western U.S.. P-values are for Welch's t-tests comparing the landscape metrics for non-forest and forest classes. Significant P-value are bolded. Jurisdictions are Department of the Interior (DOI), Bureau of Land management (BLM) and U.S. Forest Service (USFS). See Table 1 for metric definitions and units.

Metrics	Non-Forest Class				Forest Class				T-Test
	Total	**Mean**	**Range**	**SD (±)**	**Total**	**Mean**	**Range**	**SD (±)**	**P-value**
Western U.S.									
CA	15,593,237.10	764,697.47	1,589,847.75	505,578.62	14,011,577.64	673,138.58	1,973,952.18	491,341.87	0.5551
PLAND		53.41	50.42	13.89		44.85	50.85	13.68	0.0509
NP	389,503.00	18,547.76	44,587.00	11,776.33	324,977.00	15,475.10	29,359.00	9315.72	0.3543
PD		1.29	1.19	0.34		1.10	0.71	0.19	**0.0292**
LPI		7.48	23.80	5.25		5.37	12.74	3.43	0.1321
AREA_MN		47.04	83.74	25.13		43.23	80.89	18.90	0.5813
AREA_AM		28,895.81	103,293.13	23,898.56		25,178.75	82,279.23	26,375.21	0.6349
ENN_MN		782.53	1709.98	460.56		693.71	1209.15	285.57	0.4578
ENN_AM		2767.11	3443.45	1106.36		2047.84	4186.84	1306.68	0.0615
CLUMPY		0.67	0.18	0.04		0.70	0.18	0.04	0.0536
PLADJ		84.85	16.02	4.56		83.36	18.15	4.21	0.2762
IJI		48.75	32.70	10.34		33.32	44.21	14.64	**0.0004**
DOI									
CA	7,322,329.53	348,682.36	1,008,548.82	279,570.18	2,299,711.50	109,510.07	225,521.82	62,429.78	**0.0009**
PLAND		69.74	49.49	15.46		28.69	49.61	15.39	**0.0000**
NP	84,584.00	4027.81	6655.00	1932.12	119,765.00	5703.10	15,103.00	3937.88	0.0906
PD		1.08	2.13	0.53		1.23	0.75	0.20	0.2360
LPI		13.75	41.05	9.80		6.03	36.07	7.79	**0.0074**
AREA_MN		84.50	151.97	48.97		24.22	57.38	15.18	**0.0000**
AREA_AM		26,346.33	155,237.85	35,148.58		7843.58	68,162.06	14,582.19	**0.0345**
ENN_MN		1715.68	4107.95	1088.79		1157.42	2708.18	745.39	0.0605
ENN_AM		3085.97	7474.31	2040.27		3622.59	12,316.98	3717.23	0.5661
CLUMPY		0.57	0.36	0.10		0.68	0.17	0.05	**0.0001**
PLADJ		87.92	17.33	4.30		76.82	26.27	7.12	**0.0000**
IJI		51.28	41.31	12.52		28.96	46.31	13.10	**0.0000**
BLM									
CA	6,222,361.68	296,302.94	921,476.25	260,900.97	1,164,935.52	55,473.12	129,842.19	38,489.13	**0.0004**
PLAND		78.84	42.92	11.21		19.74	43.14	11.12	**0.0000**
NP	54,962.00	2617.24	4166.00	1444.97	91,773.00	4370.14	13,306.00	3446.66	**0.0408**
PD		0.99	2.25	0.55		1.29	1.07	0.26	**0.0362**
LPI		18.01	48.20	12.06		3.32	10.37	3.08	**0.0000**
AREA_MN		104.67	194.32	56.01		15.13	24.89	7.02	**0.0000**
AREA_AM		28,062.43	169,839.69	38,977.30		1967.28	4967.30	1334.79	**0.0061**
ENN_MN		2378.26	5717.05	1551.73		1380.82	4080.56	1014.29	**0.0188**
ENN_AM		3045.14	9061.29	2335.98		2332.43	5683.77	1589.39	0.2555
CLUMPY		0.43	0.76	0.18		0.63	0.25	0.07	**0.0001**
PLADJ		89.06	18.20	4.14		69.82	28.11	8.02	**0.0000**
IJI		51.71	39.40	11.20		24.74	38.52	11.69	**0.0000**
USFS									
CA	2,637,481.50	125,594.36	326,848.77	88,793.18	9,340,438.05	444,782.76	1,248,340.41	324,382.69	**0.0002**
PLAND		23.69	36.26	8.33		74.69	34.38	8.41	**0.0000**
NP	241,846.00	11,516.48	26,160.00	7542.39	89,603.00	4266.81	9844.00	2708.37	**0.0003**
PD		2.06	1.17	0.31		0.86	1.35	0.36	**0.0000**
LPI		4.54	26.17	5.73		12.47	26.82	6.69	**0.0002**
AREA_MN		11.91	28.17	5.66		102.59	191.31	44.23	**0.0000**
AREA_AM		6221.33	47,588.27	10,142.87		25,408.07	77,954.76	25,383.42	**0.0034**
ENN_MN		524.92	809.35	225.68		1238.91	2656.76	643.85	**0.0001**
ENN_AM		1688.94	12,941.05	2840.67		2492.59	6758.39	1872.38	0.2865
CLUMPY		0.56	0.21	0.05		0.49	0.33	0.07	**0.0005**
PLADJ		66.23	31.05	6.18		87.34	10.84	2.96	**0.0000**
IJI		32.99	56.76	15.07		40.11	55.49	20.05	0.2014

classes for the DOI and BLM (Fig. 5c). Interestingly, the large patch index (LPI) for the FS showed that large fire sizes decreased over this time-period for the forest class despite the increase in both the forest area burned (CA) and the mean patch size (AREA_MN) (Fig. 5c). These results combined with other metric results indicate more fires are burning in the forest class with highly variable patch sizes. Temporal trends for the aggregation metrics (IJI, PD, and ENN_AM) depicted a larger spatial distribution of wildfire across the jurisdiction over time for both classes, similar to the spatial patterns of DOI and BLM (Fig. 5c). For all agencies, the spatial distribution of wildfire increased over time at the scale of the western U.S.

3.2.2. Comparison of non-forest and forest burned patches among federal agencies

Statistical results were significant for many of the landscape metrics used to compare amongst the agencies (FS, DOI and BLM; Table 3). Between the DOI and BLM, 10 out of 12 metrics were insignificant for the non-forest class, and 8 out of 12 were insignificant for the forest class, highlighting that BLM's spatial and temporal wildfire patterns have a strong influence on DOI's fire patterns (Table 3). Metric results used to compare between the FS and DOI, and the FS and BLM were all significant except for two aggregation metrics in the non-forest class, area-weighted nearest neighbor and clumpy (ENN_AM, CLUMPY), and one aggregation metric in the forest class (ENN_AM), respectively. Results indicate that the distances between large fire patch sizes and the distribution pattern were not significantly different. The high proportion of significant metric results indicate that the FS had almost opposite temporal and spatial patterns in burned forest and non-forest classes when compared to the DOI and the BLM. These different patterns were captured by just using two life-form classes.

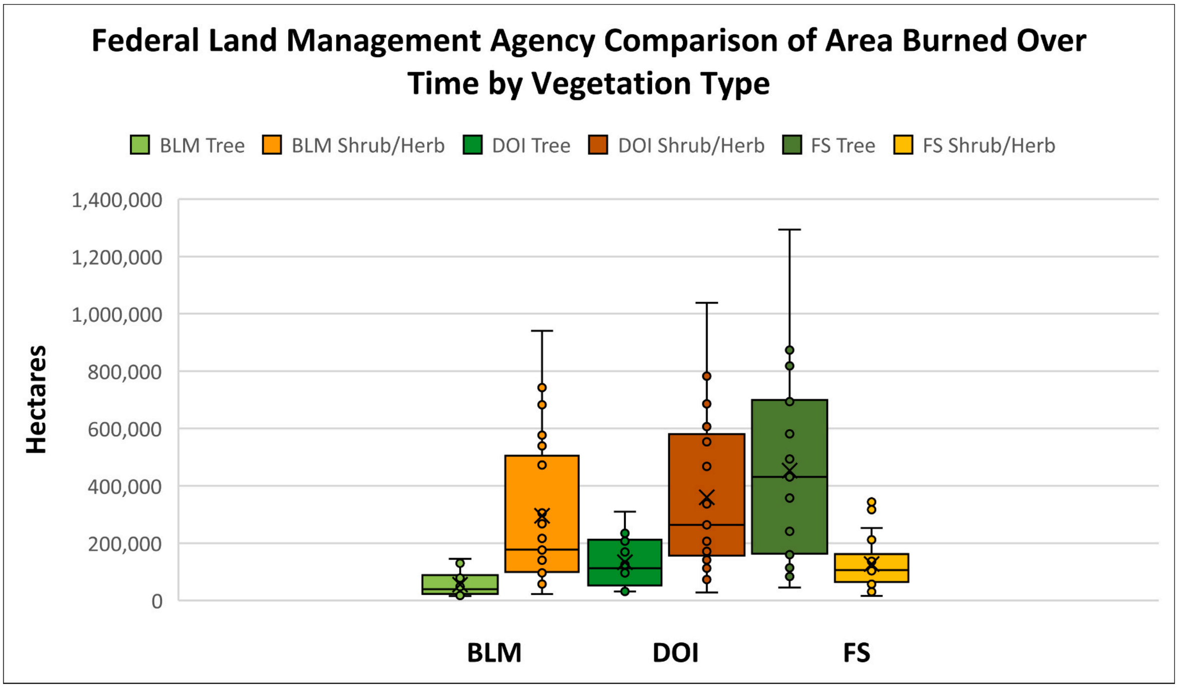


Fig. 3. Box and whisker plots comparing area burned for two vegetative class types: non-forested (shrub/herb) and forested (tree-dominated) over the past two decades for the Bureau of Land Management (BLM), Department of Interior (DOI), and the Forest Service (FS).

3.3. Areas experiencing a wildfire surplus compared to historic trends

Areas experiencing a surplus of wildfire mainly occur in the states of CA, Nevada, Idaho, Utah and Arizona with smaller areas in Washington, Oregon, Wyoming, Colorado and New Mexico (Fig. 6). Most of the area with a surplus of fire occurred in the Great Basin, one of four divisions of the North American Desert that covers 492,000 square km and includes most of Nevada, half of Utah, and sections of Idaho, Wyoming, Oregon, and California. Total area experiencing a fire frequency greater than 2 times the historic mean was approximately 7 million ha. Forty existing vegetation types experienced more wildfire compared to historic trends on 10,000 ha or more. Of these, the majority, 23, were non-forested vegetation types. The top five vegetation communities across the western U.S. were: big basin sagebrush shrubland and steppe, desert scrub, introduced annual grassland, pinyon-juniper woodlands, and spruce-fir forests. Furthermore, 74% of the area experiencing too much fire were in non-forested communities.

4. Discussion

4.1. Summaries and comparisons of area burned

Much scientific research has emphasized that the current increase in burned area is due to a deficit of fire caused by decades of fire suppression (Covington, 2000; Cohen, 2008; Schoennagel et al., 2017) and provided direction for federal agency wildland fire management, especially for fuels management programs (U.S. Executive Office of the President, 2018; USDA Forest Service, 2018; USDA-USDI, 2013; USDA Forest Service, 2012). This study quantified that over half of the area burned across the conterminous U.S. over the past two decades occurred in non-forest ecosystems. In addition, certain regions of non-forest and forest lands are experiencing wildfire more often than they experienced historically. While there has been acknowledgement of a large percentage of area burned in shrubland, grassland, and desert ecosystems on public lands, this is the first time it has been quantified and compared to forest ecosystem fire activity. Results indicate that current policies focused largely on forest and fire restoration alone will not address the unique aspects of altered fire cycles in shrubland, grassland, and desert ecosystems, especially those caused by the large-scale expansion of invasive grasses.

Summaries and comparisons of spatial and temporal patterns for area burned in two general vegetation classes (non-forest and forest) by agencies have strong implications for wildland fire policy, especially for DOI wildland fire management priorities, policies, and budgets that often replicate Forest Service priorities. Generally, the most important results were: first, differences in annual area burned between non-forest and forest lands over the past two decades were not statistically significant across the western and conterminous US, indicating that wildfire trends have changed from the 1980's when more forest area burned (Westerling, 2016; Schoennagel et al., 2017). Second, trendlines indicate that both non-forest and forest area burned increased over time and forest burned area increased at a faster rate. These results were similar to Westerling (2016) and Schoennagel et al. (2017) and were likely due to influences of climate change. Third, differences were significant when comparing between federal agencies indicating that wildland fire management agencies have different priorities for fuels management, community assistance, and wildfire suppression operations and response. Seventy percent of DOI area burned over the past two decades occurred on non-forest lands, (shrublands, grasslands, and deserts), indicating that the DOI is not a forest fire driven department like the USDA. This is due to DOI lands being largely composed of BLM's land base compared to other DOI agencies (FWS, NPS, BIA). BLM manages approximately 185 million acres across the conterminous U.S. and is unique in that 70% of its jurisdiction is composed of non-forest lands. Since 85% of burned area on DOI non-forest lands occurred on BLM over the past two decades, developing specific wildland fire management priorities and strategies based on each DOI agency's needs will better address the department's wildfire risk, rather than relying on one overarching management approach across all vegetation types such as the USDA's latest ten-year strategy (USDA, 2022), which largely focuses on the need for more forest thinning and prescribed fire to address wildfire risk.

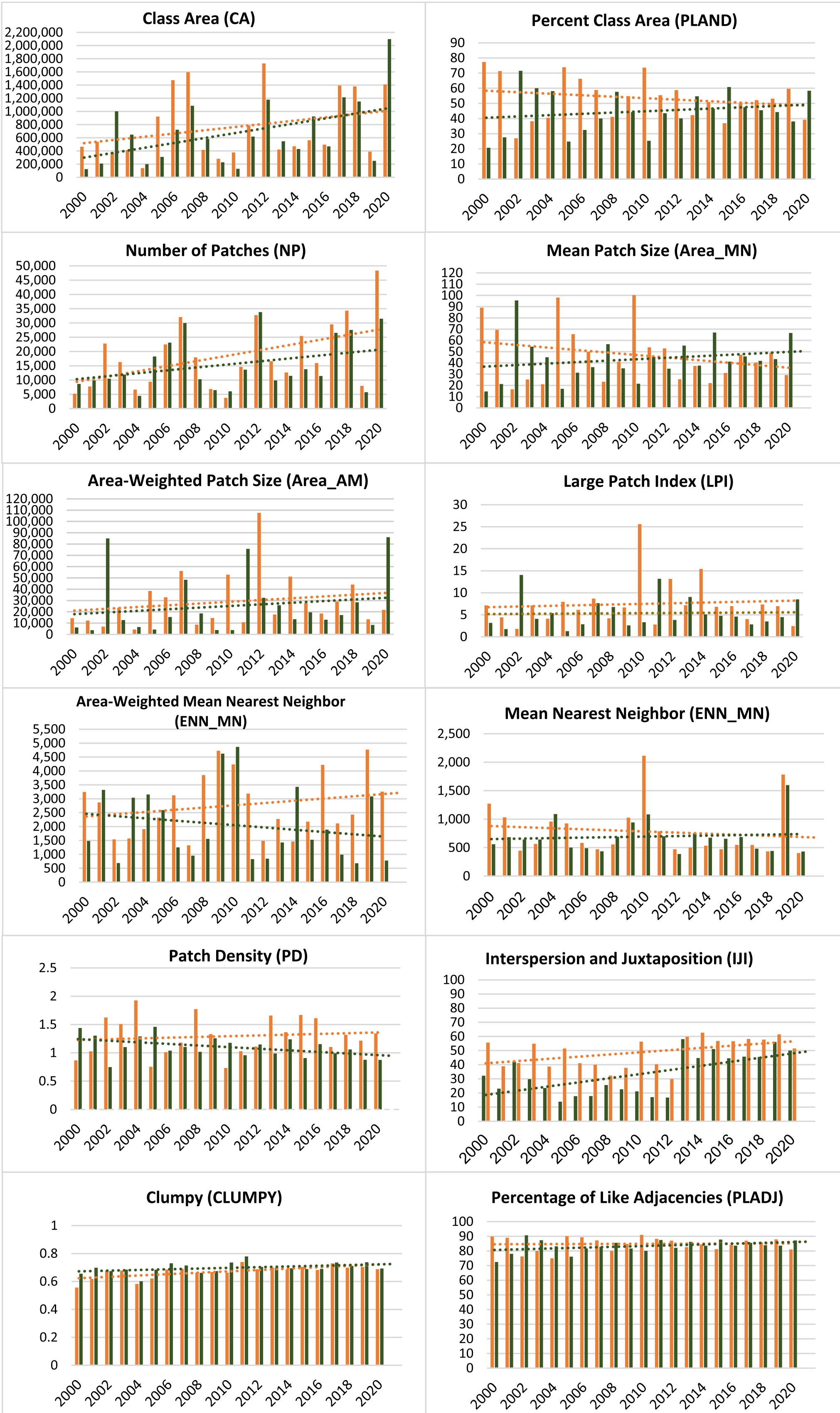


Fig. 4. Twelve area and aggregation metrics depicting trends in area burned (ha) for two classes: non-forest (shrub and herbaceous dominated; orange) and forest (tree dominated; dark green), across the western U.S. over the past two decades. See Table 1 for metric definition and units. Trendlines were derived using linear regression and depict overall increase or decrease for the landscape metrics over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5. Seven selected area and aggregation metrics comparing spatial and temporal trends between federal agencies, a) BLM, b) DOI, c) FS in area burned (ha) for two classes: non-forest (shrub and herbaceous dominated; orange) and forest (tree dominated; dark green), over the past two decades for the western U.S. See Table 1 for metric definition and units. Trendlines were derived using linear regression and depict overall increase or decrease for the landscape metrics over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

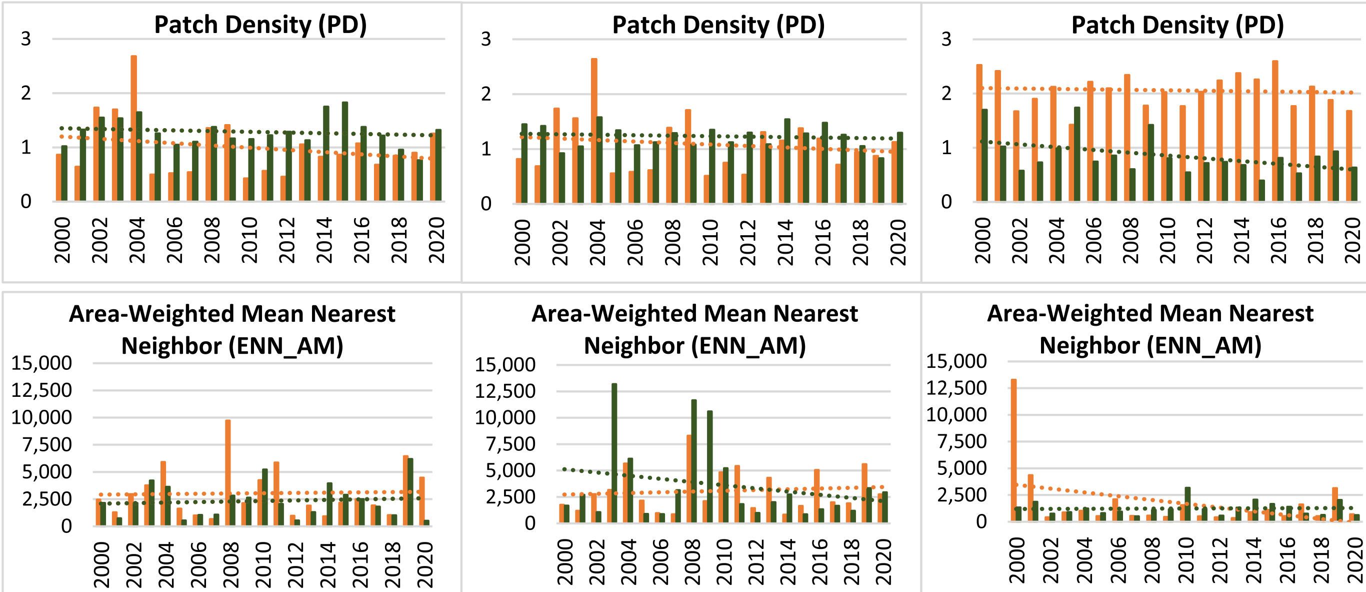


Fig. 5. (*continued*).

Table 3
Results of Welch's t-tests (P-values) comparing landscape metrics of non-forest and forest burned patches among federal land jurisdictions, specifically the DOI (includes NPS, FWS, BOI, and BLM), BLM separately, and FS. Significant P-values are bolded. See Table 1 for metric definitions and units.

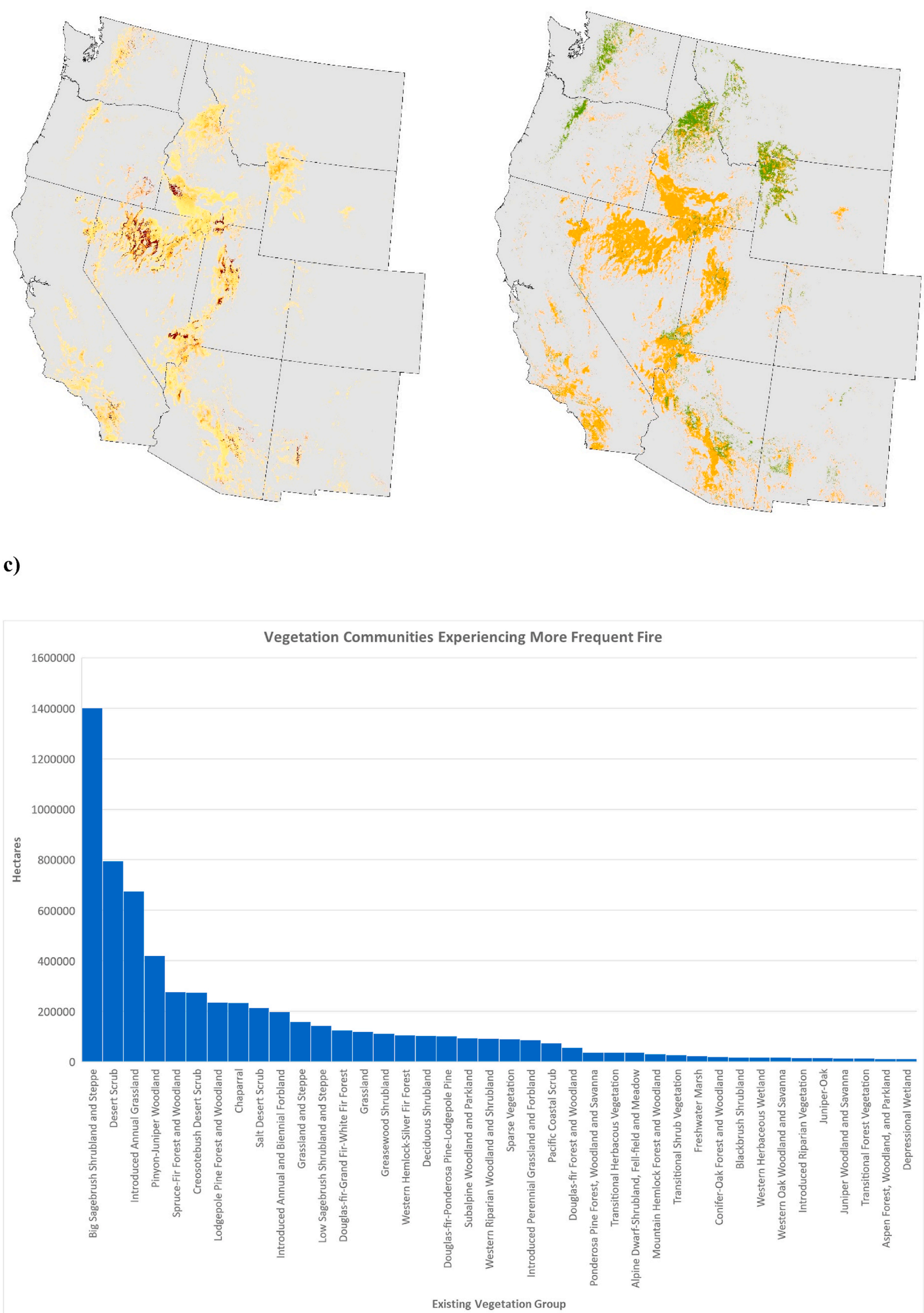
	P-values for Agency Comparisons					
	Non-Forested			Forested		
Metrics	DOI & BLM	DOI & FS	BLM & FS	DOI & BLM	DOI & FS	BLM & FS
CA	0.5725	**0.0019**	**0.0090**	**0.0032**	**0.0001**	**0.0000**
PLAND	0.0517	**0.0000**	**0.0000**	0.0528	**0.0000**	**0.0009**
NP	**0.0210**	**0.0002**	**0.0000**	0.3218	0.2414	0.9145
PD	0.6147	**0.0000**	**0.0000**	0.4537	**0.0003**	**0.0001**
LPI	0.2543	**0.0008**	**0.0001**	0.1537	**0.0091**	**0.0000**
AREA_MN	0.2664	**0.0000**	**0.0000**	**0.0273**	**0.0000**	**0.0000**
AREA_AM	0.9276	**0.0190**	**0.0208**	0.0924	**0.0108**	**0.0004**
ENN_MN	0.1500	**0.0001**	**0.0000**	0.4808	0.7988	0.5918
ENN_AM	0.9341	0.0754	0.0991	0.1620	0.2286	0.7667
CLUMPY	**0.0068**	0.8503	**0.0035**	**0.0091**	**0.0000**	**0.0000**
PLADJ	0.4267	**0.0000**	**0.0000**	**0.0068**	**0.0000**	**0.0000**
IJI	0.7443	**0.0001**	**0.0001**	0.3893	**0.0274**	**0.0047**
COHESION	0.9121	**0.0105**	**0.0085**	**0.0209**	**0.0000**	**0.0000**
AI	0.4101	**0.0000**	**0.0000**	**0.0075**	**0.0000**	**0.0000**

4.2. *Quantifying wildfire trends using landscape metrics*

Landscape metric results for the western U.S. highlight mostly similar patterns in the area metrics and differences in the aggregation metrics between non-forest and forest burned area. Generally, metric results were non-significant between non-forest and forest total burned area, large fire patch size, number of patches, and the overall spatial distribution of wildfire over the past two decades. These results highlight that wildfire occurring on forest lands are not the dominant type of fire for the western US, but rather wildfire trends occurring over the past two decades are different but relatively equal between non-forest and forest classes. While fire increasing in non-forest ecosystems is not new (Parks et al., 2015; Schoennagel et al., 2017; Westerling, 2016), the dominant role non-forest wildfire had on the extent and pattern of burned area across the western U.S. is surprising, especially given the large area of shrubland and desert ecosystems covering much of the western U.S. that historically experienced fire relatively infrequently. These results may be climate driven in that years when large areas of forest lands burn are drought induced years (Abatzoglou et al., 2020; Westerling, 2016; Holden et al., 2018); whereas large non-forest burns are typically driven by an interannual precipitation pattern combined with invasive grasses (Pilliod et al., 2017).

Landscape metric results comparing non-forest and forest burned patches indicate that the spatial distribution is changing over time. Temporal trends for *number of patches* burned increased for both non-forest and forest classes and increased at a higher rate for non-forest compared to forest. The metric *percentage of like adjacencies* indicates that for both non-forest and forest classes, a large percentage of burned area within the fire perimeters was dominated by either non-forest or forest types and this trend did not change over time despite the increase in size of burned patches. The *interspersion and juxtaposition index* shows that burned non-forest and forest patches were increasingly more interspersed and juxtaposed in closer proximity across the west over time. The *area-weighted nearest neighbor* and *patch density* metrics show that wildfires in non-forest types have become more widely distributed over time, whereas an opposite trend is occurring for forest burned patches. This suggests that forest burned patches are potentially becoming more clustered in certain geographic regions or burning more frequently in certain areas (e.g. California), while non-forest wildfires are becoming more dispersed across the west. Overall, the increasing spatial distribution of non-forest burns is surprising since the scientific literature highlights wildfire being more prominent in the Great Basin

a) b)



c)

(caption on next page)

Fig. 6. Resulting maps and graph of fire departure trends where wildfire may be burning more frequently compared to historic fire return intervals. Total area experiencing a fire surplus ratio of 2 times and higher is approximately 7 million hectares. **a)** Map on the left shows the results of fire departure trends across the western U.S. The gradient of brown to yellow represents high to low departure, respectively. Fire departure map was created by taking the ratio between LANDFIRE BPS mean fire return interval point estimates (https://landfire.gov/fri.php) and the large fire burn probability dataset (Short et al., 2016). **b)** Map on the right shows life-form categories non-forest (orange) and forest lands (green) that may be experiencing fire more often than historic trends to varying degrees. **c)** LANDFIRE Existing Vegetation Types (EVT; https://landfire.gov) that may be experiencing more wildfire than historic fire trends. Vegetation types were selected using the fire regime departure raster dataset shown in (a) as a mask to select the EVTs. The EVTs were than ranked by area. Vegetation communities graphed were 10,000 ha and greater. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sagebrush dominated lands (e.g. Brooks et al., 2004, 2015), these results suggest this trend may have changed recently. Larger and more frequent wildfires resulting from expanding fire seasons due to climate change (Westerling et al., 2006, Westerling, 2016) may also be accelerating transitions to invasive grass dominance, which in turn increases fire occurrence, frequency, and extent in a positive feedback loop (Abatzoglou and Kolden, 2011; McWethy et al., 2019). For example, warmer temperatures and earlier snowmelt, and altered timing of seasons are predicted to favor establishment, growth, and reproduction of invasive grasses throughout much of the west (Jarnevich et al., 2021; Fusco et al., 2019; Blumenthal et al., 2016; Bradley et al., 2018b; Compagnoni and Adler, 2014; Bykova and Sage, 2012).

Comparing landscape metrics results between the DOI and FS shows that wildfire spatial patterns and trends are strikingly different between non-forest and forest classes, and the trends depict opposite wildfire patterns at the scale of the western U.S. For the DOI, area and aggregation metrics for the non-forest class were significantly higher in total area burned, large patch size, and spatial distribution across the west when compared to forest class metrics. Spatial and temporal burn patterns for the DOI and BLM were similar, indicating that wildfire on BLM jurisdictions have a large influence on the DOI landscape metric results, especially for non-forest lands. Comparisons between the BLM and FS were similar to the DOI and FS, and again demonstrate that forest fires are not the dominate fire type for the DOI and the BLM. This similarity illustrates that non-forest fires have been the dominant trend over the past two decades and will likely continue to be for the DOI. The scientific literature highlights fire regime changes for non-forest lands in terms of increased total annual area burned, fire frequency, and the size and juxtaposition of fires, especially for non-forest ecosystems that historically burned relatively infrequently (Brooks et al., 2004; Balch et al., 2013; Bradley et al., 2018b; Fusco et al., 2019).

4.3. Areas experiencing a wildfire surplus compared to historic trends

Contemporary fire regime departures occurred across a broad range of non-forest and forest types that may be experiencing higher fire frequencies compared to historic fire cycle trends across the western U.S. The increase in fire frequency occurred for many non-forest existing vegetation types and was especially pronounced for western sagebrush and other shrub types found in the Great Basin that covers vast areas across the western U.S. Similar results were found by other researchers as well (Brooks et al., 2004; Balch et al., 2013; Bradley et al., 2018b; Parks et al., 2015; Fusco et al., 2019). Results also identified certain forest and woodland types experiencing higher fire frequencies. Results were supported in the literature in certain regions for rocky mountain subalpine forests (Higuera et al., 2021), ponderosa pine dominated forests (Kerns et al., 2020), and pinon-juniper woodlands (Board et al., 2018; Arendt and Baker, 2013; Floyd et al., 2004). In the arid and semi-arid regions of the western U.S. and other countries, trends and impacts from fire cycles driven by invasive grasses have, collectively, become very similar in their role of altering fire regime patterns (Setterfield et al., 2013; Fusco et al., 2019; Nicolli et al., 2020; Kerns et al., 2020; Board et al., 2018; Arendt and Baker, 2013). Research has shown that uncharacteristic fire due to the spread of fire-prone invasives is a large and pervasive threat to these ecosystems' persistence across the western U.S. (Fusco et al., 2019; Bradley et al., 2018b).

Fire regime departure results can help identify where and to what degree ecosystems may be experiencing a higher fire frequency and extent compared to historic trends. Given the ongoing and projected changes in climate and increasing wildfire trends for non-forested and forested ecosystems found in studies such as Mallek et al. (2013), Jones et al. (2016), Westerling (2016), and Reilly et al. (2017), some ecosystems will likely cross a threshold from their historic or contemporary wildfire trends to novel fire trends of more frequent fire in the future. Departure analyses combined with other information such as ignition patterns, changes in precipitation, temperature and weather patterns, and invasive grass spatial distributions, can help identify causes for increased fire frequencies and determine fuels management strategies including the development and testing of new tactics to manage these changes where appropriate.

Using remote sensing, Smith et al. (2022) quantified an 800% increase of invasives grass dominance in the Great Basin from 1991 to 2020. This expansion occurred at an average rate of >2300 km^2 per year and was associated with a broadening topographic niche, and widespread movement into higher elevations and north-facing aspects consistent with predicted effects of a warming climate. This expansion time-period corresponds well with the departure results here, and with the observed overall increase of wildfire frequency and extent seen over the past few decades for the Great Basin and other shrubland and desert ecosystems in the western U.S. (Brooks et al., 2015; Pilliod et al., 2017; Schoennagel et al., 2017; Fusco et al., 2019). In addition, more mesic biomes provide abundant fuel but are flammability limited, whereas more semiarid biomes are highly flammable, but fuel limited (Littell et al., 2009; Parks et al., 2014). Interannual climate variability and fine-resolution weather ultimately determine ignition probability and fire behavior at a given moment. Climate change is projected to alter the frequency and extent of wildfire primarily through fire potential due to increased flammability during the dry season as well as longer fire seasons and weather conditions that favor more wildfire (Westerling, 2016; Flannigan et al., 2009; Jolly et al., 2015) and invasive grasses (Fusco et al., 2019), likely resulting in an expansion of invasive grass induced wildfire cycles across the west.

4.4. Management implications

Over the past two decades, many legislation and management solutions were crafted to reduce uncharacteristic wildfire and address rising costs of suppressing wildfire (Schultz et al., 2019). Direction to federal and state agencies focused on using mechanical and prescribed fire techniques to protect communities and reduce uncharacteristic fuels loads and fire risk largely due to past fire suppression (U.S. Executive Office of the President, 2018; USDA Forest Service, 2018; USDA-USDI, 2013; USDA Forest Service, 2012). This management paradigm was applied in federal fuel management and forest restoration programs for many decades. This study quantified that non-forest lands burned more or just as much as forest lands, the spatial distribution of fires on non-forest lands increased across the western U.S. and more non-forest lands experienced abnormally frequent fire cycles compared to historic trends. Results here indicate that non-forest lands should now play a substantial role in federal and state wildland fire management.

Spatial and temporal wildfire trends analyses using landscape metrics can provide broad scale understanding of fire regime changes over time important for informing wildland fire management decisions at national and regional scales. In addition, these analyses can be run at multiple scales to inform agency prioritizations, monitoring, evaluations, and adaptive management. The area and aggregation metrics helped to illustrate differing spatial wildfire patterns and trends just over the past two decades for both non-forest and forest lands, as well as capture significant differences in class area burned among federal agencies jurisdictions. Landscape metrics can operate as larger scale performance measures for monitoring – setting baselines and used to evaluate where successes have been made and where shortfalls can be addressed at the scale of U.S. over time. Agency wildfire management programs also can use these metrics to address the different uncharacteristic wildfire trends particular to each agency, rather than rely solely on overarching wildland management strategies. Understanding wildfire patterns at large-scales by agency can inform and prioritize management strategies that target the different causes behind different and similar trends. For example, the DOI can utilize new modeling methods, spatial databases, and research to develop management actions on higher wildfire risk non-forest areas where high rates of conversion of native shrubland and desert ecosystems to non-native invasive grasslands has increased invasive fuel connectivity, crossed wildfire thresholds, and continued to spread and promote uncharacteristic fire patterns (Gray and Dickson, 2016; Hui et al., 2016; Reeves and Frid, 2016; Novak et al., 2015; Peeler and Smithwick, 2018; Pastick et al., 2021; Keeley et al., 2021; Buckholz et al., 2022). Furthermore, results revealed that large non-forest and forest fires are increasing in size and distribution across the west, while at the same time becoming clustered in certain regions, this new information can be used to inform budgeting allocations and prioritizations for fuel treatment types (i.e. invasives management, forest thinning, or fuel breaks where needed), regional placements for basing fire suppression efforts, and developing community protections plans such as defensible space around structures and evacuations (Kolden and Abatzoglou, 2018).

Large-scale fuels management strategies have not yet been developed to address areas that are burning too frequently or experiencing grass induced wildfire regime changes. While reintroducing fire as an important historical disturbance regime is considered critical for the restoration of many fire-dependent ecosystems in North America (Covington, 2000; Kolden, 2019), such strategies will not address the causes of accelerated fire frequencies for most of these shrubland, desert, grassland, and certain coniferous ecosystems. Furthermore, using prescribed fire and mechanical treatments on invaded ecosystems often results in more invasive grasses and less recovery of native vegetation in certain areas, and desired restoration outcomes are hindered by invasive species introduction and spread (Griffis et al., 2001; Keeley, 2006; Keeley and McGinnis, 2007; Ross et al., 2012; Chambers et al., 2014; Kerns and Day, 2017; Jones et al., 2018). Structured decision making based on thresholds of invasion levels, landscape resiliency, or accelerated wildfire cycle rates can help in creating large-scale management strategies that address this issue (Martin et al., 2009; Chambers et al., 2019; Crist et al., 2019; McWethy et al., 2019; Magness et al., 2021).

Developing wildland fire management strategies that address the invasive grass/fire cycle is needed across federal and state agencies. There are several strategies that could be considered in wildland fire management for invaded ecosystems. Depending on the degree of invasion, invasive species management strategies such as: early detection and rapid response, invasives removal, or containment strategies can be used to control the spread of fire-prone invasives (Lodge et al., 2016; James et al., 2017). To help address future threats, invasive species and wildfire management should integrate and focus on where invasives are likely to expand due to climate change (specifically longer summers, shorter winters and springs, higher temperatures, and persistent drought) and where human ignitions are increasing due to expanding human footprints (Crist et al., 2019; Nagy et al., 2018). Fire prevention, mitigation, education, and trespass programs, as well as fire preparations for the wildfire season can use results here to target these areas. Public outreach campaigns that focus on invasives and wildfire can help reduce invasives spread and human ignitions. In addition, this information is useful for fire preparedness where planned suppression tactics could emphasize mitigating invasives introduction and spread, while at the same time manage fast burning invasive grass fires.

While there are several challenges in addressing uncharacteristic fire in non-forest ecosystems, one of the largest is that our culture is focused on forest fires (Pyne, 1997; Cohen, 2008; Calkin et al., 2011; Moritz et al., 2014). Coniferous-focused fire research and federal policy has rightly so for decades promoted agency focus on forest and woodland fire issues, but lately this has come at a cost to non-forested lands due to tailored policies and agency expectations for forest focused management, which limits the ability to address wildfire in non-forest ecosystems. If approximately half of our wildfires are occurring on shrublands, deserts, and grasslands, wildland fire management agencies may be missing the boat on reducing uncharacteristic fire at landscape scales and protecting wildland urban interface communities. Since fire-prone invasive grasses are one of the main drivers for too frequent fire on non-forest lands, federal fuel management programs can integrate with invasive species management programs to address invasive fuel continuity and expansion as well as identify, map, and protect relatively uninvaded and intact non-forest ecosystems where they still exist across the west (Doherty et al., 2022; Maestas et al., 2022; Crist et al., 2019). A recent coordinated effort between the National Invasive Species Council (NISC) and the Wildland Fire Leadership Council (WFLC) has developed a list of opportunities and priorities for addressing invasive species and uncharacteristic fire across the U.S. (Pers. Comm. Stanley Burgel (NISC) and Mike Zupko (WFLC)). This information can be useful for integrating federal fuel management and invasive species management programs to develop common objectives that address the invasive grass wildfire cycle.

Much of the public's understanding of fire is that past fire suppression resulted in the fires they see today (Pyne, 1997; Calkin et al., 2011; Moritz et al., 2014). The media drives public perception on wildfire, and the public is not aware of other causes of uncharacteristic fires, especially increased fire frequency and extent due to large-scale invasive grasses expansion. Consequences of invasive grass-fire cycles include increased risk to human life and property from larger and/or more frequent wildfires (Crist et al., *in review*, Fusco et al., 2019; Davies et al., 2021), loss of habitat for sensitive species (Coates et al., 2016), reduced biodiversity across trophic levels (Davies et al., 2012; Pyšek et al., 2012; Brunson and Tanaka, 2011), and impacts on human health (Reid et al., 2016). The biggest impact of invasive grass/fire cycles in shrubland, grassland, and desert ecosystems is the resulting large-scale ecotype conversions from native plant communities to invasive grass monocultures after fire. Furthermore, research has shown that hotter and drier conditions combined with human-ignited fires have increased the length of the fire season by 134% for the western sagebrush dominated lands (Balch et al., 2013, 2017; Nagy et al., 2018). Approximately, 90% of wildfires in the U.S. are human-caused from campfires, target shooting, power lines, fireworks, debris burning and arson, and are increasing on non-forested lands (Crist et al., in review). A greater focus on educating the public through social media on invasive grass fire cycles and undesirable outcomes of human-caused fires can help reduce fire frequency and extent, especially where areas are experiencing too much fire.

Post-fire recovery is difficult and expensive for non-forest landscapes because invasive grasses often outcompete native plant restoration, especially in hotter, drier areas where invasives are prone to dominate after fire (Crist et al., 2019; Chambers et al., 2017). Ecotype conversions to invasive dominated areas after fire results in a permanent change to frequent fire cycles that continue to expand and operate cumulatively across large landscapes, accelerating the need for wildfire suppression operations to address more frequent fire. Emergency and stabilization and burned area rehabilitation programs can help prevent further degradation after fire and protect resources by rehabilitating landscapes unlikely to recover naturally after fire. However, more investments made in pre-fire invasive management strategies may be more effective in reducing the spread of invasives before the fire occurs and influencing the result of invasives dominance after the fire. In addition, this pre-fire strategy may help reduce funding requests for rehabilitating large fires that often exhaust annual post-fire recovery budgets and available native seed.

5. Conclusion

Federal wildland fire management agencies have largely aligned with the management goals developed by the National Cohesive Wildland Fire Management Strategy (USDA-USDI, 2013). Implementation of this strategy has focused on protection of communities and public safety, while at the same time emphasized fuels management to reintroduce the historic role of wildfire and reduce fuels in the wildland urban interface. Results of this study highlight that to adequately reduce our wildfire “crisis”, the dominant focus cannot be largely on wildfire occurring on forests and woodlands. Rather, new policies and different management strategies aimed at reducing uncharacteristic wildfire patterns for both non-forest and forest ecosystems are needed to be effective in wildland fire management. The ongoing invasive grass/fire cycle needs to receive greater focus in wildland fire and natural resource management, and-more integration between these management divisions is needed to effectively manage invasive grasses and subsequent accelerated fire cycles across the western U.S. Australia is experiencing similar invasive/wildfire issues at large-scales (Setterfield et al., 2013) and could offer lessons learned from their wildland fire management programs.

Analyzing spatial wildfire trends using landscape metrics and departure analyses can be very informative for wildland fire management agencies. The metrics used in this study helped determine that over the past two decades: more area burned on non-forest lands than forest lands; wildfire trends increased for both non-forest and forest lands; and spatial wildfire patterns and trends differed significantly between non-forest and forest lands, especially for federal agencies jurisdictions. Landscape metrics can be used widely to identify changes in management priorities, conduct risk assessments, evaluate effectiveness of fuel management strategies, and be utilized in monitoring and adaptive management. There are many factors and numerous costs associated with wildfire including direct costs of wildfire management (e.g. prevention, suppression, etc), as well as other direct and indirect costs such as loss of ecosystem services (Crist et al., in review). Given these rising costs and increasing annual area burned, there is a need to utilize metrics that provide information on the spatial and temporal contexts of contemporary wildfire regimes to address fire risk. For example, trends on vegetation spatial burn patterns, geographic differences, fire size and occurrence patterns can be used to evaluate if wildland fire management goals and outcomes are being met in agency plans.

Author contributions

MRC: Conceptualization, Methodology, Software, Data Curation, Investigation, Visualization, Writing Original Draft Preparation, Editing, Validation.

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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

Data will be made available on request.

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