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11 authors, including:

Wade T. Tinkham
Colorado State University

John T Abatzoglou
University of Idaho

Beth Newingham
United States Department of Agriculture

Eva Strand
University of Idaho

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Defining extreme wildland fires using geospatial and ancillary metrics

Karen O. Lannom[A], *Wade T. Tinkham*[A], *Alistair M.S. Smith*[A,E], *John Abatzoglou*[B], *Beth A. Newingham*[A], *Troy E. Hall*[A], *Penelope Morgan*[A], *Eva K. Strand*[A], *Travis B. Paveglio*[C], *John W. Anderson*[D] *and Aaron M. Sparks*[A]

[A]College of Natural Resources, University of Idaho, 709 S Deakin Street, Moscow, ID 83844, USA.
[B]College of Science, University of Idaho, 709 S Deakin Street, Moscow, ID 83844, USA.
[C]The Edward R. Murrow College of Communication, Washington State University, Pullman, WA 99164-2520, USA.
[D]College of Art and Architecture, University of Idaho, 709 S Deakin Street, Moscow, ID 83844, USA.
[E]Corresponding author. Email: alistair@uidaho.edu

Abstract. There is a growing professional and public perception that 'extreme' wildland fires are becoming more common due to changing climatic conditions. This concern is heightened in the wildland–urban interface where social and ecological effects converge. 'Mega-fires', 'conflagrations', 'extreme' and 'catastrophic' are descriptors interchangeably used increasingly to describe fires in recent decades in the US and globally. It is necessary to have consistent, meaningful and quantitative metrics to define these perceived 'extreme' fires, given studies predict an increased frequency of large and intense wildfires in many ecosystems as a response to climate change. Using the Monitoring Trends in Burn Severity dataset, we identified both widespread fire years and individual fires as potentially extreme during the period 1984–2009 across a 91.2×10^6-ha area in the north-western United States. The metrics included distributions of fire size, fire duration, burn severity and distance to the wildland–urban interface. Widespread fire years for the study region included 1988, 2000, 2006 and 2007. When considering the intersection of all four metrics using distributions at the 90th percentile, less than 1.5% of all fires were identified as potentially extreme fires. At the more stringent 95th and 99th percentiles, the percentage reduced to <0.5% and 0.05%. Correlations between area burnt and climatic measures (Palmer drought severity index, temperature, energy release component, duff moisture code and potential evapotranspiration) were observed. We discuss additional biophysical and social metrics that could be included and recommend both the need for enhanced visualisation approaches and to weigh the relative strength or importance of each metric.

Additional keywords: intensity, mega fires, severity, vulnerability.

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Introduction

Wildland fires are important disturbances affecting a wide array of global ecosystems. Fires can result in immediate, short- and long-term effects on terrestrial vegetation, soils, hydrology, atmospheric cycles and social systems (Seiler and Crutzen 1980; Smith *et al.* 2005*a*; Goetz *et al.* 2007; Brewer *et al.* 2013). High intensity, stand-replacing fires can lead to long-term changes in vegetation structure and composition (Kashian *et al.* 2006; Goetz *et al.* 2007; Romme *et al.* 2011) through various mechanisms, such as consumption of large woody debris (Smith and Hudak 2005; Hyde *et al.* 2011, 2012), tree girdling (Kavanagh *et al.* 2010), loss of seed sources (Rodrigo *et al.* 2012) and changes in surface and soil properties (Tozer and Auld 2006; Roy *et al.* 2010; Fontúrbel *et al.* 2011, 2012). As human populations grow and residential development expands, the effects of wildland fire on ecological systems are increasingly intertwined with human systems and warrant the evaluation of fire effects on social–ecological systems. The effects of fires and other natural disturbances on social–ecological systems are heightened when considering the backdrop of changing climatic conditions (NRC 2010) and the worldwide increase in urbanisation (UN-HABITAT 2009). The greatest socioeconomic effects of fire will most likely occur in the wildland–urban interface (WUI), which may be loosely defined as 'the area where houses meet or intermingle with undeveloped wildland vegetation' (USDA and USDI 2006). However, more robust WUI definitions that combine housing density and proximity to wildland vegetation data are also widely used (Radeloff *et al.* 2005). Currently, the WUI covers ~9.3% of the contiguous United States (US) (Stewart *et al.* 2007) and in some parts of the western US the WUI area could increase

40% by 2030 (USDA and USDI 1995; USDA 2006). The social effects of fires include property damage and economic loss, as well as perceived effects on quality of life, aesthetics and economic viability.

The size and intensity of fires in the north-western US have been linked to changing temperature and precipitation regimes over the last century (Grissino-Mayer and Swetnam 2000; Westerling *et al.* 2006; Littell *et al.* 2009), particularly in the US northern Rocky Mountain region (Westerling *et al.* 2006; Holden *et al.* 2007; Littell *et al.* 2009). Based on these observations, studies are projecting a continued trend of larger and more intense fires under expected climate scenarios (Spracklen *et al.* 2009; Westerling *et al.* 2011). Of particular concern are individual fire events that have uncharacteristically large negative effects on social–ecological systems. Statistically, such 'extreme' fires would be rare events, but they may become more common under future conditions.

Extreme wildland fire events can potentially be defined in a variety of ways, including fire size, burn severity, cost of suppression, property damage, and lives lost, among others. 'Mega-fires', 'conflagrations', 'extreme' and 'catastrophic' are descriptors interchangeably used increasingly to describe fires in recent decades in the US and globally, although in the scientific literature the term mega-fire to date is limited to describing the extent of area burnt during Eurasian fires (Dimitrakopoulos *et al.* 2011; Ito 2011). The term mega-fire has received recent attention in the US but is not yet a widely adopted or defined term. Although area burnt is clearly linked to large-scale effects of fires, such as emissions to the atmosphere, solely considering area burnt may not capture the full range of social–ecological effects that may occur as a result of truly extreme fires (Kremens *et al.* 2010). Fires considered as historically significant (Pyne 1995; Arno and Allison-Bunnell 2002) burnt over large areas for very short or extended durations, affected people by extended evacuations or loss of property or lives, and in many cases were only extinguished by changes in the weather. For example, the 1871 Peshtigo Fire of Wisconsin and Michigan burnt more than 1.5×10^6 ha and killed 1500 people. The 1910 Fires of Idaho and Montana burnt more than 1.2×10^6 ha of private and federal land (mostly in only two days) and several small towns, and killed at least 85 people. The 1988 Yellowstone fires burnt more than 640 000 ha, lasted 90 days, and caused an estimated US$3 million in property damage.

Several commonalities are apparent among these historic fire events; namely (in-line with the mega-fire description), a large area ($>1 \times 10^6$ ha) was burnt in each event, large amounts of vegetation were destroyed and numerous communities were severely affected or completely destroyed. These fires burnt the majority of their area in either very short periods (1–3 days) or over months. We sought to identify both widespread fire years (i.e. years with a statistical outlier in the quantity of area burnt) and individual extreme fire events, using selected metrics that incorporate the following biophysical and social criteria: (1) fire size, (2) distance to the WUI, (3) fire duration and (4) proportion of area burnt with high burn severity. Our working definition defined fires as potentially extreme when they exhibited characteristics at the intersection of the 90th, 95th, or 99th percentiles of the distributions of these four metrics. We discuss other possible fire metrics that could be considered extreme for social–ecological systems.

Methods

Study area

Our research focussed on a 91.2×10^6-ha area of the north-western US (Fig. 1). We analysed fires within the Commission for Environmental Cooperation ecoregions (CEC 2009), using nine Level III ecoregions nested within two Level I ecoregions: the North-western (NW) Forested Mountains and the North American Deserts.

The NW Forested Mountains Level I ecoregion contains six Level III ecoregions: The Blue Mountains, Middle Rockies, Canadian Rockies, Columbia Mountains and Northern Rockies, Eastern Cascade Slopes and Foothills, and Idaho Batholith. These areas contain extensive mountains and plateaus separated by wide valleys and lowlands. The climate ranges from arid to humid and mild to cold temperatures. Vegetation in the NW Forested Mountains ecoregion is diverse and consists of alpine, subalpine, and mountain slope forests, as well as grasslands and shrublands. Vegetation communities include (i) *Pseudotsuga menziesii* (Douglas-fir) forests ranging from the Pacific coast to across the entire Rocky Mountains range, dominated by *Pseudotsuga menziesii* associated with *Pinus contorta* (lodgepole pine), *P. ponderosa* (ponderosa pine), and *Larix occidentalis* (western larch); (ii) Cascadian forests, which extend across the Cascade Mountains Range and often include, *Thuja plicata* (western red-cedar), *Tsuga heterophylla* (western hemlock), *Abies grandis* (grand fir), *Taxus brevifolia* (Pacific yew), *Tsuga mertensiana* (mountain hemlock), and *Larix lyallii* (subalpine larch); (iii) sub-alpine white fir forests dominated by *P. albicaulis* (whitebark pine) in the central Rocky Mountains; (iv) ponderosa pine woodlands that extend throughout the Rocky Mountain Range, dominated by *P. ponderosa*; (v) juniper woodlands and sage-steppe ecosystems, which are predominately located within the US Great Basin, dominated by *Juniperus occidentalis* (western juniper) and *Artemisia spp* (sagebrush); and (vi) a scattering of Montane seral forests dominated by *P. contorta* and *Populus tremuloides* (quaking aspen) (Barbour and Billings, 2000).

The North American Deserts Level I ecoregion contains three Level III ecoregions: The Snake River Plain, Northern Basin and Range, and Columbia Plateau. This region is more arid, has fewer trees, and lower relief and elevation than the NW Forested Mountains ecoregion. The area comprises plains, mountains and plateaus primarily with grassland and shrubland vegetation. This region has an arid to semi-arid climate with both high and low temperature extremes (CEC 2009). Dominant plant communities include juniper woodlands and sage-steppe ecosystems, which are dominated by *J. occidentalis* and *Artemisia spp*.

Burnt area, severity and duration data

We acquired data on wildland fires within our study area from the Monitoring Trends in Burn Severity (MTBS) project, an inter-agency effort by the US federal government. The goal of MTBS was to map burn severity and perimeters as defined using the differenced normalised burn ratio (dNBR) and the relativised dNBR (RdNBR) for all wildland fires greater than 404 ha in the western US and 202 ha in the eastern US that burnt between 1984

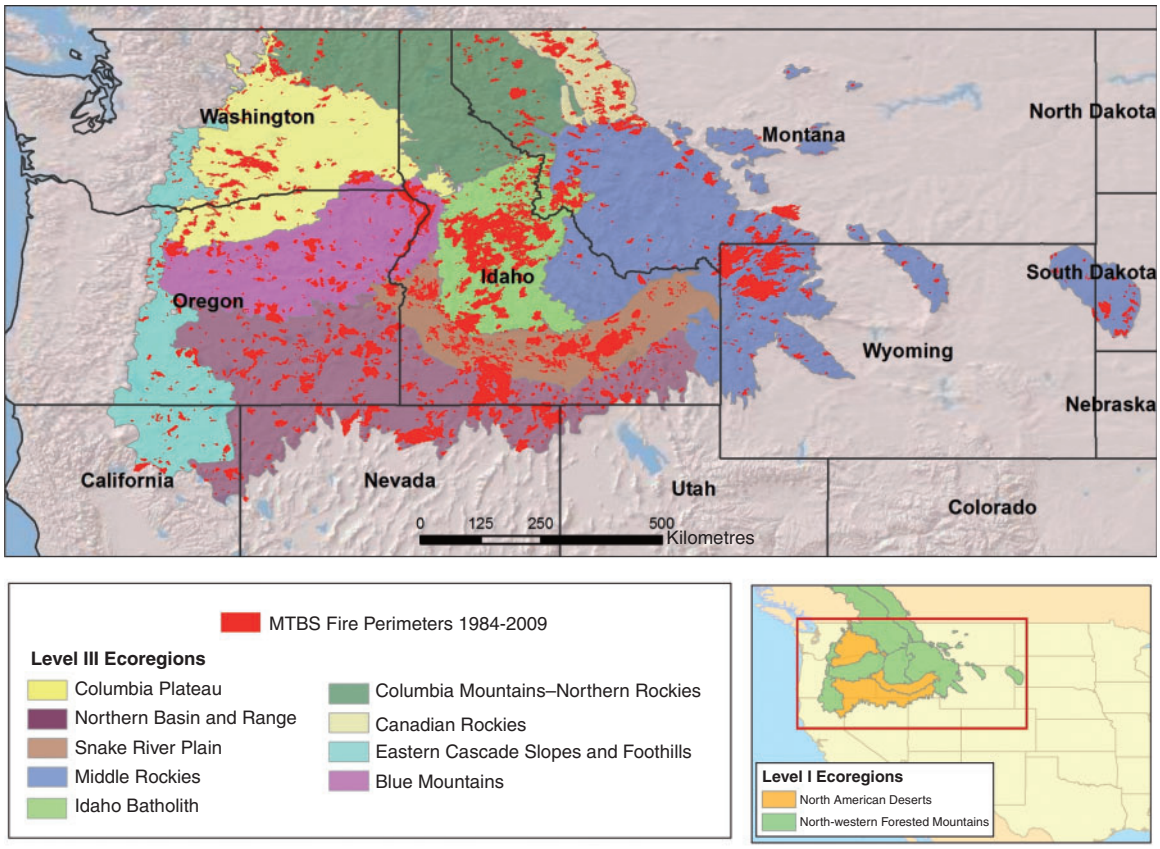

Fig. 1. Extent of fires in our study area in the north-western United States. Area encompasses the northern United States Rocky Mountains and the inland north-west.

and 2010 (Eidenshink *et al.* 2007). NBR was first presented for area burnt assessments (López Garcia and Caselles, 1991) and consequently adopted for severity analysis (Key and Benson, 2002; van Wagtendonk *et al.* 2004; Brewer *et al.* 2005; Smith *et al.* 2005*b*; Roy *et al.* 2006). The RdNBR was first presented by Miller and Thode (2007) as an improvement to dNBR in lower fuel environments.

We acknowledge three general limitations with the MTBS-derived perimeters. First, smaller fires are not included. However, this may not adversely affect the estimates of total annual area burnt within most fire-affected ecosystems because the majority of area burnt is caused by a small number of large fires (Kasischke and French 1995; Smith *et al.* 2007*a*). Second, MTBS perimeters overestimate burnt area by including unburnt islands within the perimeter, and over-smoothing edges (Kolden *et al.* 2012). Third, pre-fire imagery can often be obtained up to a year before the fire event and depending on the ecosystem, the post-fire imagery can be extended by a similar degree, leading to less certainty that observed effects were in fact caused by the fire (Smith *et al.* 2010; Heward *et al.* 2013).

We used the MTBS-classified thresholds for 'high severity', which are derived separately for each fire event by a MTBS analyst based on loosely observed thresholds associated with field-based measures of burn severity (Eidenshink *et al.* 2007; Miller *et al.* 2009*b*). Ideally, we would have selected thresholds for each individual fire using local and field literature-based regressions of dNBR to accepted field metrics related to high burn severity. These could have included, for example, percentage vegetation mortality, canopy cover loss, and aboveground biomass consumption. However, given that most researchers regress dNBR to aggregated field measures, there are few dNBR regressions with specific field measures, for example, tree mortality (Smith *et al.* 2007*b*; Lentile *et al.* 2009). We assumed that at the upper limits of the dNBR and RdNBR indices the fire effects are more predictable (i.e. high variation of fire effects is observed in 'low severity fires', but under 'high severity fires' effects are reasonably consistent) (Smith *et al.* 2005*b*).

It is important to recognise that the dNBR and RdNBR index values do not in themselves indicate 'severity'; indeed severity descriptions should always relate to a specific post-fire ecological effect (Lentile *et al.* 2006). Following Miller *et al.* (2009*b*), we assumed the MTBS-derived 'high burn severity' values to be associated with regions of near-complete above ground vegetation mortality. Several limitations to using dNBR and RdNBR to evaluate burn severity have been demonstrated (e.g. Lentile *et al.* 2006, 2009; Roy *et al.* 2006; Smith *et al.* 2010), but although alternative products exist, they are not widely applied (e.g. Disney *et al.* 2011).

We quantified fire duration as the number of days between MTBS start- and out-dates. To improve data quality, we excluded fires with no out-date, fires lasting more than a year and fires managed as wildland fire use (WFU) or prescribed (Rx) fires,

given managed fires are unlikely to be extreme events. Fires with out-dates in late November and December were cross-checked with incident reports to corroborate their duration.

Minimum distance to wildland–urban interface

To incorporate social effects, we calculated the minimum distance between individual fires and the nearest WUI area(s) using MTBS fire perimeters and WUI spatial data. WUI spatial data were obtained for 1990, 2000 and 2010 as developed by Radeloff *et al.* (2005), based on an existing WUI definition published in the US Federal Register (USDA and USDI 2006). We used the Euclidian Distance tool in ArcGIS Spatial Analyst version 10.0 (ESRI, Redlands, USA) to generate distance rasters for all the WUI polygons within 100 km of each fire, resulting in a raster where each grid cell has a distance value to the closest WUI. We assumed that the closer a fire burnt to a WUI, the greater the potential for social effects, such as evacuations, damage to property and recreational values, and public health effects.

Climate data

Inter-annual variability in annual area burnt, annual area burnt at high severity and percentage annual area burnt at high severity were examined relative to climate variables, fire danger indices and water balance metrics. Monthly mean temperature and the Palmer drought severity index (PDSI) were calculated at the 4-km scale using parameterised regression on independent slopes model data (PRISM) (Daly *et al.* 2008). Daily energy release component (ERC, fuel model G), duff moisture code (DMC) and reference potential evapotranspiration (PET) were calculated at the 4-km scale using data from Abatzoglou (2013). Gridded data were spatially aggregated across the study area to develop monthly and daily time series concurrent with the MTBS database. Pearson's correlation coefficients were calculated for the natural logarithm of annual area burnt and annual area burnt at high severity, as well as the percentage area burnt at high severity to i) monthly temperature and PDSI from January the year before the fire year through October of the fire year using monthly aggregates from 1 to 12 months, and ii) ERC, DMC and PET from 1 May to 1 November of the fire year using twice monthly time intervals ending on the 1st and 16th of each month that encompassed temporal averages of the previous 15 days to 150 days using a 15-day time step, following Abatzoglou and Kolden (2013). In addition, we calculated correlations between the aforementioned measure of annual area burnt and large-scale modes of climate variability, such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Pearson's correlations were considered statistically significant when $P < 0.05$. Statistical significance ($P < 0.05$) of linear trends was determined by computing the standard error of the trend estimate, where temporal autocorrelation is taken into account by adjusting the degrees of freedom.

Widespread fire years and annual trends

To identify widespread fire years, we used ArcGIS Spatial Analyst along with the MTBS fire perimeters for 3085 fires (1984–2009). We evaluated annual area burnt over this 26-year period using a standard outlier identification approach within SPSS (IBM, version 20) that defines outliers and extreme values based on the Tukey's 75th percentile + 1.5 × interquartile-range (IQR) rule (Dillon *et al.* 2011). Outliers are values greater (or smaller) than 1.5 times the IQR and extreme values are greater (or smaller) than 3 times the IQR. As part of the widespread fire year analysis, metrics of maximum fire size, area burnt and the number of fires per year were calculated.

We acknowledge that our temporal series of 26 years is too short for rigorous time series assessment (particularly given the stochastic nature of both wildfire activity and agency decisions on management actions about fires across this region), but included a basic description of trends in order to compare our results to contemporary studies that have analysed similar temporal series lengths (Miller *et al.* 2009*a*; Dillon *et al.* 2011). For each year, the median and mean of burnt area, percentage of area burnt with high burn severity, fire duration and minimum distance to WUI were calculated. Notably, burn severity classifications for 2008–2009 were not available at the time of analysis. Therefore, we evaluated trends in severity using data from 2916 fires over the 24-year period from 1984–2007. We applied the Time Series Modeller (SPSS, IBM. Version 20) and calculated stationary R^2, the Ljung–Box statistic, and considered the autocorrelation function of each metric for lags of 1–24 years.

Identification of individual extreme fires

To identify the individual extreme fires, we evaluated the statistical distributions of four metrics: fire size, proportion of area burnt as high severity, fire duration and minimum distance to WUI. We considered all fires within the 26-year temporal record (24 years for burn severity) as independent events. For this analysis, we identified the 90th, 95th, and 99th percentiles of each distribution (1st, 5th and 10th for distance to WUI and both tails for burn duration). Although the selection of a specific percentile is arbitrary, the 90th percentile has been used by past studies (e.g. Morgan *et al.* 2008), the 95th percentile represents the most widely used statistical significance threshold and the 99th percentile is analogous to the '1 in 100' event, for example, a 100-year flood. To evaluate whether the different metrics can be considered as independent and separate extreme criteria, the correlation between the different pairs of metrics was evaluated. The fire size, proportion of area burnt as high severity and minimum distance to WUI metrics were log-transformed to meet normality conditions. None of the resultant pairs were significantly correlated.

Results

Years of widespread fires

Four years were identified as outliers and thus denoted as widespread fire years: 1988, 2000, 2006 and 2007 (Fig. 2). Notably, 2007 was identified as a statistically extreme year within this temporal series, which may be expected given it had the largest annual burnt area and the greatest number of fires. When considering each of the separate fires that are often combined into the 1988 Yellowstone Fire, together, this collection of fires represented the largest maximum fire size in the 26-year MTBS history. Year 2000 had the second largest annual burnt area and second highest number of fires, and 2006 had the third largest number of fires. Fire year 2000 was also characterised by a few large fires that accounted for the majority of

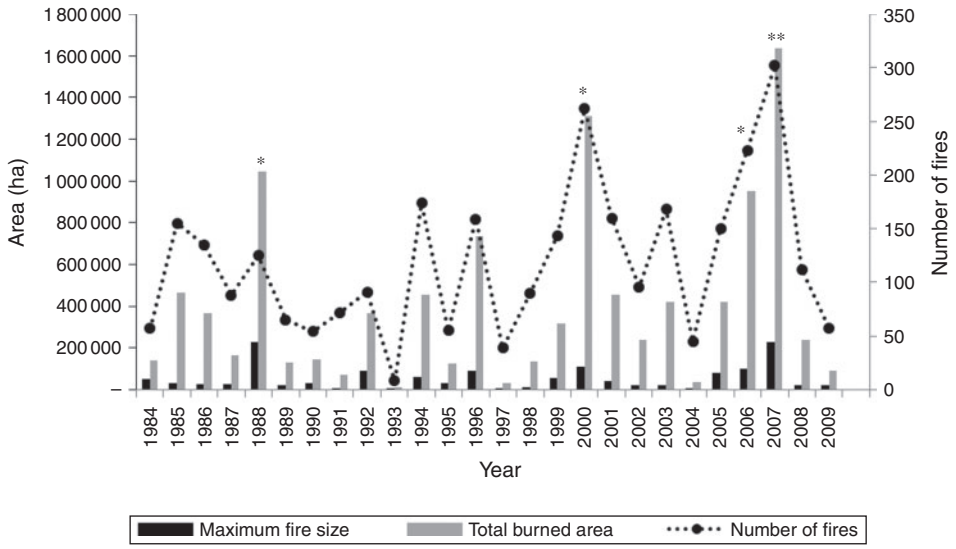

Fig. 2. Maximum fire size, total burnt area and number of fires summarised by year for the Monitoring Trends in Burn Severity (MTBS) data (1984–2009) with '*' indicating statistical outlier and '**' indicating a statistically 'extreme' event, each using the Tukey's outlier method.

the annual area burnt. Year 1988 differed from 2000, 2006 and 2007 as the number of fires was not large, but the mean fire size was greater than any other year and the total burnt area was the third largest in the 26-year period (Fig. 2).

Extreme fires

Thirty-eight individual fires were identified as extreme fires based on exceeding thresholds for combinations of three or four criteria (Table 1, Fig. 3). Burnt area within individual fires mapped by MTBS varied from 0.18 ha to 229 622 ha and the 99th, 95th and 90th percentiles were 41 629, 13 157 and 6968 ha. The 1st, 5th and 10th percentiles of minimum distance to the WUI were each zero, where non-zero values started at the 12th percentile. This illustrates that for the purposes of identifying extreme fires near the WUI, a binary classification of 'fire reached WUI' or 'fire did not reach WUI' would likely be sufficient. There were 426 fires that met the WUI minimum distance requirement. Burn duration varied from 1 to 167 days, where July and August had the greatest number of fire-starts, whereas August, September and October had the greatest number of fire-outs. The 99th, 95th and 90th percentiles in burn duration were 117, 89 and 77 days, whereas the 1st, 5th and 10th percentiles were 1, 1 and 2 days. The 99th, 95th and 90th percentiles of percentage area burnt with high severity were 54, 41 and 35%.

Fig. 3*a–c* shows the number of fires identified by one or more of the four metrics as extreme. When considering the intersection of all four metrics, six, two and zero fires were identified as potentially extreme at the 90th, 95th, and 99th percentile thresholds. Based on fires that met the 90th percentile thresholds for any three of the four metrics (or the 10th percentile for duration or minimum distance to WUI), between 10 and 25 fires were identified as potentially extreme (Fig. 3*a*). The combination of duration, high burn severity and WUI was the only combination of three or four metrics to produce a potentially extreme fire at the 99th percentile (Fig. 3*c*). The individual fires identified as potentially extreme are described in Table 1 and locations are shown in Fig. 4. These 38 potentially extreme fires represent ~15% of the total area burnt within the studied temporal series.

Climate and temporal trends

The widespread fire years identified in this study experienced above-average summer temperatures, mid-summer drought (PDSI < -1.5), fire-season (1 July–16 September) ERCs and DMCs in the upper quintile, relative to 1979–2012 observations. Moreover, the spatial extent of anomalies during these years (Fig. 5) relative to 1981–2010 normals provides further evidence of top-down climatic controls on wildfire conducive to the widespread nature of fuel availability and potential fire growth.

The natural logarithm of area burnt was correlated with standard climate variables including August PDSI and June–July temperatures ($r = -0.60$ and $r = 0.69$, $P < 0.01$), as well as in-season biophysical variables including 1 July–16 September ERC ($r = 0.83$), 1 July–16 September DMC ($r = 0.84$) and PET from 1 July–16 September ($r = 0.83$). We found significant concurrent correlations to ENSO during the summer months ($r = -0.56$, $P < 0.01$) using the multivariate El Niño index (Wolter and Timlin, 1993) and the PDO index (Mantua *et al.* 1997) during August–September ($r = -0.58$). Correlations were also found for the natural logarithm of area burnt at high severity with each of August PDSI and June–July temperatures ($r = -0.69$ and $r = 0.80$) and each of 1 July–16 September ERC and 1 July–16 September PET ($r = 0.91$ and $r = 0.92$). The stronger correlations to area burnt at high severity were reflected by significant correlations between the percentage total area burnt at high severity and each of 1 July–1 October ERC and 16 June–1 November PET ($r = 0.66$ and $r = 0.75$). Linear trends in extreme fire metrics from 1984 to 2009 and climatic factors were strongly correlated with area burnt.

Over all analysed time lags (1–24 years), none of the analysed temporal series exhibited residual autocorrelation

Table 1. List of 38 potentially extreme fires that meet all or a combination of three metrics (size, duration, high burn severity and minimum distance to wildland–urban interface, WUI)

Criteria are met for cells marked with Y. The 90th, 95th and 99th percentile thresholds are high burn severity 34, 41 and 54%; burnt area size 6968, 3157 and 41 629 ha; and duration 77, 89 and 117 days. The 1st, 5th, and 10th percentiles for duration are 1, 1 and 2 days. The 1st, 5th, and 10th percentiles for minimum distance to WUI were each zero. ID, Idaho; MT, Montana; NV, Nevada; OR, Oregon; WA, Washington

Fire name	Year	State	Size			Duration			Severity			WUI		
			90	95	99	90	95	99	90	95	99	10	5	1
Davis	2003	OR	Y			Y	Y	Y	Y	Y	Y	Y	Y	Y
Canyon Creek	1988	MT	Y	Y		Y	Y		Y	Y		Y	Y	Y
Lincoln Complex (Snowbank)	2003	MT	Y	Y		Y	Y		Y	Y		Y	Y	Y
Dooley Mountain	1989	OR	Y			Y	Y		Y	Y		Y	Y	Y
Cascade Complex (Monumental)	2007	ID	Y	Y		Y	Y		Y			Y	Y	Y
Grizzly Complex (Winter)	2002	OR	Y	Y		Y	Y		Y			Y	Y	Y
Fool Creek	2007	MT	Y	Y		Y	Y		Y	Y				
North Fork	1988	WY/MT/ID	Y	Y		Y	Y		Y	Y				
Mussigbrod Complex (Mussigbrod)	2000	MT	Y	Y		Y	Y		Y	Y				
Little Blue	2000	MT				Y	Y		Y	Y		Y	Y	Y
East Zone Complex (Raines)	2007	ID	Y	Y		Y	Y					Y	Y	Y
Lake Creek	1988	WY	Y	Y		Y	Y					Y	Y	Y
Murphy Complex	2007	ID/NV	Y	Y		Y	Y					Y	Y	Y
Flossie Complex	2000	ID	Y	Y		Y	Y					Y	Y	Y
Sawmill Complex (Wyman #2)	2007	MT	Y	Y		Y	Y					Y	Y	Y
Canyon Ferry Complex (Cave Gulch)	2000	MT	Y						Y			Y	Y	Y
Jungle	2006	MT	Y						Y			Y	Y	Y
Red Bench	1988	MT	Y						Y			Y	Y	Y
Trail Creek	2000	ID	Y						Y			Y	Y	Y
Storm Creek	1988	MT/WY	Y						Y			Y	Y	Y
Tower	1996	OR	Y						Y			Y	Y	Y
Ahorn	2007	MT	Y			Y			Y					
Fridley	2001	MT	Y			Y			Y					
Swet-Warrior Complex (Swet Creek)	1996	ID	Y			Y			Y					
Snowshoe	2001	ID	Y			Y			Y					
Red Eagle	2006	MT	Y			Y			Y					
Confluence Complex (Clear Sage)	2007	ID	Y			Y						Y	Y	Y
Meriwether	2007	MT	Y			Y						Y	Y	Y
Porphyry South	1994	ID	Y			Y						Y	Y	Y
Poe Cabin	2007	ID	Y			Y						Y	Y	Y
Burgdorf Junction	2000	ID	Y			Y						Y	Y	Y
Canal	1989	OR	Y			Y						Y	Y	Y
Upper Nine Mile Complex (Nine Mile)	2000	MT	Y			Y						Y	Y	Y
Porcupine Creek	1992	ID	Y			Y						Y	Y	Y
Burnt Flats	2000	ID	Y			Y						Y	Y	Y
Rosa[A]	1985	WA	Y			Y						Y	Y	Y
Ringer[A]	1986	ID	Y			Y						Y	Y	Y
Coyote Butte[A]	1996	ID	Y			Y						Y	Y	Y

[A]Fires with durations lower than the 10th percentile of the fire duration. Fire polygons of the same fire name were combined into a single entry.

coefficients that exceeded the 95% confidence limits. No discernible temporal trends were observed with percentage area burnt with high severity, area burnt or minimum distance to WUI as a function of time (Fig. 6*a*,*b* and Fig. 7*b*). A notable trend was observed for the mean fire duration over time (Fig. 7*a*: stationary $R^2 = 0.826$, Ljung–Box $P = 0.709$). A correlation between annual mean duration of the individual fires and the average percentage area burnt at high severity was observed ($r = 0.64$, $n = 24$, $P < 0.001$). Likewise, a correlation between median minimum distance to WUI and median fire duration was observed ($r = -0.4$, $n = 26$, $P < 0.05$). Climatic factors strongly correlated with area burnt showed non-significant increases in June–July temperature and fire-season DMC from 1979–2012 in addition to insignificant changes in summer PDSI. In contrast, significant increases in ERC and PET averaged over the fire season were observed for the Northern Rockies from 1979 to 2012, particularly for the latter part of the fire season including August and September.

Discussion

Years of widespread fires

In agreement with past studies seeking to characterise widespread fire years within the studied region, a disproportionate

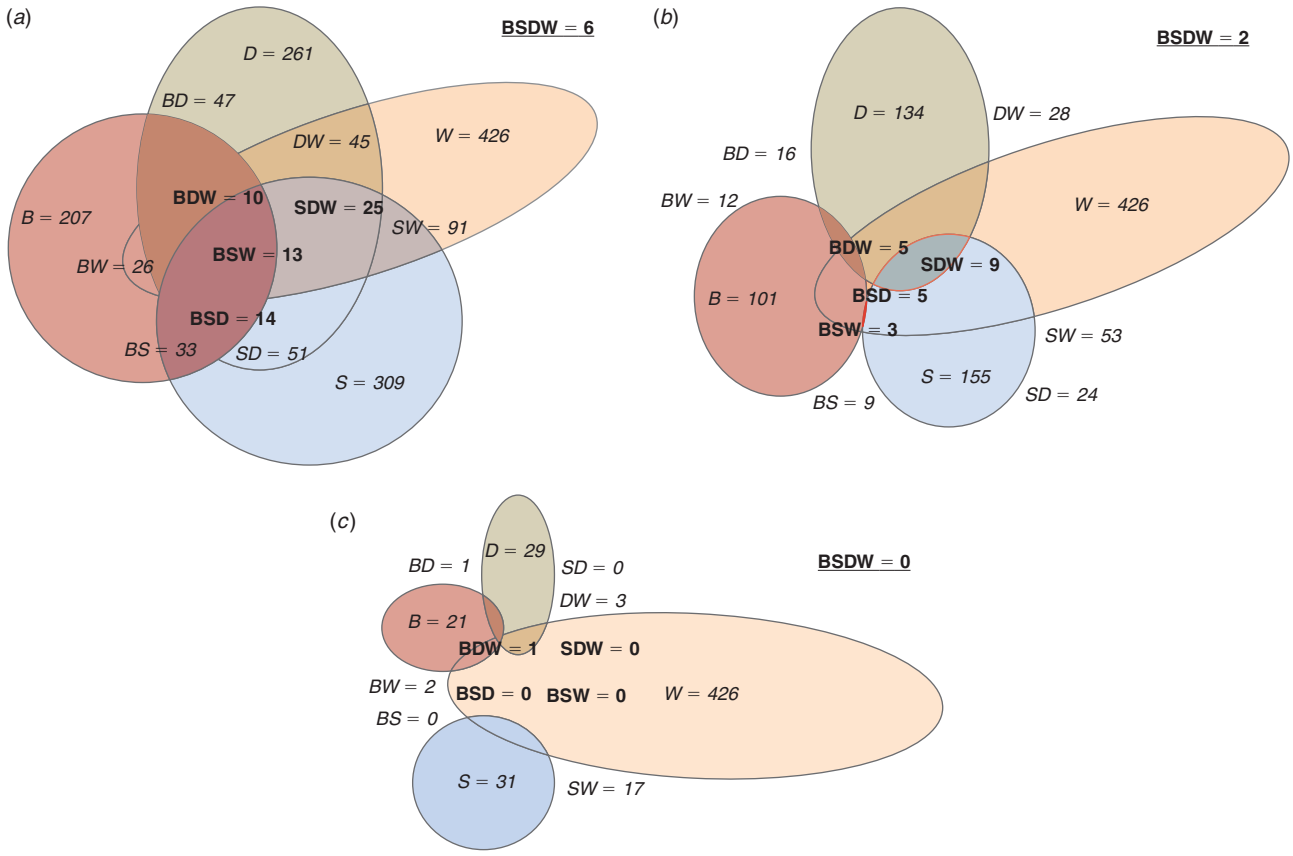

Fig. 3. Number of fires identified by selection criteria (B, high burn severity; S, size, i.e. burnt area; D, duration; W, minimum distance to wildland–urban interface). Overlap areas represent fires meeting multiple criteria. Three percentile groups, (*a*) 90th/10th, (*b*) 95th/5th and (*c*) 99th/1st, were applied for each metric. In six cases, the MTBS record had multiple polygons for a single fire. In this figure all polygons were treated as separate fires, whereas in subsequent figures and Table 1 these were combined to represent the single fire name.

amount of the burnt area occurred within the four years (1988, 2000, 2006 and 2007) identified by our study (Strauss *et al.* 1989; Morgan *et al.* 2008). Two prior studies also analysed spatial subsets of our study area to identify widespread fire years. Morgan *et al.* (2008) applied the 90th percentile of area burnt to forests of Idaho and north-western Montana from 1900 to 2003 and identified eleven widespread fire years, as would be expected for a 103-year temporal series using this method. The years 1988, 1994, 2000 and 2003 were the similar widespread years contained in our analysis timeframe. As in the current study, Dillon *et al.* (2011) applied the Tukey's outlier detection criteria to each of the Inland North-west and Northern Rockies ecoregions. They identified five widespread fire years for each ecoregion: 1994, 1996, 2001, 2002 and 2006 in the Inland North-west, and 1988, 1996, 2000, 2003 and 2006 in the Northern Rockies ecoregion. Although we identify some of the same years, differences across and within these studies (e.g. Dillon *et al.* 2011) highlight that the spatial scale of analysis used is an important determinant in selecting widespread fire years. Given the large spatial extent of the climate anomalies within these widespread fire years (Fig. 5), it is quite possible that the large fires would strain fire-suppression resources, thereby further allowing for growth of initially lower priority fires.

Extreme fires

Of the 38 fires that intersected with at least three criteria at the 90th percentile, half occurred during the identified widespread fire years. This was expected given that the widespread fire years accounted for a disproportionate amount of the total area burnt within the temporal series. However, only one out of six fires that was considered potentially extreme with all four metrics occurred during a widespread fire year. Thus, potentially extreme fire events do not always occur in years of widespread fire and they can occur within any year when fires ignite under sufficiently hot, dry, and windy conditions such that they exceed initial attack fire-suppression efforts. Extreme fire events may be driven by a convergence of conditions that could occur in any year.

Examining the intersection of various metrics revealed several interesting patterns. First, the intersection of high burn severity and the WUI produced 26 fires, which was the lowest number of intersecting fires for any pair of metrics at the 90th percentile. This low degree of overlap may be expected given 1) fuel reduction projects are more prevalent closer to the WUI leading to fires that exhibit lower burn severity (Hudak *et al.* 2011), 2) forests are more likely to be actively managed in areas that are not remote and 3) mixed land use in the WUI creates a patchwork of fuels and vegetation broken by features such as

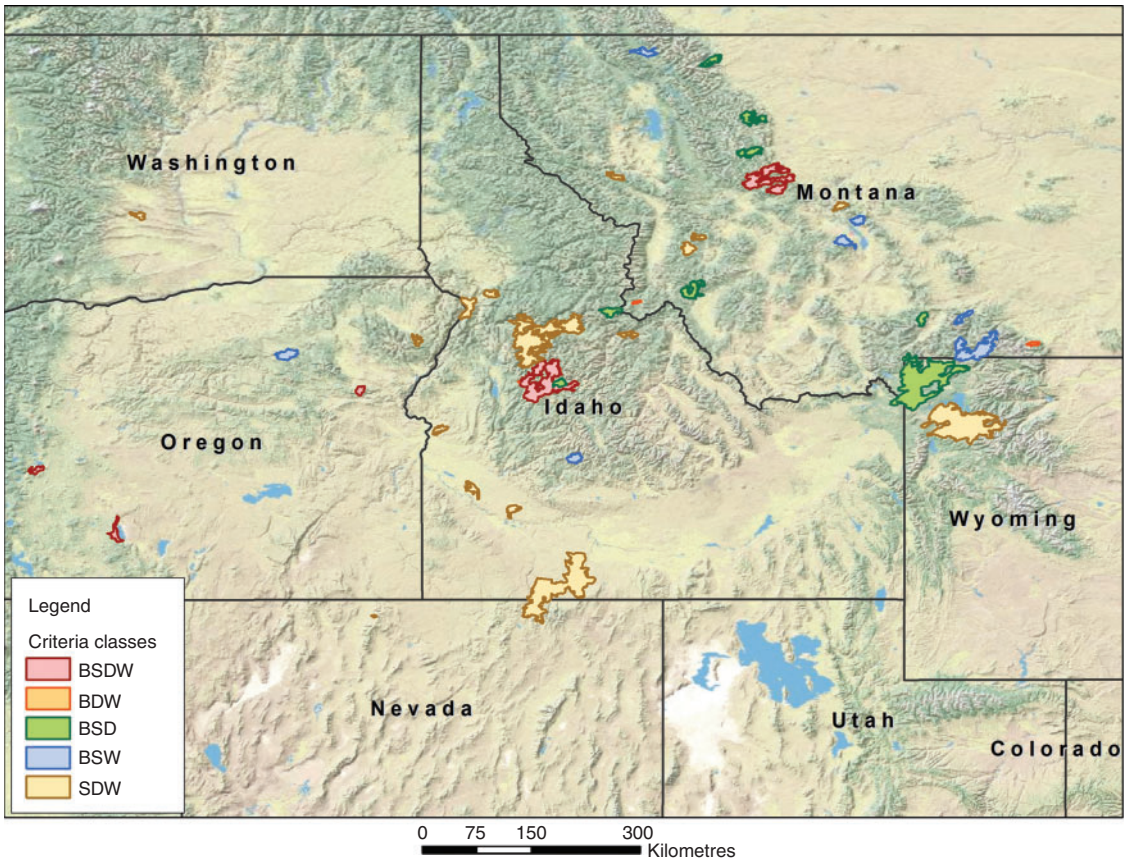

Fig. 4. The 38 fires identified as potentially extreme based on the intersection of three or more fire criteria of high burn severity (B), size (S), duration (D) and wildland–urban interface (W).

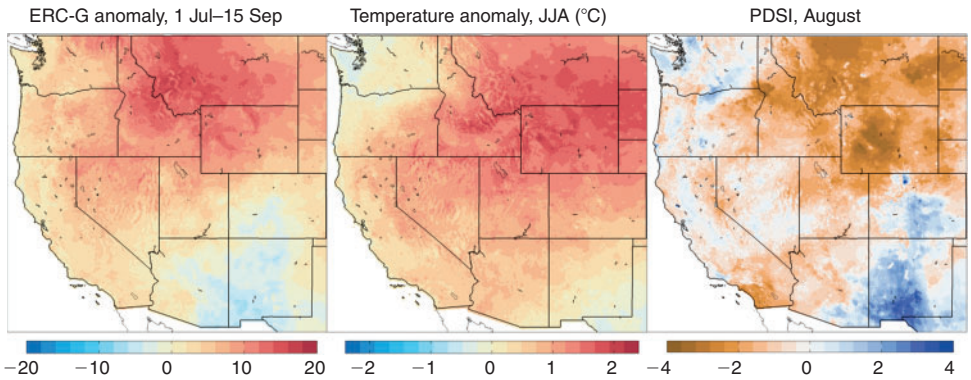

Fig. 5. Composite of the four identified widespread fire years (1988, 2000, 2006 and 2007) for climate variables expressed as a departure from the 1981–2010 climate normal. Image shows elevated fire danger indices (ΔERC-G, energy release coefficient), warm summer conditions (Δ temperature) and antecedent drought across the region (ΔPDSI, Palmer drought severity index).

homes and roads, reducing the likelihood of continuous fuels and high burn severity.

Analysis of fire duration identified 261 fires lasting at least 117 days and 536 fires that lasted fewer than three days. Although large, long duration fires are clearly of interest when considering potentially extreme events, fires that burn the largest areas for the shortest periods are also important because they are fast-moving events and may be indicative of extreme fire behaviour. Seventeen fires met the 90th percentile threshold for size and 10th percentile threshold for duration. These fires burnt at rates ranging from 7535 to 49 741 ha day^{-1}. However, none met any of the high-burn-severity thresholds, an indication

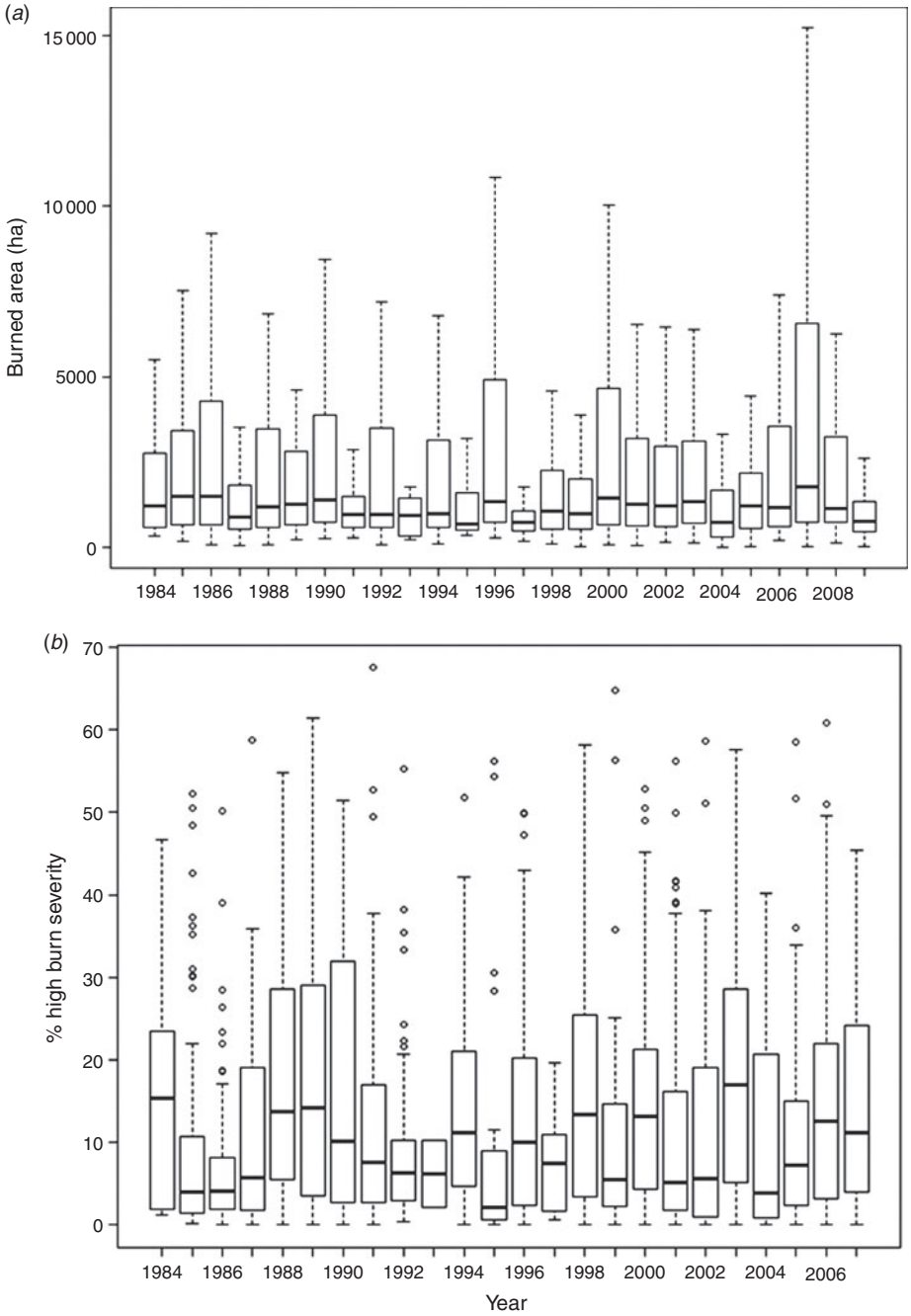

Fig. 6. Box-and-whisker plot of the (*a*) area burnt over the 26-year time period ('84–'09) and (*b*) percentage high severity (as mapped by MTBS, '84–07 fires only). In both cases, the lower whisker represents the lowest value within 1.5 times the interquartile range (IQR) of the lower quartile, and the upper whisker represents the highest data value still within 1.5 IQR of the upper quartile. The bottom and top of the boxes represent the 25th and 75th percentile and the bands within the boxes represent the median. Part (*a*) does not display the 122 outlier data points (values beyond the whiskers), to aid visual assessment of the temporal series.

that fast-moving fires do not necessarily result in high burn severity. One reason for this could be fast moving fires in grasslands or semi-arid to arid lands where burn severity methods have been less effective. The intersection of high burn severity and fire size identified 33 fires, which is the second smallest number of intersecting fires at the 90th percentile on two metrics. This suggests that as fires get larger they continue to burn with mixed degrees of fire effects.

Of the three criteria combinations, the intersection of fire size, duration and WUI produced the most potentially extreme candidates at both the 90th and 95th percentiles, with 21 and nine fires (Fig. 3*b*, *c*). Including the shortest duration fires increased the

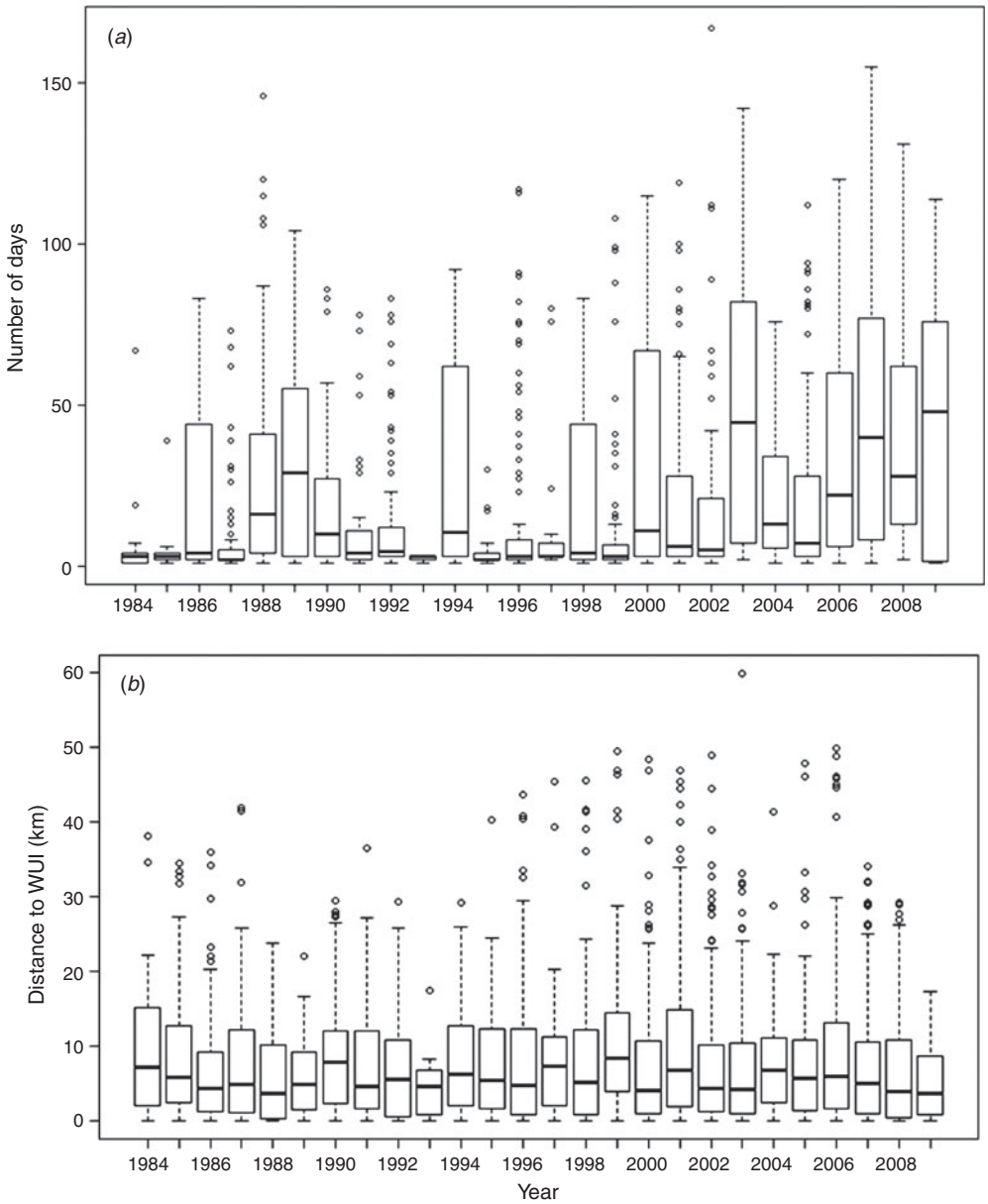

Fig. 7. Box-and-whisker plot of the (*a*) duration (number of days) of all the fires (with available out-dates) and (*b*) minimum distance to WUI. In both cases, the lower whisker represents the lowest value within 1.5 times the interquartile range (IQR) of the lower quartile, and the upper whisker represents the highest data value still within 1.5 IQR of the upper quartile. The bottom and top of the boxes represent the 25th and 75th percentile, the bands within the boxes represent the median.

total number of fires to 25. Fire size, proximity to WUI and either long duration or high rates of spread could identify them as potentially extreme events to manage. Fires exceeding the combined high burn severity, size and duration thresholds represent those with the greatest potential for ecological effects.

Regional-scale climatic variability

We found correlations between area burnt and PDSI, temperature, ERC, DMC and PET. These results corroborate results of climate–fire studies in the region (Westerling *et al.* 2006; Morgan *et al.* 2008) that show strong flammability-limited climatic controls on wildfire activity, where drought concurrent to the fire season is important. Likewise, similar to Littell and Gwozd (2011) and Abatzoglou and Kolden (2013), significantly more variance (>20%) in inter-annual variability in area burnt was explained through biophysical metrics over first-order climate variables.

The typical antecedent influence of ENSO and PDO manifested through modulating precipitation and temperature during the cool season and their influence on fuel availability and accumulation was not observed during the period of record. In contrast, relationships were found with ENSO during the

summer months and with PDO during August–September. Curiously, these relationships are at odds with prior studies that found wildfire activity in this region to be preferentially higher during the warm phase of ENSO and PDO. Wang *et al.* (2012) showed above-average precipitation and below-normal surface temperature from the upper-Midwest westward into the study region during the developing phase of El Niño years, which supports our results. However, relatively weak concurrent teleconnections between PDO and ENSO to summer atmospheric circulation over western North America suggests that additional analysis is required to evaluate the degree to which summertime large-scale climate variability influences wildfire activity. Although the 26-year temporal series is arguably too short to make conclusions regarding annual trends, the increase in average fire duration with time over the 1984–2007 period is notable (Fig. 7*a*).

Alternative criteria for future studies

Our list of criteria to identify potentially extreme fires could be expanded for both biophysical and social parameters beyond fire size, fire duration, high burn severity and distance to WUI. Although difficult to determine with geospatial data, in addition to high burn severity, changes in plant community composition may also be an important indicator of extreme fire effects. For example, fire can dramatically shift plant communities from forests, woodlands, native grasslands and shrublands to annual grasslands (D'Antonio and Vitousek 1992). Shifts to annual grass dominance can severely alter ecosystem function and fire regimes (Brooks *et al.* 2004). Additionally, rate of fire growth or remote sensing metrics of the fire radiative energy could prove interesting metrics to assess potentially extreme fires (Smith and Wooster 2005; Wooster *et al.* 2005; Kumar *et al.* 2011; Heward *et al.* in press). Metrics reflecting the proximity of fire or potential fire effects on other values-at-risk, including those that could be affected by sediment from post-fire erosion, could prove useful. The metrics explored in this study are retrospective but could be used to help identify future conditions under which extreme fires occur, thus allowing managers to plan accordingly. The US Forest Service and research as part of the Fire Program Analysis program are currently developing such predictive products (Finney *et al.* 2011; Miller and Ager 2013).

Defining the influence of fires on social systems must go beyond minimum distance to WUI, though this may be a good initial indicator of potential effect on people and private property (see example in Fig. 8). Furthermore, metrics that marry biophysical and social aspects could hold the answer to defining extreme fires. These merged metrics may evolve by coupling spectral indices with metrics such as slope or proximity to WUI through spatial weighting (see example in Fig. 9). We acknowledge that metrics of severity or fire intensity near to the WUI may not necessarily provide a clear indication as to likely social effects, given research has demonstrated that low-intensity surface fires can lead to destruction of houses (Graham *et al.* 2012; J. Cohen, unpubl. data). Wildfire effects on social systems can be direct (e.g. injury or death, residential destruction, timber losses) or indirect (e.g. loss of aesthetic value, recreational value and compromised air quality from smoke emissions) (Paveglio and Prato 2012). Additional quantitative and qualitative data indicative of direct effects on social systems could be incorporated into future efforts to define extreme wildfires. However, consistent data on these aspects are not as readily available as are ecological indicators, nor are they consistently documented across smaller geographical scales (e.g. community and county). Research is warranted to explore the economic and property effect of fires at the community level, especially studies that work across many fires and through time to identify alternative meaningful metrics.

We identified fires as potentially extreme that others have judged to be historically significant. For instance, two fires we identified as extreme (2007 Murphy Complex and 1988 Yellowstone) were historically significant according to the US National Interagency Fire Center (NIFC). Most of the fires we identified as extreme were not judged historically significant, and five fires (1985 Butte, 1992 Foothills, 1994 Idaho City Complex, 1996 Cox Wells and 2003 Cramer), were identified as historically significant by NIFC because lives or structures were lost, or the fires burnt large areas, yet none of these were extreme by our criteria. This in part may be due to buildings and structures such as barns or cabins not meeting the WUI criteria. When considering historically significant fires in the US, the 1871 Peshtigo Fire, the 1881 Thumb Fire, the 1910 Fire and many other historically significant fires identified by NIFC would likely have met the majority of the criteria used in this study but they were outside the 1984–2007 period we considered.

Identifying extreme fires and the conditions favouring them are useful to a wide variety of stakeholders (e.g. scientists, managers and the public). Moreover, the identification of where and how often extreme fires occur could aid in accurately characterising the variability within fire regimes and fire seasons, leading to differences in how these events are communicated by the scientific and management communities to the public and policy makers. With projected increases in the area of the WUI, and changing climate potentially leading to longer fires, the effects of extreme fires may become more pronounced.

Conclusion

We identified extreme fires based upon the intersection of the 90th, 95th and 99th percentile of four metrics including area burnt, fire duration, percentage burnt with high burn severity and minimum distance to the WUI. Fires that reach the WUI, in addition to being large and having high burn severity, may also result in larger economic effects on individuals, businesses and communities through property losses and costs of suppression. Indeed, the 38 fires identified as extreme burnt 15% of the total area burnt though they represented only 1.5% of fires >404 ha that burnt during 1984–2009. Over half these potentially extreme fires occurred during the identified widespread fire years.

Although there is little agreement on whether more extreme fires are occurring, as the WUI continues to expand fire will increasingly affect people's lives and property. Although our data could not be used to robustly evaluate trends of extreme fires with climate because of the short timeframe, the identified widespread fire years did occur during years that significantly departed from historic climate norms and 25% of the potentially extreme individual fire events occurred during the statistically extreme 2007 fire year. Moreover, burn duration exhibited a significant increasing trend over the 26 years, although this may

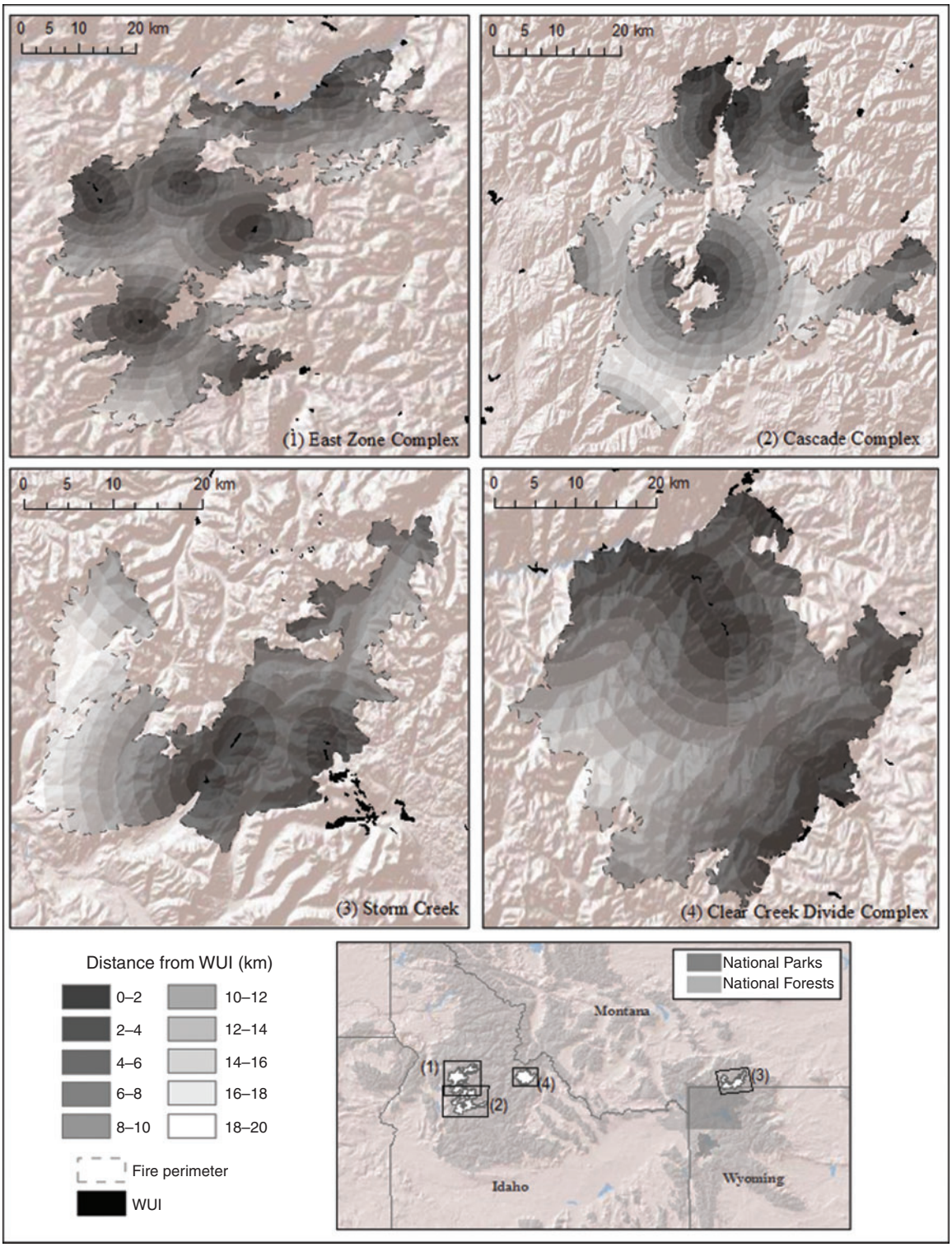

Fig. 8. Example WUI distance calculation output for four fires.

be due to land management policy approaches over that period rather than climate. Climate projections for the north-western US include increased temperature and vapour pressure deficit, as well as decreased precipitation during the fire season. These conditions are likely to increase the frequency of extreme fires, while projected growth in the area of the WUI will expose larger segments of human development to such fire conditions by virtue of their proximity to wildland vegetation.

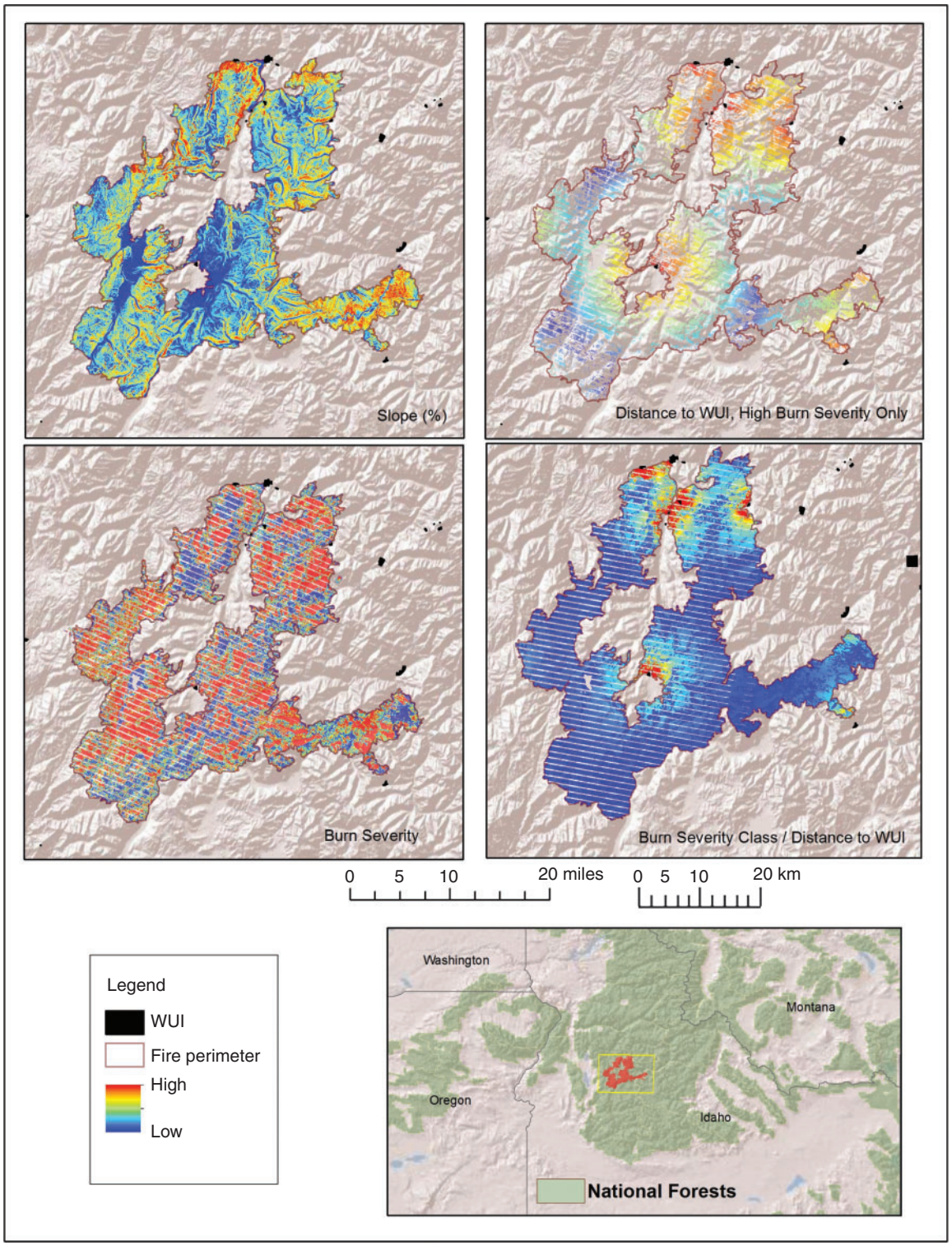

Fig. 9. Indices of extreme fires that marry social and ecological factors, such as this one combining high burn severity and distance to WUI for the Columbia Complex Fire, may be especially useful.

Importantly, the approaches used in this study are readily transferable to other regions and ecosystems, because our study covered a broad array of vegetation types. The identification of extreme or uncharacteristic fire years in other locations should be done using statistical outlier detection methods, such as the method applied herein and in Dillon *et al.* (2011). In terms of identifying extreme individual fire events, the intersection of different percentiles is readily transferable to other regions and

could easily be expanded to investigate the intersection of many more metrics. We did not weight the different metrics used in this study. However, it is quite likely that the incorporation of a wide array of additional metrics would require weighting. Survey techniques and consultation with fire or land managers could be used to infer the relative importance of additional metrics. Although we visualised potentially extreme fires through Venn diagrams, as the list of spatial, ecological and social variables grows and their interconnections become more complicated, other visualisation approaches that allow for multi-dimensional viewing and weighting of metrics will become necessary to advance our scientific understanding.

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