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Relationships between fire danger and the daily number and daily growth of active incidents burning in the northern Rocky Mountains, USA

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Abstract. Daily National Fire Danger Rating System (NFDRS) indices are typically associated with the number and final size of newly discovered fires, or averaged over time and associated with the likelihood and total burned area of large fires. Herein we used a decade (2003–12) of NFDRS indices and US Forest Service (USFS) fire reports to examine daily relationships between fire danger and the number and growth rate of wildfires burning within a single predictive service area (PSA) in the Northern Rockies, USA. Results demonstrate that daily associations can be used to: (1) extend the utility of the NFDRS beyond the discovery date of new fires; (2) examine and justify the temporal window within which daily fire danger indices are averaged and related to total burned area; (3) quantify the probability of managing an active incident as a function of fire danger; and (4) quantify the magnitude and variability of daily fire growth as a function of fire danger. The methods herein can be extended to other areas with a daily history of weather and fire records, and can be used to better inform fire management decisions or to compare regional responses of daily fire activity to changes in fire danger.

Additional keywords: daily associations, energy release component (ERC), prolonged fire activity.

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Introduction

Nearly a century of theoretical, experimental and applied wildland fire science in the US has culminated in the modern National Fire Danger Rating System (NFDRS; Hardy and Hardy 2007). At the core of the NFDRS is a computational process (Cohen and Deeming 1985) that inputs fuels, weather and topographic variables and outputs a suite of relative indices that reflect the potential for a fire to ignite, spread and resist control (Deeming *et al.* 1972, 1977). Rather than providing site-specific fire behaviour predictions, the NFDRS is designed to provide indices that indicate the worst-case burning conditions averaged across large (10^4–10^6 ha) fire danger rating areas (FDRAs; Fosberg and Furman 1971). The earliest applications of the NFDRS typically characterised FDRAs using a single fuel model (Bradshaw *et al.* 1984), a single slope class and a single mid-afternoon remote automated weather station (RAWS) observation (National Wildfire Coordination Group (NWCG) 2012). Although the development of increasingly higher-resolution fuel model maps (e.g. Burgan *et al.* 1998) and gridded meteorological datasets (e.g. Abatzoglou 2013) has enabled the production of fine-scale fire danger maps, sometimes at hourly intervals (Carlson *et al.* 2002), most US fire management decisions are still guided by NFDRS outputs generated at coarse spatial resolutions and at daily temporal resolution (e.g. Predictive Services 2009; National Interagency Fire Center (NIFC) 2014).

The performance of the NFDRS (or any other fire danger rating system) is evaluated based on its ability to generate indices that are successful indicators of fire activity (Viegas *et al.* 1999; Andrews *et al.* 2003; Eastaugh *et al.* 2012; Arpaci *et al.* 2013). Fire managers in the US use NFDRS indices almost exclusively to indicate new fire potential; therefore, fire activity is typically condensed into two metrics: (1) the number of newly discovered fires on a particular date; and (2) their final size (Andrews 1987). In the context of new fire potential, the final fire size is not intended to indicate the total burned area *per se*, but rather to indicate whether or not a newly discovered fire escaped initial attack. Historical relationships between fire danger rating indices, the number of newly discovered fires and the number of newly discovered fires that escaped initial attack are traditionally used to inform fire prevention and presuppression planning decisions (Schlobohm and Brain 2002).

Preventing, preparing for and responding to newly discovered fires is only part of the wildland firefighting enterprise. Considerable resources in the US are also directed at managing wildland fires that escape initial attack, the largest of which account for most of the annual area burned and fire suppression expenditures (Calkin *et al.* 2005). The ecological, economical and societal effects of large wildland fires have prompted several recent evaluations of the NFDRS based on its ability to indicate the probability of large fire occurrences (Preisler *et al.* 2004, 2008), the absolute number of large fires (Preisler *et al.* 2008, 2009; Riley *et al.* 2013; Barbero *et al.* 2014*a*, 2014*b*) and total burned area (Roads *et al.* 2005; Abatzoglou and Kolden 2013). Depending on the rationale for the evaluation, the definition of a large fire can vary between >40.5 ha (Preisler *et al.* 2004, 2009) and >400 ha (Preisler and Westerling 2007; Preisler *et al.* 2008; Riley *et al.* 2013) and for these applications the final fire size is more genuinely used as an indicator of total burned area.

Associating NFDRS indices recorded on the discovery date with metrics that characterise new fire potential is well justified because the acts of ignition, discovery, initial attack and escape generally occur within a few days of each other. In contrast, associating fire danger recorded on a discovery date with a genuine estimate of total burned area is less justified because large fires often burn for long durations, and the accumulation of burned area depends on the evolution of fire danger through the incident's lifetime. Hence, NFDRS indices are often averaged over some temporal interval and then related to total burned area, presumably accumulated over the same time frame. For example, Mees and Bednar (1989) and Mees and Chase (1991) use 3-day averages, Riley *et al.* (2013) use the average over the first 7 days of the incident, Barbero *et al.* (2014*a*) use a 21-day window centred on the discovery date and Preisler *et al.* (2008) use monthly averages. However, identifying the appropriate temporal window over which to associate average fire danger and total burned area poses a challenge (Riley *et al.* 2013; Barbero *et al.* 2014*a*) because: (1) daily indices lose their ability to capture high-frequency fluctuations when averaged over time (Preisler *et al.* 2008); and (2) a few high fire spread days (Podur and Wotton 2011) may account for most of the final fire size.

Weekly, monthly and seasonal relationships between average fire danger and total burned area are inherently determined by their underlying daily relationships. However, as of yet daily NFDRS indices and daily measures of wildland fire activity have rarely (if ever) been associated beyond the discovery date. Consequently, the underlying daily relationships between fire danger and persistent wildland fire activity remain largely unknown. Herein we present a case study that addresses this knowledge gap by associating a decade (2003–12) of daily NFDRS indices and daily US Forest Service (USFS) fire reports within a single northern Rocky Mountains predictive service area (PSA). We develop and analyse relationships between daily fire danger and persistent fire activity characterised by the daily number and daily growth of active incidents burning within this particular PSA. Ultimately we discuss the scientific and management implications of associating daily fire danger with daily metrics of persistent fire activity, and we suggest directions for future work.

Methods

Study area

The 2.0-Mha study area is located on the Idaho and Montana border in the northern Rocky Mountains, USA, and is specifically defined by the boundary of an individual PSA, referred to hereafter as NR06 (Fig. 1). We chose a PSA, and in particular NR06, for several reasons. First, selecting a predefined PSA

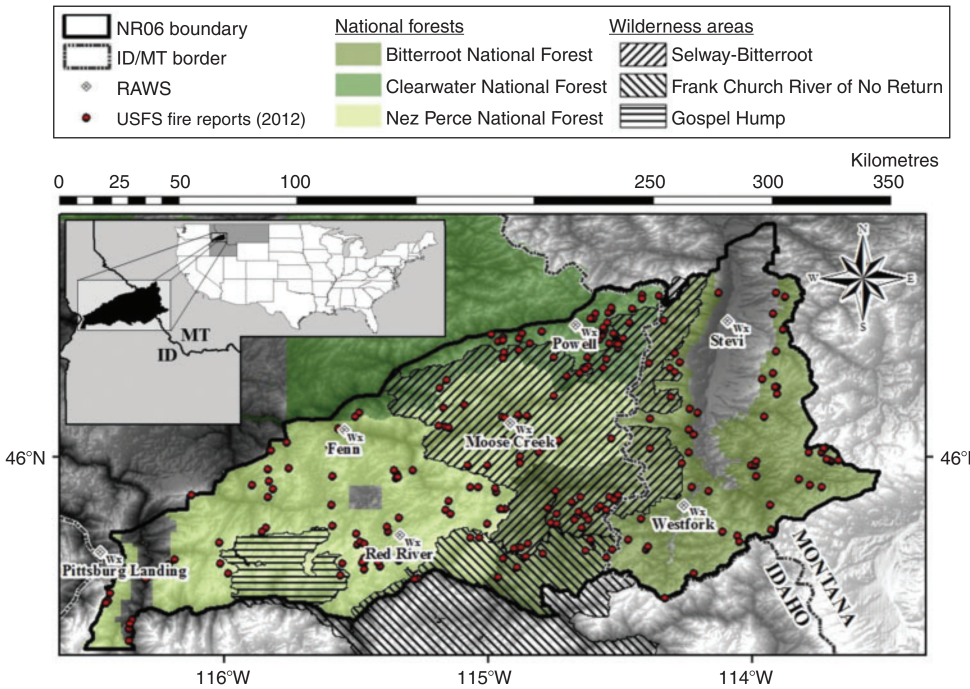

Fig. 1. Map of the predictive service area (PSA) encompassing north-central Idaho and the Bitterroot and Sapphire Mountains, referred to as NR06. RAWS, remote automated weather station; USFS, US Forest Service.

inherently eliminates the often subjective task of (i) identifying FDRAs that encompass similar fuels, climate and topography; (ii) identifying a collection of RAWS to represent the FDRAs; and (iii) identifying the seasonal window within which to perform the analysis. Herein we capitalise on the decisions already made by expert Geographic Area Coordination Center (GACC) meteorologists. We also selected a PSA because of its relevance in disseminating fuels, fire danger and fire occurrence information to support proactive fire management decisions. For example, the 7-day significant fire potential outlooks are organised into PSAs (Predictive Services 2009). Furthermore, because a PSA is typically larger than a single FDRA or a fire management unit (FMU), it offers the advantage of circumscribing a greater number of wildland fires, thereby increasing the sample size from which to develop associations.

We specifically selected NR06 from among all PSAs because it is administratively simple (three national forests combine to occupy 89% of the area) and because 43% of NR06 is designated wilderness (Fig. 1). The Selway-Bitterroot, the Frank Church River of No Return and the Gospel Hump wildernesses all have long-established wildland fire use (WFU) programs that, when possible, allow lightning-caused fires to fulfil their ecological role as natural disturbances (Parsons 2000). Hence, NR06 provides an opportunity to capture associations between fire danger and fire activity where the ignition, daily fire growth, duration and final size of prescribed natural fires are largely determined by weather conditions.

Daily fire danger

A daily time series of NFDRS indices was obtained directly from the Northern Rockies Coordination Center (NRCC) Predictive Services program. Each daily NFDRS index for NR06 is calculated by averaging the mid-afternoon values recorded across seven key RAWS (Fig. 1). Despite recent concerns over RAWS locations, density and data quality (Brown *et al.* 2002, 2011), we use the time series provided by the Predictive Services program because this dataset has been screened by GACC meteorologists and deemed reliable enough to generate the fire danger maps, graphs and 7-day significant fire potential outlooks (Predictive Services 2009) widely distributed throughout the US fire management community.

To facilitate comparisons between PSAs in the Northern Rockies, the Predictive Services program universally reports the energy release component (ERC) calculated for NFDRS Fuel Model G (ERC(G)). The ERCs indicate the maximum potential heat released per unit area within the flaming front of an initiating fire (Deeming *et al.* 1972) and are not affected by wind speed, but are strongly influenced by fuel type, particularly the100-h and greater time lag fuels. Because NFDRS Fuel Model G is composed of a substantial proportion of dead and downed material as well as a live woody and herbaceous component (Deeming *et al.* 1977; Bradshaw *et al.* 1984), ERC(G) exhibits minimal daily fluctuations and tracks well with seasonal drying trends. Calculations of ERCs do not carry over from season to season and are therefore less suitable than the Palmer drought severity index (PDSI; Palmer 1965) or the standardised precipitation index (SPI; McKee *et al.* 1993) for characterising longer-term water deficits (e.g. Guttman 1998).

Although records extend back to 1954 for some RAWS, we used 10 years (2003–12) of data in order to overlap the decadal archive of Incident Status Summary (ICS-209) reports (see below). Reassuringly, the fire danger technical committees on both the Nez Perce-Clearwater and the Bitterroot National Forests also use ERC(G) to indicate fire danger, and also use 20 and 10 years of data to develop their fire danger operating plans (FDOPs) respectively (USDA Forest Service, unpubl. data).

To facilitate future comparisons between PSAs and to ensure that our results are more generalised, daily values of ERC(G) are normalised according to the formula presented by Viegas *et al.* (1999) and reproduced here:

$$I_d = 100 \times \frac{I_d - I_{\min}}{I_{\max} - I_{\min}} \quad (1)$$

where I represents a generic parameter (e.g. a fire danger rating index), the subscript d indicates the observation day, the subscripts *max* and *min* refer to the maximum and minimum daily values recorded during the decade, and I'_d is the normalised value of I_d. For example, ERC(G)′ is the normalised value of ERC(G). Although converting ERC(G) into percentiles is another option (e.g. Riley *et al.* 2013), we used Eqn 1 to preserve the proportionality between equal intervals of the normalised values.

USFS fire information

Federal wildland fire occurrence data files for the Bitterroot, Clearwater and Nez Perce National Forests between 2003 and 2012 were downloaded using Kansas City Fire Access Software (KCFAST), accessible from the Fire and Aviation Management Website (FAMWEB; https://fam.nwcg.gov/fam-web/, accessed 16 May 2015). Fire occurrence data were subset to only those fire records with origins located within NR06 and filtered to remove duplicate fire records. Despite the quality control and assurance issues associated with historical fire records (Brown *et al.* 2002), the dataset downloaded from the FAMWEB exhibited an error of omission of <0.1% compared with the most recent, complete and error-checked spatial database (Short 2014). The fire occurrence data are used here only to characterise new fire potential; therefore, only the origin location, discovery date and final fire size are used in this analysis.

Information pertaining to ongoing fire activity beyond the discovery date was retrieved from a decade of ICS-209 reports. Since 2002, the NWCG has maintained an archive of ICS-209 reports for fires greater than approximately 40 ha burning in timber fuel types, greater than approximately 121 ha burning in grass or brush fuel types or if a Type 1 or 2 incident management team (IMT) was assigned (NIFC 2011). ICS-209 forms include fields for the current date, origin location and current fire size, which is typically derived from hand-held global positioning system (GPS) units or by digitising night-time National Infrared Operations (NIROPS) imagery (Frederick 2012). Forms submitted by the USFS between 2003 and 2012 with an origin located in NR06 were downloaded from the FAMWEB (http://fam.nwcg.gov/fam-web/hist_209/report_list_209, accessed 16 May 2015).

Similar to Finney *et al.* (2009), current fire sizes recorded on ICS-209 forms were used to construct cumulative burned area

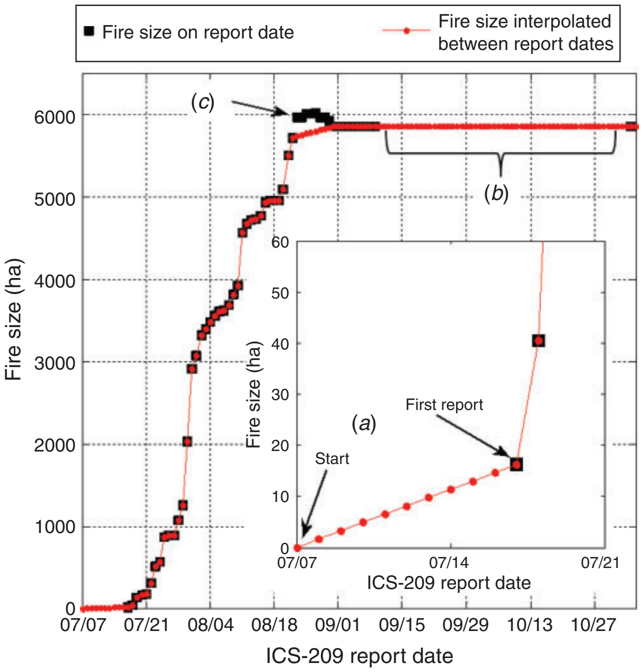

Fig. 2. Cumulative burned area profile for the Slims Complex on the Nez Perce National Forest in 2003 derived from current fire sizes recorded on a time series of Incident Status Summary (ICS-209) reports. Linear interpolations are performed to account for the occasionally missing observations between the ignition date and the first report date (*a*, inset), to account for lapses between individual reports at times of low fire activity or low fire risk (*b*) and to adjust mapping and/or reporting discrepancies, such as anomalous spikes and decreases in burned area (*c*).

profiles for each incident (Fig. 2). However, a preliminary inspection of the raw time series revealed several inconsistencies that required attention.

1. Although the earliest fire size was always assigned to the discovery date, on occasion an ignition date was also recorded. In these situations, the delay between the ignition date and the discovery date likely corresponded to the holdover period between the time a dry lightning storm tracked over the PSA and the time that the first smoke was reported.
2. Because ICS-209 forms were not submitted every day, particularly during periods of low fire activity or low fire risk, there were often lapses (upwards of several weeks) between consecutive report dates.
3. Because of mapping and reporting errors and refinements, there were anomalous spikes and decreases in the cumulative burned area profiles.

Discarding current fire sizes that exceeded the final fire size, or were substantially smaller than reported previously, and linearly interpolating between dates with confident burned area estimates resolved many of the mapping and/or reporting errors. The cumulative burned area profile of each incident was visually inspected for consistency and edited by hand if necessary. Other interpolation techniques and methods for ensuring the quality of the data (including automated routines) may be possible, but as of yet remain unexplored. For each incident, this process yielded an approximate fire size on each day from the discovery date (and sometimes from the ignition date) until the control date (Fig. 2). The current fire size of all reported USFS incidents in NR06 was then summed to generate a seasonal cumulative burned area profile at daily resolution for the entire PSA. The combined daily fire growth in NR06 was then calculated by differencing the aggregate cumulative burned area profile between successive days.

Other than the geographic coordinates of the origin, there is no other spatial information reported on the ICS-209 forms. Therefore, it is possible for the seasonal cumulative burned area profiles to include areas that burned beyond the boundaries of NR06. Conversely, the seasonal cumulative burned area profiles may fail to include area burned by fires that spread into NR06 from an origin located outside the PSA. Furthermore, fire sizes reported on ICS-209 forms generally encompass the entire area within the current fire perimeter and therefore may include unburned interior islands (e.g. Kolden *et al.* 2012). Despite these limitations, the ICS-209 forms are the only source of agency information from which to derive a time series of current fire sizes.

Daily associations

The daily time series of normalised fire danger rating indices and fire occurrence data were merged so that each day contained a record of ERC(G)′, as well as the number and final size of newly discovered fires (Fig. 3*a* and 3*b*). The daily time series of ERC(G)′ was also associated on a day-by-day basis with the number and combined growth of active incidents burning in NR06 (Fig. 3*c*). Although an incident can be considered 'uncontrolled' between the discovery and control dates recorded in the federal wildland fire occurrence database, this definition of 'uncontrolled' includes all ongoing fires regardless of their size or behaviour. To better capture the incidents likely contributing to the majority of daily fire activity, we define an 'active incident' as an incident that has submitted an ICS-209 form, but has yet to achieve 95% of its final area. Other methods for identifying the number of uncontrolled or ongoing incidents are possible and should be considered depending on the reasons for which the NFDRS is being evaluated or applied. The combined daily growth of active incidents simultaneously burning in NR06 was determined from the ICS-209 forms and, as with fire danger, the daily number and daily growth of active incidents were normalised using Eqn 1 to enable comparisons between regions with varying degrees of fire activity.

Analysis

Historical distributions of fire danger are sensitive to the length of the climatological record as well as the seasonal window within which the data are summarised (Heinsch *et al.* 2009). Here we temporally bracket the analysis between 15 June and 31 October. The start of the window coincides with earliest date during the decade that an ICS-209 was submitted and the end of the window coincides with the last day that the Predictive Services program reports fire danger in NR06. Days between 15 June and 31 October when fire danger was not calculated by the Predictive Services program (8% of the working set) were excluded from the analysis.

Despite truncating the analysis before 15 June, the seasonal dataset still includes days (spanning a broad range of fire danger) without an active incident burning in NR06. Consequently, the

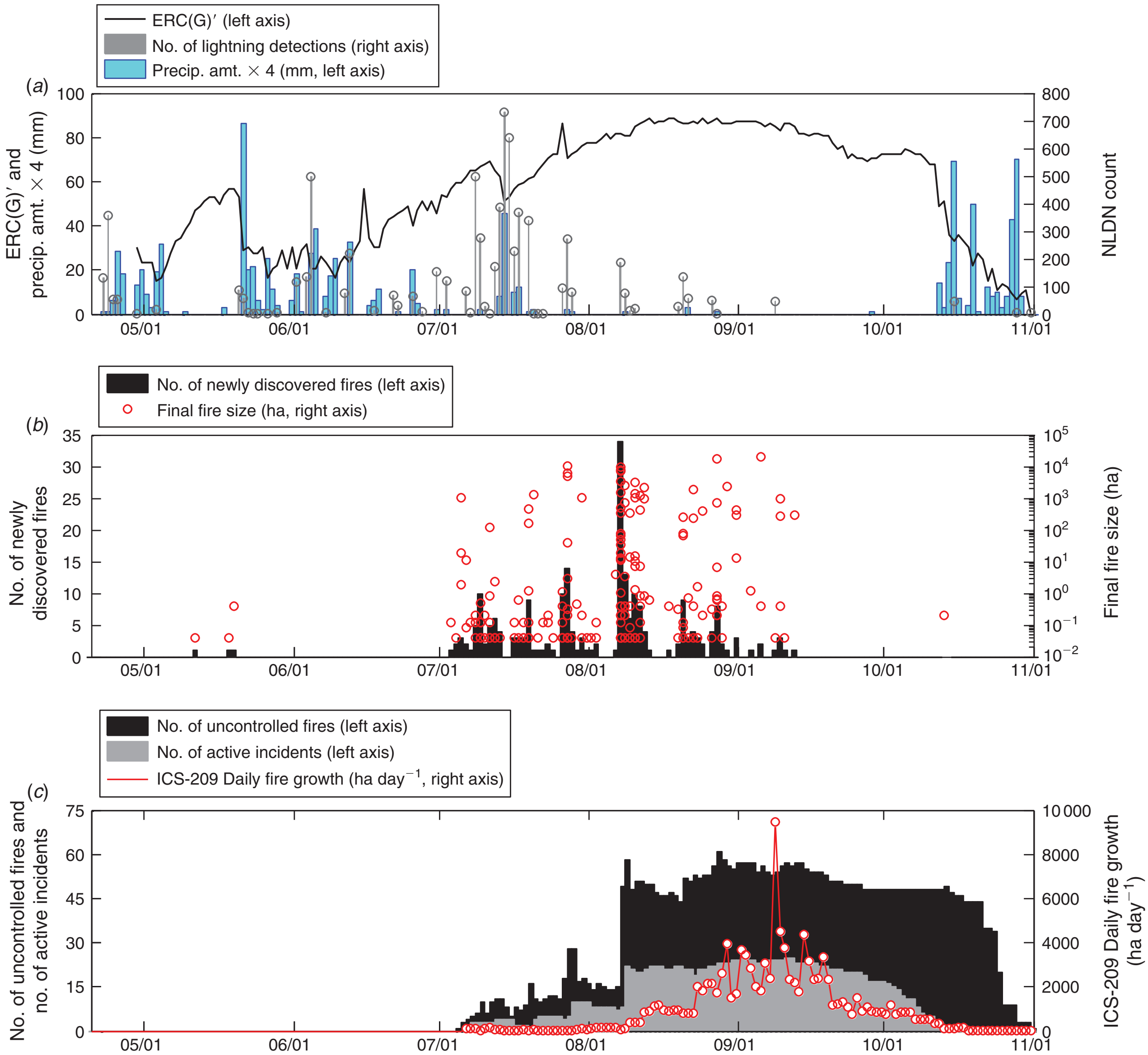

Fig. 3. Seasonal profiles in 2012 illustrating the daily dynamics of fire danger, natural ignition sources, new fire occurrences and ongoing wildland fire activity for a single predictive service area (NR06) located in the northern Rocky Mountains, USA. (*a*) Energy release component (ERC), the daily precipitation amount (scaled by a factor of 4 for presentation) and the number of lightning detections recorded by the National Lightning Detection Network (NLDN). (*b*) Daily number of newly discovered fires and their final size. (*c*) Daily number and combined growth rate of active incidents.

relationships between daily fire danger and daily fire activity are complicated by the commingled presence and absence of active incidents. To disentangle fire days (i.e. a day when at least one active incident is burning in NR06) from non-fire days, the analysis is decomposed into two components. First, the probability of a fire-day, P_f, is calculated as a function of fire danger:

$$P_{f,i} = \frac{N_{f,i}}{N_{t,i}} \quad (2)$$

where i is an interval of fire danger, $N_{f,i}$, is the number of fire days in the interval i with at least one active incident burning in NR06, and $N_{t,i}$ is the total number of days in the interval i. After excluding non-fire days, the second component of the analysis utilises only the fire days to develop relationships between fire danger and the number and daily growth of active incidents burning in NR06.

Results

Decadal summary

There were 1302 days during the decade between 15 June and 31 October when the Predictive Service program reported fire danger in NR06. New fires were discovered on 563 days, and there was at least one active incident burning on 942 days. Hence there are approximately 68% more days during the core fire season when the NFDRS can be used as an indicator of ongoing

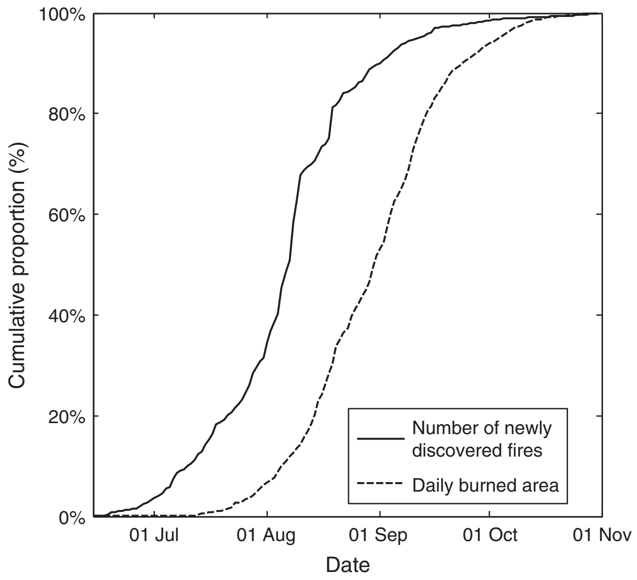

Fig. 4. Cumulative proportion of the number of newly discovered fires (solid line) and daily burned area (dashed line) accumulated in the study area (NR06) over 10 years during the core fire season between 15 June and 31 October. The offset in the cumulative distributions demonstrates that the utility of the National Fire Danger Rating System (NFDRS) can be extended an additional 3 weeks (on average) into the fire season if used to indicate ongoing fire activity rather than just new fire potential.

fire activity rather than just new fire potential. Half of all new fires were discovered on or before 6 August, and most fires (95%) were discovered on or before 10 September. In contrast, half the area was burned by 31 August, and most of the area (95%) was burned by 6 October. Thus, compared with new fire potential, the utility of the NFDRS can be extended (on average) an additional 3 weeks in NR06 if indices are used as indicators of ongoing fire activity (Fig. 4).

The top 369 days with the highest fire growth accounted for 95% of the decadal burned area. Furthermore, 80% of these high fire growth days (accounting for 85% of the decadal burned area) occurred when ERC(G)′ exceeded 70 (Fig. 5). Distributions of the mean ERC(G)′ calculated within the 7- and 21-day windows proposed by Riley *et al.* (2013) and Barbero *et al.* (2014*a*) generally captured the distribution of fire danger recorded when most of the area burned in NR06 (Fig. 5). However, the ability of these temporal windows to successfully represent the fire danger recorded on high fire growth days comes with two caveats. First, to avoid including numerous days with low fire danger, temporal windows were constructed around the discovery dates of large fires (≥400 ha) only (Fig. 5). Second, although the 7- and 21-day windows successfully captured 50% and 63% of high fire growth days respectively, these windows also included 150 and 353 days that were not considered high fire growth days.

Probability plots

Probability plots quantifying the likelihood of managing an active incident in NR06 as a function of fire danger demonstrate that ERC(G) is a suitable indicator of the presence of ongoing fire activity (Fig. 6). The probability of managing at least one

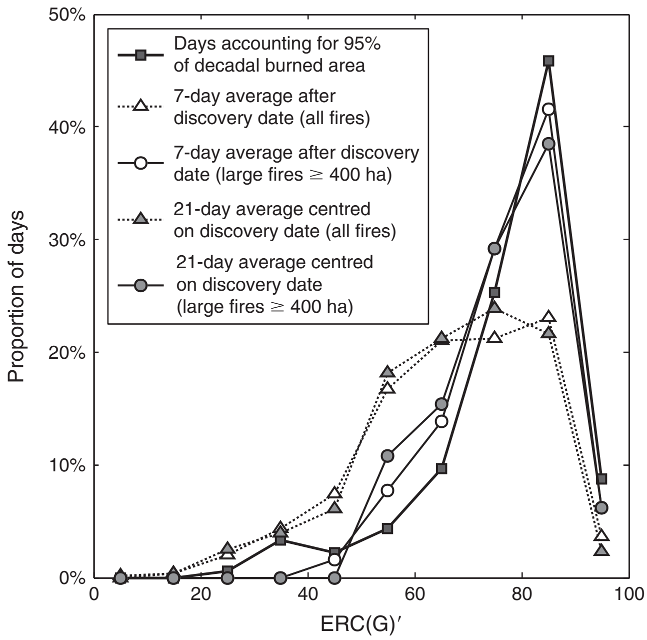

Fig. 5. Distributions of the normalised fire danger (ERC(G)′) in the study area (NR06) derived from a decade (2003–12) of National Fire Danger Rating System (NFDRS) indices and US Fire Service fire reports submitted between 15 June and 31 October. Calculating the average fire danger near the discovery date of large fires (circles) generally captures the distribution of fire danger recorded on the days when most (95%) of the area actually burned in the study area (squares).

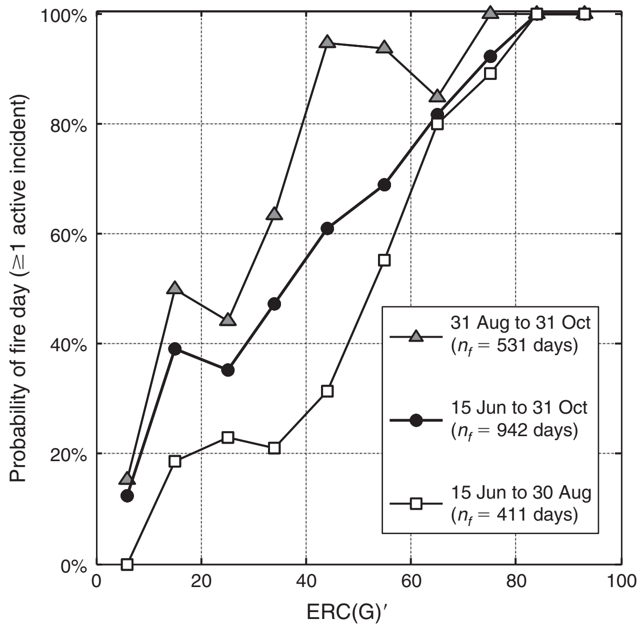

Fig. 6. Probability of a fire day (i.e. a day with at least one active incident burning in the study area) calculated as a function of fire danger according to Eqn 1. Differences in the probability of managing an active incident at the beginning and end of the summer (squares and triangles respectively) demonstrate that the relationship between fire danger and the presence of fire activity is seasonally dynamic.

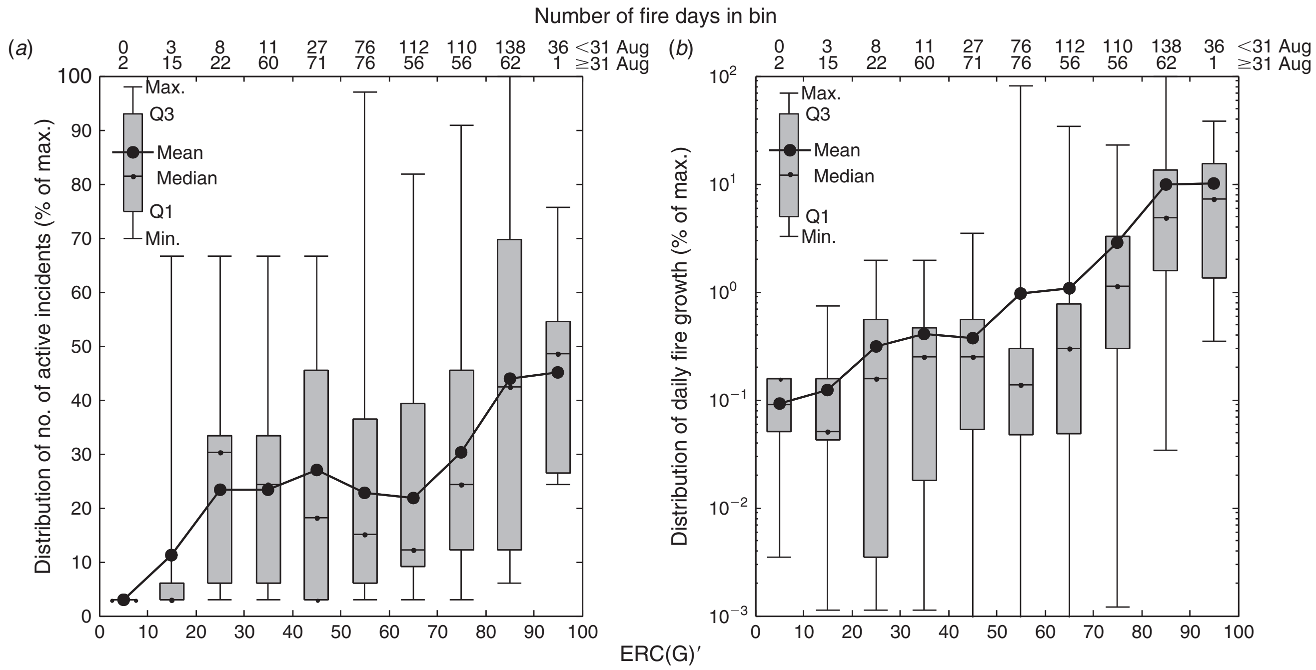

Fig. 7. Direct relationships between daily fire danger and daily fire activity in NR06 generated from a decade (2003–12) of daily National Fire Danger Rating System (NFDRS) indices and US Fire Service (USFS) fire reports submitted between 15 June to 31 October. Relationships were developed using data recorded only on the days when an active incident was burning in the study area (i.e. non-fire days were excluded). (*a*) Distributions of the number of active incidents simultaneously managed by the USFS and (*b*) distributions of their combined daily fire growth. Note the logarithmic scale in (*b*).

active incident is near zero when ERC(G) is low; this probability increases as fire danger increases such that when ERC(G)′ exceeds 80, the USFS is guaranteed to be managing at least one active incident in NR06; and, finally, the overall range of probabilities is sufficient to resolve an incremental change in the likelihood of an managing active incident for a given one unit change in fire danger.

Dividing the core fire season at the halfway point in burned area (31 August) revealed two distinct probability curves (Fig. 6). For example when ERC(G)′ is between 40 and 50, the USFS is threefold more likely to be managing an active incident after 31 August compared with before 31 August. These results indicate that the relationship between fire danger and the presence of active incidents is temporally dynamic, and that as a consequence, identical ERC(G) values should be interpreted differently depending on the time of year.

Direct relationships

Relationships between daily fire danger and daily fire activity were developed using only the data recorded on days with at least one active incident burning in NR06. In general, results indicate that as fire danger increases, there is a corresponding increase in: (1) the average number of active incidents simultaneously managed by the USFS (Fig. 7*a*); and (2) the average combined daily fire growth (Fig. 7*b*). The latter correlation is largely determined by the seasonal synchronicity between the peak in fire danger and the peak in fire activity (Fig. 3). Moreover, an exponential relationship between ERC(G)′ and daily fire growth in NR06 (Fig. 7*b*) suggests that incremental increases ERC(G)′ during periods of higher fire danger are much more consequential than an equivalent increase in ERC(G)′ during periods of lower fire danger.

The wide range of fire activity observed at a particular fire danger level can be attributed, in part, to confidence in the information reported on the ICS-209 forms as well as any data processing artefacts induced by the interpolation procedure. Nevertheless, an expanding window of realised fire activity over much of the range of ERC(G)′ indicates that wildland fires burn differently in NR06 even at the same fire danger. At a coarser temporal resolution not captured in the calculation of ERC(G), lagged drought conditions 3–4 years before the fire season in the Idaho Rockies (e.g. Westerling *et al.* 2003) and recent burn scars (e.g. Teske *et al.* 2012) can affect interannual differences in fuel loads and fuel connectivity, and thus induce interannual variability in daily fire growth rates at the same fire danger. The variability in the realised fire activity at a particular ERC(G)′ is also due, in part, to early and late-seasonal dependencies. Fig. 8*a*, *b* demonstrates that the same ERC(G)′ recorded at the beginning and end of the fire season does not correspond to the same level of fire activity. For example, when $70 \leq ERC(G)' \leq 80$, the USFS can expect to manage an average of approximately 1.6 more active incidents and nearly threefold greater daily fire growth rates after 31 August than before 31 August. Finally, at the finest temporal resolution, daily fire growth rates can vary at the same ERC(G)′ even over the course of a few days. For example, between 24 August and 20 September 2012, ERC(G)′ ranged from 80% to 90% of its decadal maximum, whereas the daily fire growth in NR06 ranged from 16% to 100% of its decadal maximum (Fig. 3). Large fluctuations in daily fire growth during periods of stable fire danger

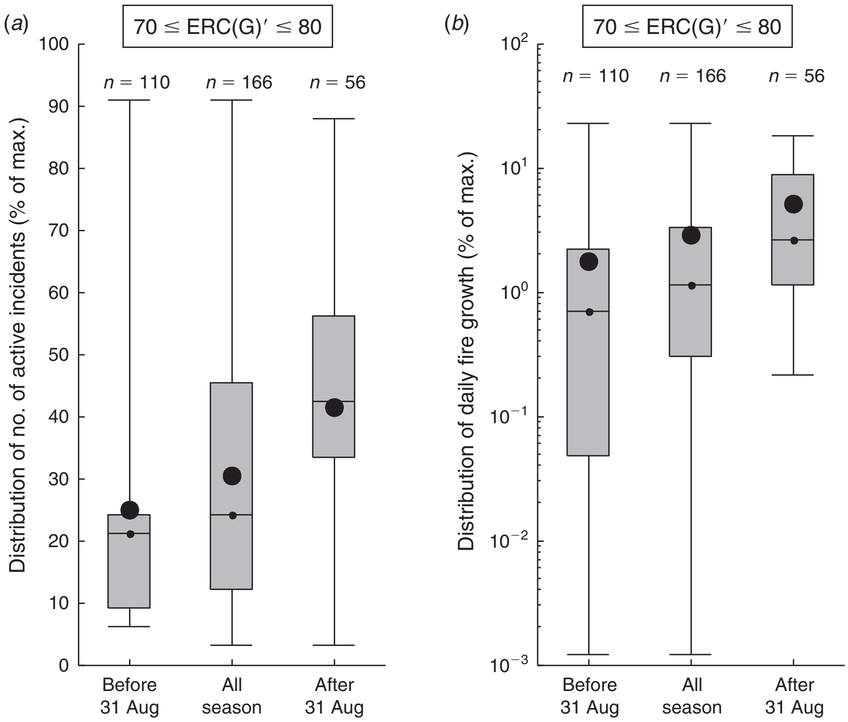

Fig. 8. Early and late seasonal distributions of (*a*) the number of active incidents and (*b*) their combined daily fire growth for a narrow range of normalised fire danger (ERC(G)′). Note the logarithmic scale in (*b*). Relationships were developed using data recorded on days when $70 \leq$ ERC(G)′ < 80 and an active incident was burning in the study area (i.e. non-fire days were excluded). Seasonal differences indicate that the same fire danger corresponds to different fire activity levels depending on the time of year.

likely coincide with short duration, high spread events where the active fire perimeter aligned with winds, fuels and topography conducive to burning.

The positive correlation (Fig. 7*b*) and seasonal dependencies (Figs 8*b*) between daily fire danger and daily fire growth are attributed, in part, to the accumulation of increasingly larger fires on the landscape as the summer progresses. That is, high fire growth days are more likely to occur later in the fire season at higher fire danger due to the greater number of larger fires that have accumulated on the landscape. However, normalising the daily fire growth in NR06 by the number of active incidents reveals an exponential relationship between fire danger and the daily area burned per active incident (Fig. 9*a*). Furthermore, calculating the relative change in daily fire sizes reveals that regardless of size, there is proportionally greater daily fire growth at higher fire danger (Fig. 9*b*). Although Fig. 9 suggests that fire danger may have an effect on daily fire growth that is independent of the number and size of fires in NR06, these results do not preclude the possibility that multiple fires, as well as large and small fires, behave differently under the same weather and fuels conditions. For example, fire-on-fire interactions can influence spread rates and intensities (Finney and McAllister 2011) and, at least in grasslands, there is evidence that longer fire fronts correlate with faster spread rates (Cheney *et al.* 1993; Mell *et al.* 2007).

Discussion

The methods and results presented herein carry both management and scientific implications. First, federal, state, local and tribal fire managers in the US are already familiar with the Predictive Services program and the ICS-209 reporting system. Rather than identifying changes in the conditions that affect the ignition and spread of new fires near their origin, the methods proposed herein can be conveniently used by fire managers to identify the changes in weather and fuel conditions that affect wildland fire activity beyond the discovery date. Because Figs 6 and 8 demonstrate early and late seasonal dependencies between fire danger and persistent fire activity, we suggest that fire managers reinterpret the relationships between NFDRS indices and fire activity as the summer progresses and as the fire situation evolves. Although using fire danger as an indicator of persistent fire activity extends the utility of the NFDRS later into the fire season, at some time during the fire season the management response to ongoing wildland fire activity becomes reactive rather than proactive. Hence, at times during the fire season when fire activity saturates suppression resources, the use of the NFDRS in any planning capacity may be limited.

In addition to the management implications, associations between daily fire danger and daily fire activity offer an additional fine-scale temporal dimension to the cross-scale

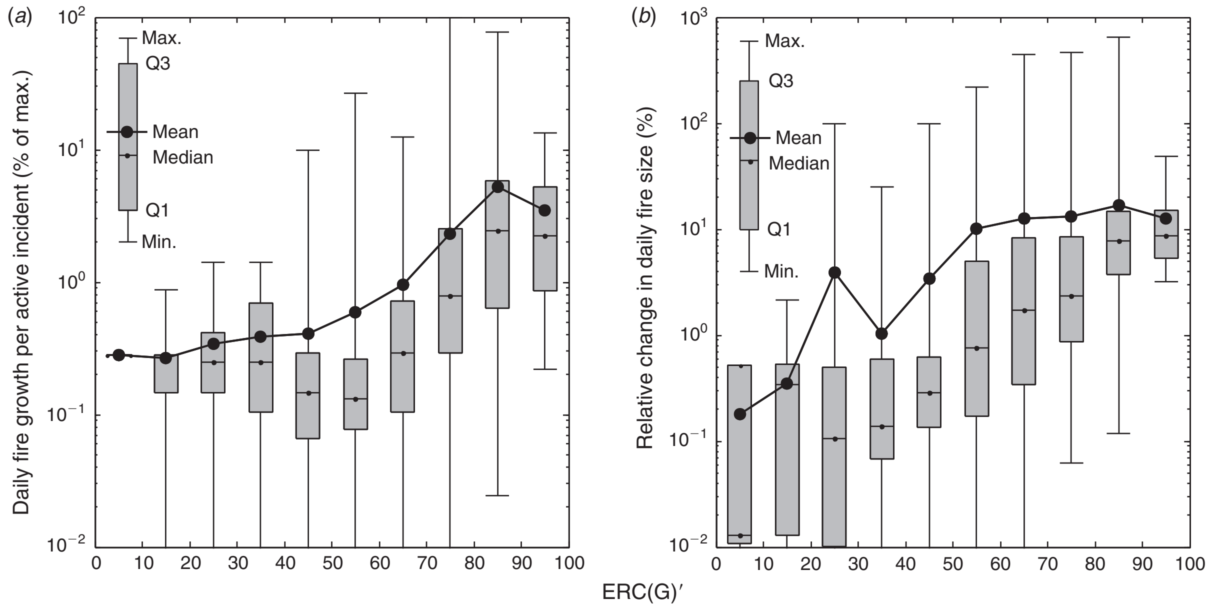

Fig. 9. Relationships between the daily fire growth per incident (*a*) and the relative change in daily fire sizes (*b*) as a function of normalised fire danger (ERC(G)′). Note the logarithmic scales. Both plots are generated from a decade (2003–12) of daily National Fire Danger Rating System (NFDRS) indices and US Fire Service fire reports submitted between 15 June to 31 October in the study area NR06. Results indicate that increasing fire danger has an effect on the combined daily fire growth in NR06 that is independent of the number or size of active incidents burning across the landscape.

analysis of fire–climate relationships (e.g. Slocum *et al.* 2010; Barbero *et al.* 2014*a*). As demonstrated here, daily associations can be used to justify the selection of the temporal window within which fire danger is averaged and related to total burned area. Although two of the most recently proposed window sizes (Riley *et al.* 2013; Barbero *et al.* 2014*a*) capture distributions of fire danger similar to that recorded on large fire growth days, this may be due, in part, to a seasonal plateau in ERC(G) that spans both the ignition and propagation of large fires (Fig. 3). As such, care should be taken when interpreting the average fire danger calculated within windows that capture a significant proportion of days without fire activity or large fluctuations in fire danger.

Although the exponential relationship in Fig. 7*b* suggests that wildland fires in NR06 respond differently to equivalent changes in ERC(G)′ at different ends of the fire danger spectrum, it cannot be concluded, as of yet, what proportion of this response is due to a non-linear effect of fire weather on fire activity (and extreme fire behaviour) as ERC(G)′ increases or changes in the extent and geometry of actively burning fires as ERC(G)′ increases. Nevertheless, the exponential relationship between daily fire danger and daily fire growth suggests that, at least in NR06, higher fire danger should receive greater weight than lower fire danger when averaging over longer durations or larger areas. This can be accomplished in a manner similar to the Canadian Forest Fire Weather Index (FWI) system, which converts the daily FWI to a Daily Severity Rating (DSR) through a power law relationship before averaging over weekly to seasonal time frames (Van Wagner 1987). Alternatively, rather than transforming fire danger rating indices, many studies have instead calculated the logarithm of annual burned area (e.g. Westerling *et al.* 2002, 2003; Roads *et al.* 2005; Abatzoglou and Kolden 2013) in order to normalise fire size distributions that otherwise exhibit power law behaviour (Malamud *et al.* 2005). In addition to normalising the fire size distributions, the results herein indicate that taking the logarithm of total burned area in NR06 also conveniently accounts for the underlying exponential relationship between daily fire danger and daily fire growth.

An increase in fire danger in NR06 is generally accompanied by an expanding window of realised fire activity. If possible, further studies should determine to what degree low-frequency climate signals, high-frequency weather events or current fire sizes and geometry are responsible for the large variability in daily fire growth rates that occur at the same fire danger. From a predictive standpoint, an increasing mean-variance relationship supports the conclusions of Littell *et al.* (2009) in so far as increases in the annual area burned in NR06 (due to increasing fire danger) will be accompanied by an increase in the interannual variability.

Recent studies have demonstrated that fire–climate relationships are ecosystem dependent (Westerling *et al.* 2003; Littell *et al.* 2009). Because the seasonality of fire weather and fire activity are not universally synchronous (Le Page *et al.* 2010), we too expect the functional form and the strength of the relationships between daily fire danger and daily fire growth to exhibit regional differences. To perform geographical comparisons, the methods developed herein can be reproduced in any other PSA, or any other smaller or larger land management or ecological unit, provided there is a history of daily weather and fire information. However, because of the quality and spatial limitations of the information reported on the ICS-209 forms, we recommend assessing the usefulness of satellite-based burned area products (e.g. Giglio *et al.* 2009) or active fire products (e.g. Giglio *et al.* 2003) for comparing and contrasting daily fire activity patterns between administrative areas or ecoregions.

Conclusion

This work presents the first ever relationships between daily NFDRS indices and persistent wildland fire activity characterised by the daily number and daily growth of active incidents burning in the Northern Rockies, USA. Results indicate that the utility of the NFDRS can be extended (on average) an additional 3 weeks in the study area if indices are used as indicators of ongoing fire activity rather than new fire potential. Moreover, as fire danger increases there is a seasonally dependent increase in the probability of managing an active incident, as well as an increase in the average in and variability of the daily number and daily growth of active incidents. The methods developed herein can be expanded to any administrative or ecological unit with an archive of daily weather and fire information. Constructing daily relationships at regional scales has clear management and scientific implications. By maintaining dynamic day-to-day evaluations of fire danger for all existing wildfires within a region, much better decision-making capacity is afforded to fire managers for allocating scarce resources as fire weather conditions change during the season. Moreover, associating NFDRS indices and fire activity on a day-by-day basis permits the seasonal evolution of fire danger to be linked directly to the accumulation of burned area on the landscape, thereby offering an additional fine-scale temporal dimension to the cross-scale analysis of regionally dependent fire–climate relationships.

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