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Wildland fire limits subsequent fire occurrence

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Abstract. Several aspects of wildland fire are moderated by site- and landscape-level vegetation changes caused by previous fire, thereby creating a dynamic where one fire exerts a regulatory control on subsequent fire. For example, wildland fire has been shown to regulate the size and severity of subsequent fire. However, wildland fire has the potential to influence other properties of subsequent fire. One of those properties – the extent to which a previous wildland fire inhibits new fires from igniting and spreading within its perimeter – is the focus of our study. In four large wilderness study areas in the western United States (US), we evaluated whether or not wildland fire regulated the ignition and spread (hereafter occurrence) of subsequent fire. Results clearly indicate that wildland fire indeed regulates subsequent occurrence of fires ≥ 20 ha in all study areas. We also evaluated the longevity of the regulating effect and found that wildland fire limits subsequent fire occurrence for nine years in the warm/dry study area in the south-western US and over 20 years in the cooler/wetter study areas in the northern Rocky Mountains. Our findings expand upon our understanding of the regulating capacity of wildland fire and the importance of wildland fire in creating and maintaining resilience to future fire events.

Additional keywords: age-dependence, failure time analysis, fire as a fuel treatment, fire history, hazard analysis, ignition, self-limiting, self-regulation, survival analysis, wilderness.

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Introduction

Ecological theory and recent empirical evidence suggest that landscapes with active fire regimes can 'self-regulate' (Agee 1999; Peterson 2002). Self-regulation theory suggests that several aspects of wildland fire are moderated by site- and landscape-level vegetation changes caused by previous fire, thereby creating a dynamic where one fire exerts a negative feedback regulatory control on subsequent fire (McKenzie *et al.* 2011). For example, wildland fire acts as a barrier to subsequent fire spread and therefore regulates fire size (Collins *et al.* 2009; Parks *et al.* 2015). Wildland fire also regulates fire activity and area burned (Héon *et al.* 2014; Parisien *et al.* 2014). Finally, when wildland fire does reburn within the perimeter of a previous fire, it regulates subsequent fire severity (Miller *et al.* 2012; Parks *et al.* 2014*a*). The strength of these regulatory feedbacks tends to decay over time as fuel re-accumulates (Collins *et al.* 2009; Parks *et al.* 2015). Positive feedbacks, however, are also possible and have the potential to transition ecosystems to alternative stable states (e.g. forest to shrub), thereby increasing subsequent fire severity and likelihood of burning (Cochrane *et al.* 1999; Larson *et al.* 2013).

Wildland fire occurrence requires that three environmental factors coincide in space and time: an ignition source, fuels, and fire-conducive weather (Parisien and Moritz 2009; Chang *et al.* 2013). Ignitions may be natural or human-caused, vary temporally and spatially (Bartlein *et al.* 2008; Syphard *et al.* 2009; Parks *et al.* 2012), and directly influence fire activity and area burned (Peterson *et al.* 2010; Faivre *et al.* 2014). Fuels are comprised of ground, surface, or canopy biomass (either live or dead) (Pierce *et al.* 2012; Keane and Gray 2013), although the spatial continuity of fuels and the rate at which biomass accumulates are particularly relevant for understanding and managing fire regimes (Chou *et al.* 1993; Meyn *et al.* 2007; Krawchuk and Moritz 2011). Lastly, weather conditions conducive to fire ignition and spread are necessary over relatively short time periods (i.e. daily to seasonally) and have been well studied in certain regions (Abatzoglou and Kolden 2011; Sedano and Randerson 2014; Wang *et al.* 2014). Wildland fire affects one of these factors (fuels); it consumes biomass and reduces fuel load and continuity (e.g. McCaw *et al.* 2012), and as a result, has the potential to lessen the likelihood of subsequent fire occurrence – at least until vegetation and fuel structure recover and biomass re-accumulates on the site.

The potential influence of previous wildland fire on subsequent fire occurrence (i.e. ignition and spread) is an understudied aspect of self-regulation yet to be quantified. Although some simulation studies have partly addressed this issue (e.g. Davis *et al.* 2010) and other fire studies implicitly incorporated

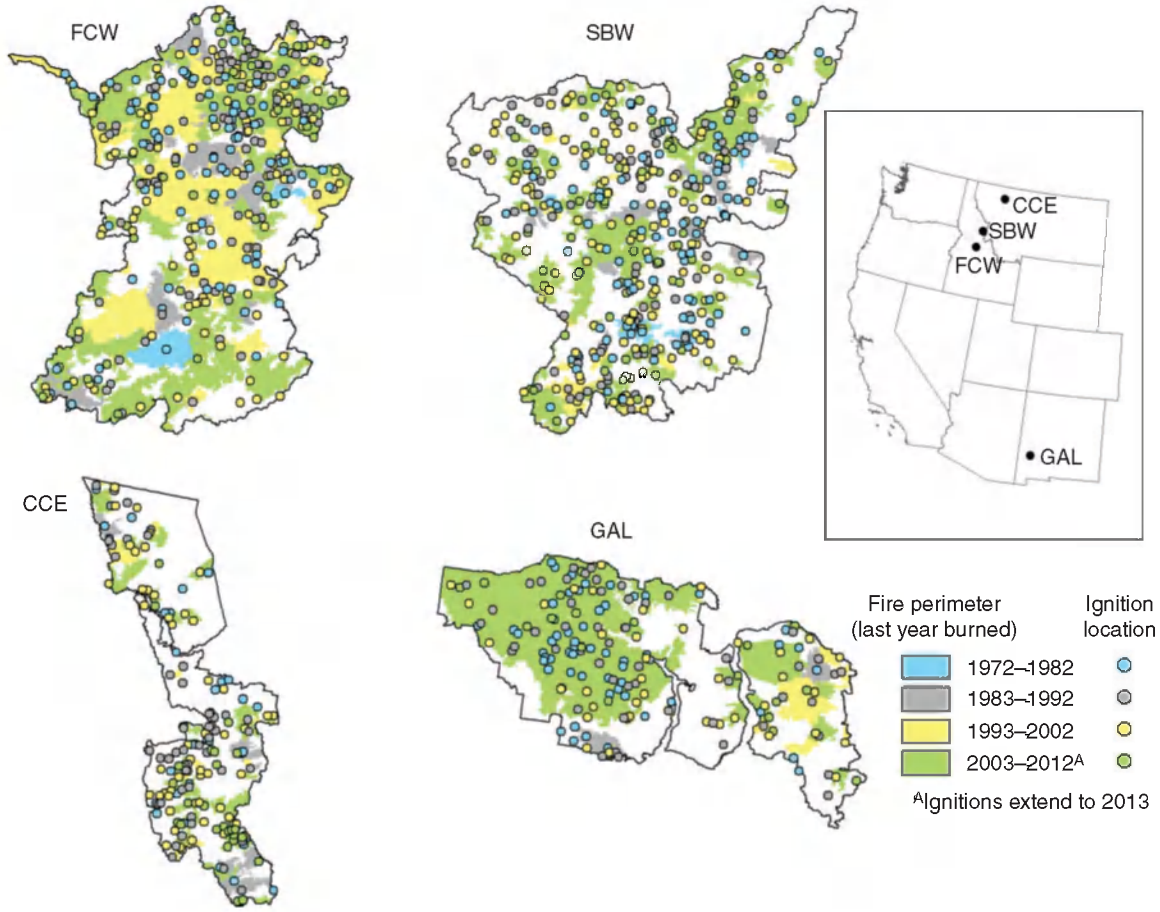

Fig. 1. The four study areas for which we evaluated the effect of wildland fire on the occurrence of subsequent fire. Solid colours represent fire perimeters; points represent ignition locations. Inset shows locations of study areas in the western US. FCW: Frank Church – River of no Return Wilderness; SBW: Selway-Bitterroot Wilderness; CCE: Crown of the Continent Ecosystem; GAL: Gila and Aldo Leopold Wilderness areas.

these feedbacks (e.g. Moritz 2003; Krawchuk *et al.* 2006; Héon *et al.* 2014; Price *et al.* 2015), there are relatively few examples of studies that have explicitly evaluated the influence of previously burned areas on subsequent wildland fire occurrence (Penman *et al.* 2013). An evaluation of fire occurrence in relation to previous wildland fire perimeters would allow for a more complete understanding of the self-regulation property, as well as providing useful insights as US federal agencies strive to restore wildland fire as a natural disturbance process. Specific quantitative information on this feedback may assist land managers in evaluating short- and long-term benefits and costs when deciding how to best manage the complexities of any particular wildland fire event.

We evaluated how wildland fire affects subsequent fire occurrence in four large study areas in the western US. This study was designed and conducted to: (1) determine whether or not wildland fire regulates subsequent fire occurrence. That is, we explicitly evaluate whether or not fires are less likely to ignite within the perimeters of previous burns. (2) If a regulating effect is detected, quantify the longevity of the effect; that is, quantify the number of years wildland fire reduces subsequent fire occurrence. (3) If a regulating effect is detected, quantify the strength of this effect as time since fire increases. In this study, a fire occurrence is defined as an ignition that results in a fire ≥20 ha. We expected that wildland fire indeed limits subsequent fire occurrence. We also expected that the longevity of the effect would vary by study area due to differences in fire regime and other ecosystem characteristics (e.g. productivity). Finally, we expected that the strength of this negative feedback would be strong immediately (for the first few years) after the initial fire but would decrease with time as biomass re-accumulated.

Methods

Study areas

We conducted our investigation within four study areas composed entirely of federally protected lands (wilderness and national park) in the western United States (Fig. 1), thereby limiting potential confounding effects of land management activities that are more common outside such areas (Parks *et al.* 2014*b*). All four study areas have experienced substantial fire activity in recent decades, thus providing sufficient data to evaluate the influence of previous wildland fire on the occurrence of subsequent fire.

FCW (Frank Church – River of No Return Wilderness)

The FCW (9777 km^2) is located in central Idaho and is the second largest wilderness area in the contiguous US. Elevations range from 600 m to 3136 m and topographic features include river breaks, deep canyons, mountains, and glaciated basins (USDA Forest Service 2003). The fire season runs from early-July to mid-September (USDA Forest Service 2013). Vegetation is dominated by mixed-conifer (≃40%) and subalpine forest types (≃30%) (Rollins 2009). FCW has a mainly mixed severity fire regime where low elevation, open ponderosa pine forests typically experience frequent, low intensity fires, and, generally, fire frequency decreases and severity increases with increasing elevation, moisture, and tree density (Crane and Fischer 1986).

SBW (Selway-Bitterroot Wilderness)

The SBW (5471 km^2) is the third-largest wilderness area in the contiguous US and is located in western Montana and north-central Idaho. Elevations range from 531 m to over 3000 m. Subalpine forest types comprise the large portion of the study area (≃50%), followed by Douglas fir and mixed-conifer forests (≃30%) (Rollins 2009). The fire season runs from late-June through mid-September (Brown *et al.* 1994). The fire regime is categorised as mixed: lower severity surface fires are common in the lower elevations and patchy, stand replacing fires become more common as elevation increases, although during extremely dry years, stand replacing fires can occur throughout the study area (Brown *et al.* 1994).

CCE (Crown of the Continent Ecosystem)

The CCE is the largest study area (10 331 km^2) and comprises Glacier National Park and the Great Bear, Bob Marshall, and Scapegoat wilderness areas in Montana. Elevations range from 950 m to over 3100 m. In this rugged study area, alpine glacial canyons and cirques drain into major river valleys (Barrett *et al.* 1991; Keane *et al.* 1994). Areas of ponderosa pine and mixed-conifer forest compose a relatively small proportion of CCE (≃15%) (Rollins 2009) and were historically maintained by low and mixed severity regimes (Arno *et al.* 2000). Most of the study area (>60%), however, is comprised of subalpine forest types and characterised by a mixed to high severity fire regime. The fire season runs from mid-July through September (USDA Forest Service 2013).

GAL (Gila and Aldo Leopold Wilderness)

The GAL (3087 km^2) comprises the Gila and Aldo Leopold Wilderness Areas in western New Mexico. Elevations range from 1462 m to 3314 m and topographic features include mountains, broad valleys, steep canyons and extensive mesas. Vegetation in GAL is composed largely of ponderosa pine forest (≃30%), juniper-pinyon pine woodland (≃40%), and mixed-conifer forest types (≃20%) (Rollins 2009). The fire season runs early-May through mid-July (USDA Forest Service 2013), although fires are less likely after mid-June due to rains associated with monsoonal storms from the Gulf of Mexico (Rollins *et al.* 2002). Fires in GAL are generally frequent and low severity surface fires, but fire severity tends to increase with elevation (Swetnam and Dieterich 1985) and varies with aspect, incident radiation and topographic position (Holden *et al.* 2009).

Fire data

For each study area, we obtained a fire history atlas from Parks *et al.* (2015), which depicts the perimeters of all wildland fires ≥20 ha that occurred between 1972 and 2012 (Fig. 1). Briefly, this fire history atlas contains perimeters of large fires (≥400 ha) from 1984-2011 as mapped by the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink *et al.* 2007). This was augmented by identifying and mapping all fires ≥20 ha that occurred from 1972-2012 using pre- and post-fire Landsat imagery and metrics of fire-induced change (Key and Benson 2006; Miller and Thode 2007). We also identified the spatial location of all wildland fire ignitions that resulted in a fire ≥20 ha from 1972-2013 for each study area (Fig. 1). Because data availability and quality vary over the 1972-2013 time period, we developed a rule-set to identify the location of each ignition (described in Table 1). From 1972-2013, there were a total of 330 ignitions in FCW, 380 in SBW, 160 in CCE, and 168 in GAL.

Statistical analysis

Failure time analysis (also called survival analysis) is useful for analysing data in the form of 'time until an event occurs.' In the industrial sciences, it is commonly used to analyse the time until the failure of an industrial product. In the biomedical context where the event of interest is commonly the death of a patient, survival analysis is often used to compare a drug treatment to a placebo (cf. Thatcher *et al.* 2005). Failure time analysis has also been used in wildland fire studies to evaluate, for example, fire frequency (e.g. Moritz *et al.* 2004; Moritz *et al.* 2009; Senici *et al.* 2010). In our study, we used it to evaluate the time between an initial wildland fire and a subsequent ignition that resulted in a fire ≥20 ha. This subsequent ignition is analogous to the 'death' or 'failure' in the context of traditional failure time analysis.

For each wildland fire that ignited within the perimeter of a previous fire that occurred since 1972, we recorded the elapsed time, t (number of years), between the previous fire and the subsequent ignition. We then developed a failure function, denoted as $F(t)$, for each study area, which depicts the probability that a wildland fire will ignite and spread within the perimeter of a previous fire within the time interval 0 to time t. The majority of ignitions in our dataset do not fall within the perimeter of a documented previous fire; the 'time to event' for these observations is unknowable because our fire history before 1972 is unknown. In failure time analysis, such observations are considered 'right-censored' (Lindsey and Ryan 1998). We generated all failure functions using the R statistical program (R Development Core Team 2007) with the 'survPresmooth' package (López-de-Ullibarri and Jacome 2013); this is a pre-smoothed version of the Kaplan-Meier estimator (Jácome and Cao 2007) that provides increased accuracy when data are heavily censored. Confidence intervals for each failure function were generated by producing failure functions for 1000 bootstrap replicates (i.e. resampling with replacement).

To determine whether wildland fire limits subsequent fire occurrence (objective 1) we compared our observed failure function (i.e. the treatment) to a null failure function that represents the chance expectation (i.e. the control) for each

Table 1. Systematic rule-set used to identify ignition locations

Fire size	Years	Rule
<400 ha	1972–2013	Ignition was placed in approximately the centre[A] of the fire perimeter.
≥400 ha	1972–1991	Ignition was placed in approximately the centre[A] of the fire perimeter.
≥400 ha	1992–2001	Ignition(s) from Short (2014) were used. However, if: • an ignition was <250 m from the fire perimeter boundary, yet fell within the fire perimeter boundary, the ignition was moved towards the interior of the perimeter to a distance of 250 m. • no ignition from this source fell within the fire perimeter, yet there was an ignition obviously meant to represent the fire perimeter (spatial misplacement), then the ignition was moved towards the interior of the perimeter to a distance of 250 m. • no ignition from this source was identifiable for any given fire perimeter, the ignition was placed in approximately the centre of the fire perimeter.
≥400 ha	2002–2013	Ignition was placed in the centre of the first day of burning of fire progression maps. Fire progression maps were created using MODIS fire detection data using the methods described in Parks (2014). In some cases (e.g. large fire complexes), more than one ignition could be detected and additional ignitions were placed as appropriate.

[A]This assumption likely has negligible influence on our findings given that time intervals would usually be the same even if a different strategy was used to place ignition locations.

Note that: a) Perimeters 1972–2012 were obtained from Parks *et al.* (2015) and perimeters from 2013 fires were obtained from the Geospatial multi-agency coordinating group (Geospatial multi-agency coordinating group [GeoMAC] 2013); b) all ignitions were placed without consulting with the fire perimeters from previous years; and c) ignitions that fell in water, barren or swamp (Rollins 2009) were shifted to the nearest non-water/barren/swamp pixel.

study area. The null model was generated using randomly placed ignitions in a stratified random sampling design to ensure that random ignitions were representative of both the year and vegetation types (Rollins 2009) in which the observed ignitions occurred. The stratification by vegetation type ensures that random ignitions were not placed in non-flammable areas (e.g. barren and open water). This process was repeated 1000 times, thereby generating 1000 random samples. As with the observed ignitions, random ignitions that did not fall within a fire perimeter from previous years were right-censored with an unknown time interval between fires. The results of the 1000 random samples were combined into one dataset for which we produced the null failure function. Confidence intervals were generated by producing failure functions for each of the 1000 random samples. We plotted the observed and random failure functions and examined overlap between 90% confidence intervals; non-overlapping confidence intervals are interpreted as an indication that wildland fire indeed limits the occurrence of subsequent fire.

To quantify how long (i.e. how many years after fire) wildland fire limits the occurrence of subsequent fire for each study area (objective 2), we compared the observed and random hazard functions. The hazard function, also referred to as the hazard rate and denoted as $h(t)$, depicts the rate at which wildland fire ignites and spreads within the perimeter of a previous fire at time interval t given the condition that the fire has not yet occurred before time t. The conditional nature of the hazard rate acknowledges that the number of 'available' fire occurrences decreases over time. For example, at $t = 1$, there may be 300 ignitions available to ignite within a previous fire perimeter but at $t = 10$ there are fewer available since some fires ignited within a previous fire perimeter between $t = 1$ and $t = 9$. For each time since fire interval t in which the observed hazard rate is less than the random hazard rate, the interpretation is that wildland fire limits subsequent fire occurrence. Hazard functions were calculated using the kernel hazard function estimator of Tanner and Wong (1983) as implemented in the 'survPresmooth' package (López-de-Ullibarri and Jacome 2013) within R; the smoothing parameter (which controls the degree of kernel smoothing) was set to seven, which we deemed an appropriate compromise between overly rough and spurious estimates and smoothing away important features (López-de-Ullibarri and Jacome 2013). Confidence intervals (90%) were generated using previously described methods.

We then quantified the strength of wildland fire's regulating effect on subsequent fire occurrence as time intervals increased (objective 3). We quantified strength of the effect in terms of the ratio between the observed and random hazard functions, which is termed the hazard ratio. Hazard ratios less than one indicate that ignitions are less likely to occur within a previous fire perimeter than expected by chance, whereas values greater than one indicate that ignitions are more likely to occur within a previous fire than expected by chance. As such, the ratio describes the strength of the self-regulating effect of wildland fire on subsequent ignitions. To evaluate how the strength of this effect varies with time since fire (we hypothesised it would decay), we first needed to formally (i.e. statistically) test whether or not it changed as time since fire increased by testing whether or not the observed hazard function was proportional to the random hazard function. If the hazards are proportional, then the hazard ratio is invariant (i.e. constant) through time and would be an indication that the regulating effect does not change over time. If the hazards are not proportional, however, the regulating effect changes over time. This test was conducted with the coxph and cox.zph functions using the 'survival' package (Therneau 2014) in R on 1000 replicates (using the 1000 bootstrapped replicates of the observed data and the 1000 random samples of the random ignitions). We assessed statistical significance of the 1000 independent tests of proportional hazard using Fisher's method of interpreting p-values from several independent tests (Fisher 1934). We determined that the observed and random hazard functions are not proportional (Fisher's method p-value <0.001 for all study areas), and thus, the strength of the self-regulating effect changes over time.

Table 2. Percent of observed and random ignitions located within the perimeter of previous fire for each year post-fire
Data for intervals longer than 25 years are not shown for FCW, SBW and CCE due to sparse data. Intervals longer than 15 years are not shown for GAL. *n* represents the number of observed uncensored ignitions. Note that a high proportion of observed ignitions did not fall within a documented fire perimeter and were therefore right-censored – see Methods. In 'Random' columns, percentages are of 1000 random samples

Years post-fire	FCW			SBW			CCE			GAL		
	n	Observed (%)	Random (%)	*n*	Observed (%)	Random (%)	*n*	Observed (%)	Random (%)	*n*	Observed (%)	Random (%)
1	0	0	2.66	0	0	1.15	0	0	0.37	0	0	2.27
2	1	0.30	2.16	1	0.26	1.27	0	0	0.90	1	0.60	2.41
3	2	0.61	2.51	0	0	1.00	0	0	0.87	0	0	2.02
4	2	0.61	2.08	0	0	0.92	0	0	1.27	4	2.38	2.52
5	1	0.30	2.87	1	0.26	1.27	0	0	0.78	1	0.60	2.34
6	5	1.52	3.32	2	0.53	1.08	0	0	0.99	2	1.19	2.43
7	4	1.22	2.22	2	0.53	0.97	1	0.62	0.32	4	2.38	2.13
8	3	0.91	1.56	2	0.53	0.63	0	0	0.88	5	2.98	2.48
9	2	0.61	1.05	1	0.26	0.77	0	0	0.82	2	1.19	1.34
10	1	0.30	1.57	0	0	0.45	0	0	0.84	1	0.60	1.05
11	6	1.82	1.70	1	0.26	0.48	0	0	0.49	1	0.60	0.59
12	8	2.43	1.83	3	0.79	0.62	0	0	0.61	2	1.19	0.42
13	4	1.22	1.29	3	0.79	0.67	3	1.88	0.62	3	1.79	0.54
14	0	0	0.55	1	0.26	0.39	0	0	0.08	2	1.19	0.66
15	3	0.91	0.87	0	0	0.73	0	0	1.17	1	0.60	0.44
16	0	0	0.52	1	0.26	0.33	0	0	0.03	–	–	–
17	5	1.52	0.96	0	0	0.56	0	0	0.20	–	–	–
18	1	0.30	0.76	5	1.32	0.54	0	0	0.64	–	–	–
19	3	0.91	0.81	2	0.53	0.59	0	0	0.40	–	–	–
20	1	0.30	0.56	2	0.53	0.35	0	0	0.07	–	–	–
21	0	0	0.39	1	0.26	0.36	0	0	0.04	–	–	–
22	0	0	0.25	1	0.26	0.32	0	0	0.04	–	–	–
23	2	0.61	0.25	0	0	0.19	1	0.62	0.40	–	–	–
24	0	0	0.40	1	0.26	0.44	0	0	0.41	–	–	–
25	1	0.30	0.29	2	0.53	0.23	1	0.62	0.17	–	–	–

Consequently, we plotted the hazard ratio for each time interval *t* by dividing the observed hazard function at time interval *t* by the random hazard function at time interval *t*. The hazard ratio measures the relative effect of wildland fire in limiting subsequent fire occurrence for each time interval *t*. For example, a hazard ratio of 0.5 at time interval *t* indicates fires are half as likely to ignite within the perimeter of a fire *t* years post-fire compared with the null model; a hazard ratio of 1.0 at time interval *t* indicates that fires are just as likely to ignite within the perimeter of a fire *t* years post-fire compared with the null model.

Results

The occurrence of observed ignitions within the perimeters of previous fires is clearly different than that of random ignitions, evidenced by their frequency (Table 2) and distinctively different failure functions (Fig. 2). The failure functions show that the probability of a fire occurring within the perimeter of a previous fire is lower for observed, compared with random, ignitions in all four study areas. Moreover, this holds true at the 90 percent confidence interval for at least a portion of the time since fire axis (Fig. 2), indicating that observed ignitions fall within previous fire perimeters far less often than would be expected by chance in all four study areas.

A comparison of the observed and null hazard functions reveals that the observed hazard is less than the random hazard for all time since fire intervals in FCW, indicating that wildland fire limits subsequent ignitions for at least 25 years (Fig. 2). In SBW and CCE, the observed hazard is less than the random hazard for 21 and 24 years after fire, respectively. In GAL, the observed hazard is less than the random hazard for the first 9 years (Fig. 2). The confidence intervals for the observed and random hazard functions substantially overlap when the time since fire is greater than 10 years in FCW, SBW, and CCE and 5 years in GAL, indicating a moderate degree of uncertainty in these estimates.

The hazard ratio, which depicts the relative rate (i.e. to that expected by chance) of a fire igniting within the perimeter of previous fire for each time interval *t*, was generally less than one and more-or-less increased through time for all study areas except FCW (Fig. 2) where it increased immediately after fire, peaked at 14 years, then decreased again. In the other three study areas, the increasing ratio indicates that the regulating effect was strongest immediately after fire and decreased with fire age, matching our expectations.

Discussion

Wildland fire consumes fuel and alters landscape pattern, thereby triggering a negative feedback that regulates subsequent fire behaviour and effects (Agee 1993; Peterson 2002; McKenzie *et al.* 2011). As such, our study adds to and complements the growing body of literature concerning fuel-mediated negative feedbacks (e.g. Collins *et al.* 2009;

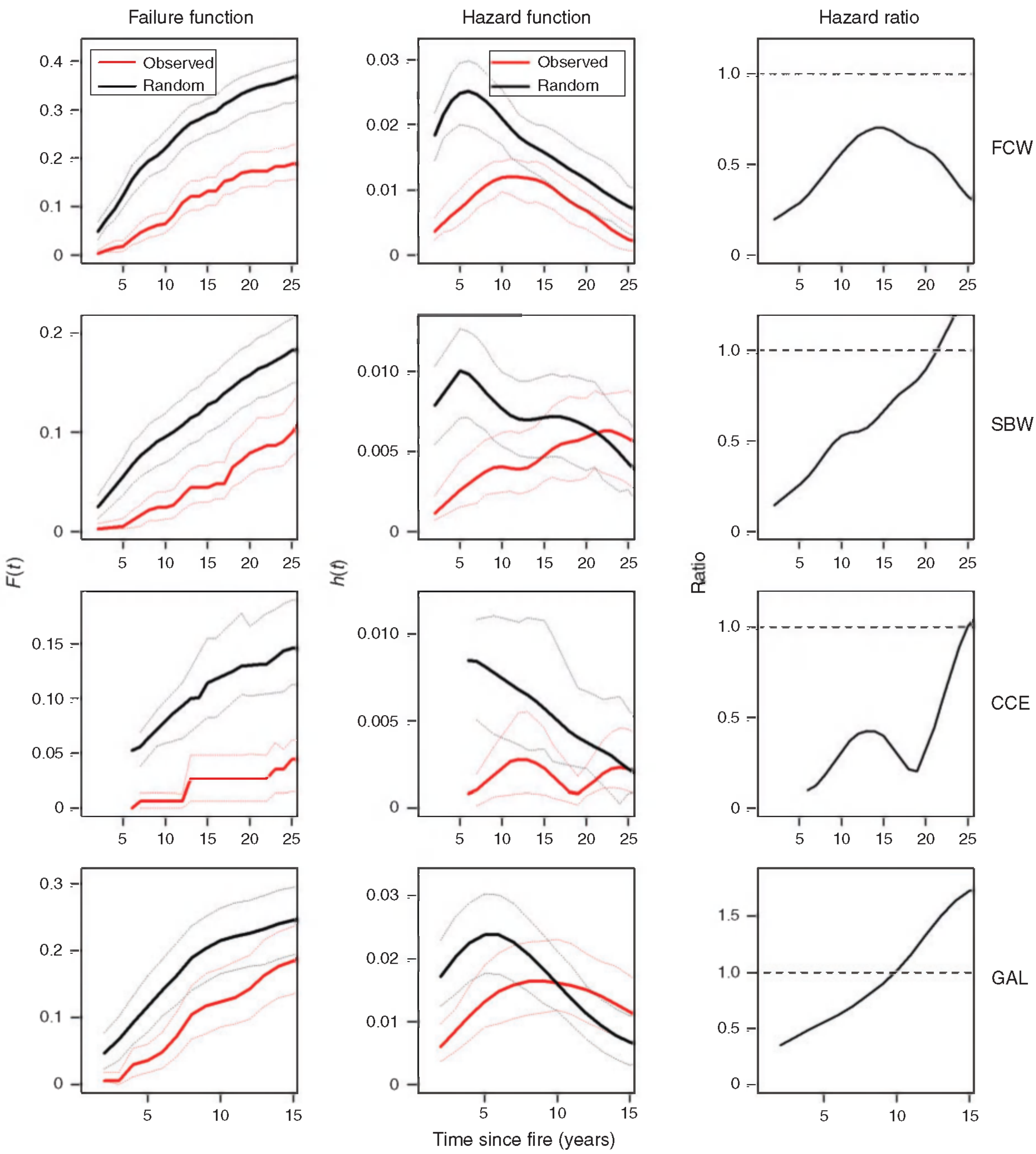

Fig. 2. The left column shows the failure function, denoted as $F(t)$, for each study area; 90% confidence intervals shown as thin dotted lines. These functions represent the probability that a fire will ignite and spread within the perimeter of a previous fire within the time interval 0 to time t. The middle column shows the hazard function, denoted as $h(t)$; 90% confidence intervals shown as thin dotted lines. These functions depict the rate that fires ignite and spread within the perimeter of a previous fire at time interval t given the condition that the fire has not yet occurred before time t. Each post-fire year t in which the observed hazard is less than the random hazard is an indication that observed fires are less likely to ignite and spread within the perimeter of a previous fire than expected by chance. The right column shows the hazard ratio, which is the observed hazard divided by the random hazard. Values below one (dashed horizontal line) indicate that fires are less likely to occur within the perimeter of a previous fire than expected by chance. For area abbreviations, see Fig. 1 caption.

Parks *et al.* 2015) by showing that wildland fire regulates subsequent fire occurrence. Our results also demonstrate that the longevity of this regulating effect varies among study areas and decays over time in three out of four study areas. Our use of failure time (or survival) analysis coupled with observed and random fire occurrence data accounted for spatial and temporal variability in fire data and provided a robust evaluation of feedbacks between wildland fire and subsequent fire occurrence.

Wildland fire regulates subsequent fire occurrence in all study areas; this is consistent with the findings of Krawchuk *et al.* (2006) who implicitly tested this feedback in the boreal forest of Alberta, Canada and found that fires were less likely to initiate in landscapes that had recently burned (also see Penman *et al.* 2013). One obvious explanation for this finding is that fuel is limited after a wildland fire (i.e. fire consumes live and dead fuel). Another potential explanation, however, is that the high moisture content of young, successional forests reduces the potential for subsequent fire occurrence (cf. Renkin and Despain 1992). Finally, factors such as topography, land-cover, and human activities could also affect the timing and location of ignitions (Syphard *et al.* 2007; Narayanaraj and Wimberly 2011; Faivre *et al.* 2014); these factors, however, were not explicitly evaluated in this study.

The longevity for which wildland fire limited subsequent fire occurrence varied among study areas. The study area in the south-western US (GAL) is dramatically different from the three northern study areas (FCW, SBW, and CCE). Wildland fire limits subsequent fire occurrence for only nine years in GAL but for over 20 years in FCW, SBW, and CCE. Such differences likely reflect differences in productivity and fire regime characteristics among study areas and ecosystems (Cleveland *et al.* 1999; Rollins *et al.* 2002). In GAL, for example, the relatively short longevity of the effect is consistent with the dominant vegetation (ponderosa pine forest with a grassy surface fuel understory) and fire regime (primarily low severity surface fires) (Swetnam and Dieterich 1985). In this ecosystem, overstory trees have low fire mortality and fine fuels such as grasses and surface litter (i.e. pine needles) recover quickly after fire, thereby quickly resetting the stage for the occurrence of subsequent wildland fire. In FCW, SBW, and CCE, however, fire conducive conditions are less frequent, and as such, when fire does occur, it tends to be of higher severity (i.e. higher tree mortality) and is less influenced by fine fuels than it is by downed wood and ladder and canopy fuels that develop during the relatively long fire free intervals (Schoennagel *et al.* 2004).

The monotonic increase in the hazard ratio in SBW and GAL is consistent with our expectation that the regulating effect of wildland fire on subsequent fire occurrence diminishes over time as biomass reaccumulates (Mack *et al.* 2008). This trend is also consistent with other studies that concluded that the strength of regulatory feedbacks between wildland fires decrease as the fire free interval increases (Collins *et al.* 2009; Bradstock *et al.* 2010; Penman *et al.* 2013; Parks *et al.* 2015). Although the temporary 'dip' in the hazard ratio in CCE starting at year 14 (see Fig. 2) does not hold true to a consistent increase over time, the overall trend does suggest the effect diminishes over time. However, the expected trend did not hold true in FCW, as the hazard ratio demonstrated a modal or 'hump' pattern at 14 years post-fire (Fig. 2). Because this modal pattern was not found for the adjacent SBW study area and has no obvious ecological explanation, we suggest that it is either an artefact of the heterogeneous nature of fire data or due to incorrect ignition location data (Brown *et al.* 2002; Short 2014). We suggest these factors are also responsible for the temporary dip in CCE.

In this study, we did not evaluate the influence of weather even though fires are more likely to ignite and spread during hot, dry or windy conditions (Chang *et al.* 2013; Penman *et al.* 2013; Sedano and Randerson 2014). However, because other studies have found that extreme weather weakens other aspects of self-regulation (cf. Collins *et al.* 2009; Price and Bradstock 2012; Parks *et al.* 2015), we would expect the longevity and strength of wildland fire's regulating effect on subsequent fire occurrence to be reduced during extreme weather. Given that extreme weather is expected to become more common in the future as a result of climate change (Nitschke and Innes 2008), a plausible extension is that the regulating effect of wildland fire demonstrated in this study will weaken in the future. However, a formal evaluation of the effect of weather on wildland fire's capacity to regulate subsequent fire occurrence is necessary.

Conclusions

Our study clearly indicates that wildland fire regulates subsequent fire occurrence. However, the longevity of this regulating effect varies by study area, ranging from 9 years in the study area in the south-western US to over 20 years in the study areas in the northern US Rocky Mountains. Furthermore, the strength of this effect is strong immediately after fire and generally weakens as fire intervals increase. More broadly, however, multiple lines of evidence indicate that feedbacks associated with wildland fire regulate several aspects of subsequent fire. That is, wildland fire regulates subsequent fire severity (Miller *et al.* 2012; Parks *et al.* 2014*a*), fire size (Collins *et al.* 2009; Parks *et al.* 2015), and, as explored in this study, fire occurrence (Krawchuk *et al.* 2006). The additive effect of the latter two feedbacks results in an overall reduction in fire activity or area burned in subsequent years (Héon *et al.* 2014; Parisien *et al.* 2014). When these feedback mechanisms are interrupted by human activities such as fire suppression, the result is larger and more severe fire in future years (Calkin *et al.* 2015). As such, these studies collectively suggest that fuel-mediated negative feedbacks are necessary components of self-regulating landscapes and for creating and maintaining resilience to future wildland fire events (McKenzie *et al.* 2011; Larson *et al.* 2013). Furthermore, the negative feedbacks elucidated in this and other studies serve as a reminder to managers that wildland fire can act as an effective 'fuel treatment' and that, under suitable fuels and weather conditions, there may be substantial long-term benefits resulting from a wildland fire that is managed for resource benefit as opposed to one that is suppressed.

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References

Abatzoglou JT, Kolden CA (2011) Relative importance of weather and climate on wildfire growth in interior Alaska. *International Journal of Wildland Fire* **20**, 479–486. doi:10.1071/WF10046

Agee JK (1993) Fire Ecology of Pacific Northwest Forests. Washington, D.C., Island Press.

Agee JK (1999) Fire effects on landscape fragmentation in interior west forests. In 'Forest fragmentation: wildlife and management implications'. (Eds JA Rochelle, LA Lehmann, J Wisniewski) pp. 43–60. (Koninklijke Brill NV: Leiden, Netherlands)

Arno SF, Parsons DJ, Keane RE (2000) Mixed-severity fire regimes in the northern Rocky Mountains: consequences of fire exclusion and options for the future. Wilderness Science in a Time of Change Conference, Missoula, MT, USDA Forest Service, Rocky Mountain Research Station, RMRS-P-15-VOL-5.

Barrett SW, Arno SF, Key CH (1991) Fire regimes of western larch – lodgepole pine forests in Glacier National Park, Montana. *Canadian Journal of Forest Research* **21**, 1711–1720. doi:10.1139/X91-237

Bartlein PJ, Hostetler SW, Shafer SL, Holman JO, Solomon AM (2008) Temporal and spatial structure in a daily wildfire-start data set from the western United States (1986–96). *International Journal of Wildland Fire* **17**, 8–17. doi:10.1071/WF07022

Bradstock RA, Hammill KA, Collins L, Price O (2010) Effects of weather, fuel and terrain on fire severity in topographically diverse landscapes of south-eastern Australia. *Landscape Ecology* **25**, 607–619. doi:10.1007/S10980-009-9443-8

Brown JK, Arno SF, Barrett SW, Menakis JP (1994) Comparing the Prescribed Natural Fire Program with Presettlement Fires in the Selway-Bitterroot Wilderness. *International Journal of Wildland Fire* **4**, 157–168. doi:10.1071/WF9940157

Brown TJ, Hall BL, Mohrle CR, Reinbold HJ (2002) Coarse Assessment of the Federal Wildland Fire Occurrence Data: Report for the national wildfire coordinating group. Program for Climate, Ecosystem and Fire Applications, Desert Research Institute. CEFA Report 02–04.

Calkin DE, Thompson MP, Finney MA (2015) Negative consequences of positive feedbacks in US wildfire management. *Forest Ecosystems* **2**, 9. doi:10.1186/S40663-015-0033-8

Chang Y, Zhu ZL, Bu RC, Chen HW, Feng YT, Li YH, Hu YM, Wang ZC (2013) Predicting fire occurrence patterns with logistic regression in Heilongjiang Province, China. *Landscape Ecology* **28**, 1989–2004. doi:10.1007/S10980-013-9935-4

Chou YH, Minnich RA, Chase RA (1993) Mapping probability of fire occurrence in San-Jacinto Mountains, California, USA. *Environmental Management* **17**, 129–140. doi:10.1007/BF02393801

Cleveland CC, Townsend AR, Schimel DS, Fisher H, Howarth RW, Hedin LO, Perakis SS, Latty EF, Von Fischer JC, Elseroad A, Wasson MF (1999) Global patterns of terrestrial biological nitrogen (N-2) fixation in natural ecosystems. *Global Biogeochemical Cycles* **13**, 623–645. doi:10.1029/1999GB900014

Cochrane MA, Alencar A, Schulze MD, Souza CM, Nepstad DC, Lefebvre P, Davidson EA (1999) Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science* **284**, 1832–1835. doi:10.1126/SCIENCE.284.5421.1832

Collins BM, Miller JD, Thode AE, Kelly M, van Wagtendonk JW, Stephens SL (2009) Interactions Among Wildland Fires in a Long-Established Sierra Nevada Natural Fire Area. *Ecosystems* **12**, 114–128. doi:10.1007/S10021-008-9211-7

Crane MF, Fischer WC (1986) Fire ecology of the forest habitat types on central Idaho. USDA Forest Service, Intermountain Research Station. GTR-INT-218.

Davis BH, Miller C, Parks SA (2010) Retrospective fire modeling: quantifying the impacts of fire suppression. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-236WWW. (Fort Collins, CO)

Eidenshink J, Schwind B, Brewer K, Zhu ZL, Quayle B, Howard S (2007) A project for monitoring trends in burn severity. *Fire Ecology* **3**, 3–21. doi:10.4996/FIREECOLOGY.0301003

Faivre N, Jin Y, Goulden ML, Randerson JT (2014) Controls on the spatial pattern of wildfire ignitions in Southern California. *International Journal of Wildland Fire* **23**, 799–811. doi:10.1071/WF13136

Fisher RA (1934) 'Statistical methods for research workers', 5th edn. (Oliver and Boyd: Edinburgh, UK)

Geospatial multi-agency coordinating group (GeoMAC) (2013) Fire perimeter dataset (http://rmgsc.cr.usgs.gov/outgoing/GeoMAC).

Héon J, Arseneault D, Parisien M-A (2014) Resistance of the boreal forest to high burn rates. *Proceedings of the National Academy of Sciences of the United States of America* **111**, 13 888–13 893. doi:10.1073/PNAS.1409316111

Holden ZA, Morgan P, Evans JS (2009) A predictive model of burn severity based on 20-year satellite-inferred burn severity data in a large southwestern US wilderness area. *Forest Ecology and Management* **258**, 2399–2406. doi:10.1016/J.FORECO.2009.08.017

Jácome M, Cao R (2007) Almost sure asymptotic representation for the presmoothed distribution and density estimators for censored data. *Statistics* **41**, 517–534. doi:10.1080/02331880701529522

Keane RE, Gray K (2013) Comparing three sampling techniques for estimating fine woody down dead biomass. *International Journal of Wildland Fire* **22**, 1093–1107. doi:10.1071/WF13038

Keane RE, Morgan P, Menakis JP (1994) Landscape assessment of the decline of whitebark-pine (pinus-albicaulis) in the Bob Marshall Wilderness Complex, Montana, USA. *Northwest Science* **68**, 213–229.

Key CH, Benson NC (2006) Landscape assessment (LA). In 'FIREMON: fire effects monitoring and inventory system'. (Eds D Lutes, RE Keane, JF Caratti, CH Key, NC Benson, S Sutherland, L Gangi). USDA Forest Service, Ricky Mountain Research Station, General Technical Report RMRS-GTR-164-CD, p. LA-1-55. (Fort Collins, CO)

Krawchuk MA, Moritz MA (2011) Constraints on global fire activity vary across a resource gradient. *Ecology* **92**, 121–132. doi:10.1890/09-1843.1

Krawchuk MA, Cumming SG, Flannigan MD, Wein RW (2006) Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest. *Ecology* **87**, 458–468. doi:10.1890/05-1021

Larson AJ, Belote RT, Cansler CA, Parks SA, Dietz MS (2013) Latent resilience in ponderosa pine forest: effects of resumed frequent fire. *Ecological Applications* **23**, 1243–1249. doi:10.1890/13-0066.1

Lindsey JC, Ryan LM (1998) Tutorial in biostatistics – Methods for interval-censored data. *Statistics in Medicine* **17**, 219–238. doi:10.1002/(SICI)1097-0258(19980130)17:2<219::AID-SIM735>3.0.CO;2-O

López-de-Ullibarri I, Jacome MA (2013) survPresmooth: An R Package for Presmoothed Estimation in Survival Analysis. *Journal of Statistical Software* **54**, 1–26.

Mack MC, Treseder KK, Manies KL, Harden JW, Schuur EAG, Vogel JG, Randerson JT, Chapin FS, III (2008) Recovery of aboveground plant biomass and productivity after fire in mesic and dry black spruce forests of interior Alaska. *Ecosystems* **11**, 209–225. doi:10.1007/S10021-007-9117-9

McCaw WL, Gould JS, Cheney NP, Ellis PF, Anderson WR (2012) Changes in behaviour of fire in dry eucalypt forest as fuel increases with age. *Forest Ecology and Management* **271**, 170–181. doi:10.1016/J.FORECO.2012.02.003

McKenzie D, Miller C, Falk DA (2011) Toward a theory of landscape fire. In 'The landscape ecology of fire.' (Eds D McKenzie, C Miller, DA Falk) pp. 3–25. (Springer: Dordrecht, Netherlands).

Meyn A, White PS, Buhk C, Jentsch A (2007) Environmental drivers of large, infrequent wildfires: the emerging conceptual model. *Progress in Physical Geography* **31**, 287–312. doi:10.1177/0309133307079365

Miller JD, Thode AE (2007) Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment* **109**, 66–80. doi:10.1016/J.RSE.2006.12.006

Miller JD, Skinner CN, Safford HD, Knapp EE, Ramirez CM (2012) Trends and causes of severity, size, and number of fires in northwestern California, USA. *Ecological Applications* **22**, 184–203. doi:10.1890/10-2108.1

Moritz MA (2003) Spatiotemporal analysis of controls on shrubland fire regimes: Age dependency and fire hazard. *Ecology* **84**, 351–361. doi:10.1890/0012-9658(2003)084[0351:SAOCOS]2.0.CO;2

Moritz MA, Keeley JE, Johnson EA, Schaffner AA (2004) Testing a basic assumption of shrubland fire management: how important is fuel age?

Frontiers in Ecology and the Environment **2**, 67–72. doi:10.1890/1540-9295(2004)002[0067:TABAOS]2.0.CO;2

Moritz MA, Moody TJ, Miles LJ, Smith MM, de Valpine P (2009) The fire frequency analysis branch of the pyrostatistics tree: sampling decisions and censoring in fire interval data. *Environmental and Ecological Statistics* **16**, 271–289. doi:10.1007/S10651-007-0088-Y

Narayanaraj G, Wimberly MC (2011) Influences of forest roads on the spatial pattern of wildfire boundaries. *International Journal of Wildland Fire* **20**, 792–803. doi:10.1071/WF10032

Nitschke CR, Innes JL (2008) Climatic change and fire potential in South-Central British Columbia, Canada. *Global Change Biology* **14**, 841–855. doi:10.1111/J.1365-2486.2007.01517.X

Parisien MA, Moritz MA (2009) Environmental controls on the distribution of wildfire at multiple spatial scales. *Ecological Monographs* **79**, 127–154. doi:10.1890/07-1289.1

Parisien M-A, Parks SA, Krawchuk MA, Little JM, Flannigan MD, Gowman LM, Moritz MA (2014) An analysis of controls on fire activity in boreal Canada: comparing models built with different temporal resolutions. *Ecological Applications* **24**, 1341–1356. doi:10.1890/13-1477.1

Parks SA (2014) Mapping day-of-burning with coarse-resolution satellite fire-detection data. *International Journal of Wildland Fire* **23**, 215–223. doi:10.1071/WF13138

Parks SA, Parisien M-A, Miller C (2012) Spatial bottom-up controls on fire likelihood vary across western North America. *Ecosphere* **3**(1), 12. doi:10.1890/ES11-00298.1

Parks SA, Miller C, Nelson CR, Holden ZA (2014*a*) Previous fires moderate burn severity of subsequent wildland fires in two large western US wilderness areas. *Ecosystems* **17**, 29–42. doi:10.1007/S10021-013-9704-X

Parks SA, Parisien M-A, Miller C, Dobrowski SZ (2014*b*) Fire activity and severity in the western US vary along proxy gradients representing fuel amount and fuel moisture. *PLoS One* **9**, e99699. doi:10.1371/JOURNAL.PONE.0099699

Parks SA, Holsinger LM, Miller C, Nelson CR (2015) Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. *Ecological Applications* **25**, 1478–1492. doi:10.1890/14-1430.1

Penman T, Bradstock R, Price O (2013) Modelling the determinants of ignition in the Sydney Basin, Australia: implications for future management. *International Journal of Wildland Fire* **22**, 469–478. doi:10.1071/WF12027

Peterson GD (2002) Contagious disturbance, ecological memory, and the emergence of landscape pattern. *Ecosystems* **5**, 329–338. doi:10.1007/S10021-001-0077-1

Peterson D, Wang J, Ichoku C, Remer LA (2010) Effects of lightning and other meteorological factors on fire activity in the North American boreal forest: implications for fire weather forecasting. *Atmospheric Chemistry and Physics* **10**, 6873–6888. doi:10.5194/ACP-10-6873-2010

Pierce AD, Farris CA, Taylor AH (2012) Use of random forests for modeling and mapping forest canopy fuels for fire behavior analysis in Lassen Volcanic National Park, California, USA. *Forest Ecology and Management* **279**, 77–89. doi:10.1016/J.FORECO.2012.05.010

Price OF, Bradstock RA (2012) The efficacy of fuel treatment in mitigating property loss during wildfires: Insights from analysis of the severity of the catastrophic fires in 2009 in Victoria, Australia. *Journal of Environmental Management* **113**, 146–157. doi:10.1016/J.JENVMAN.2012.08.041

Price OF, Pausas JG, Govender N, Flannigan M, Fernandes PM, Brooks ML, Bird RB (2015) Global patterns in fire leverage: the response of annual area burnt to previous fire. *International Journal of Wildland Fire* **24**, 297–306. doi:10.1071/WF14034

R Development Core Team (2007) R: A language and environment for statistical computing. R foundation for computing. Vienna, Austria.

Renkin RA, Despain DG (1992) Fuel moisture, forest type, and lightning-caused fire in Yellowstone National Park. *Canadian Journal of Forest Research* **22**, 37–45. doi:10.1139/X92-005

Rollins MG (2009) LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. *International Journal of Wildland Fire* **18**, 235–249. doi:10.1071/WF08088

Rollins MG, Morgan P, Swetnam T (2002) Landscape-scale controls over 20(th) century fire occurrence in two large Rocky Mountain (USA) wilderness areas. *Landscape Ecology* **17**, 539–557. doi:10.1023/A:1021584519109

Schoennagel T, Veblen TT, Romme WH (2004) The interaction of fire, fuels, and climate across rocky mountain forests. *Bioscience* **54**, 661–676. doi:10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2

Sedano F, Randerson JT (2014) Multi-scale influence of vapor pressure deficit on fire ignition and spread in boreal forest ecosystems. *Biogeosciences* **11**, 3739–3755. doi:10.5194/BG-11-3739-2014

Senici D, Chen HYH, Bergeron Y, Cyr D (2010) Spatiotemporal variations of fire frequency in central boreal forest. *Ecosystems* **13**, 1227–1238. doi:10.1007/S10021-010-9383-9

Short KC (2014) A spatial database of wildfires in the United States, 1992–2011. *Earth System Science Data* **6**, 1–27. doi:10.5194/ESSD-6-1-2014

Swetnam TW, Dieterich JH (1985) Fire history of ponderosa pine forests in the Gila Wilderness, New Mexico. In 'Proceedings – symposium and workshop on wilderness fire'. (Eds JE Lotan, BM Kilgore, WC Fischer and RW Mutch) USDA Forest Service General Technical Report GTR-INT-182. (Ogden, UT)

Syphard AD, Radeloff VC, Keeley JE, Hawbaker TJ, Clayton MK, Stewart SI, Hammer RB (2007) Human influence on Califoirnia fire regimes. *Ecological Applications* **17**, 1388–1402. doi:10.1890/06-1128.1

Syphard AD, Radeloff VC, Hawbaker TJ, Stewart SI (2009) Conservation Threats Due to Human-Caused Increases in Fire Frequency in Mediterranean-Climate Ecosystems. *Conservation Biology* **23**, 758–769. doi:10.1111/J.1523-1739.2009.01223.X

Tanner MA, Wong WH (1983) The estimation of the hazard function from randomly censored data by the kernel method. *Annals of Statistics* **11**, 989–993. doi:10.1214/AOS/1176346265

Thatcher N, Chang A, Parikh P, Rodrigues Pereira J, Ciuleanu T, von Pawel J, Thongprasert S, Tan EH, Pemberton K, Archer V, Carroll K (2005) Gefitinib plus best supportive care in previously treated patients with refractory advanced non-small-cell lung cancer: results from a randomised, placebo-controlled, multicentre study (Iressa Survival Evaluation in Lung Cancer). *Lancet* **366**, 1527–1537. doi:10.1016/S0140-6736(05)67625-8

Therneau T (2014) A package for survival analysis in R - R package version 2.37–7, http://CRAN.R-project.org/package=survival.

USDA Forest Service (2003) The Frank Church – river of no return wilderness management plan. Available at http://www.wilderness.net/toolboxes/documents/resourceProtection/FCRNRW%20Plan%20Table%20of%20Contents.pdf [Verified 29 September 2015]

USDA Forest Service (2013) MODIS Fire detection GIS data, available at: http://activefiremaps.fs.fed.us/gisdata.php.

Wang X, Parisien M-A, Flannigan MD, Parks SA, Anderson KR, Little JM, Taylor SW (2014) The potential and realized spread of wildfires across Canada. *Global Change Biology* **20**, 2518–2530. doi:10.1111/GCB.12590