Research Article

Changes in Severity Distribution after Subsequent Fires on the North Rim of Grand Canyon National Park, Arizona, USA

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ABSTRACT

Understanding the distribution of fire severity patches across a landscape is of critical importance to managers and researchers. Of particular interest are those areas that burn multiple times. Understanding the complexity of these "multiple entry, mixed severity" patches is an important component of managing the landscape. We investigated the role that initial fire severity might play on subsequent fire severity (for a given re-burned area) to assess whether high severity patch distribution was impacted by initial burn conditions. In our study area, the North Rim of Grand Canyon National Park, USA, the fire severity patch distribution of one fire had little influence on the fire severity distribution of a subsequent fire and second entry severity patches were distributed on top of the first entry severity patches in a close to random distribution. Of all areas that burned twice between 2000 and 2011 on the North Rim of Grand Canyon National Park, 48 % burned with equal severity, 26 % burned with a lower severity, and 26 % burned with a

RESUMEN

Comprender la distribución de parches con distintos grados de severidad del fuego a lo largo del paisaje es de importancia crítica para los gestores de recursos e investigadores. De particular interés son aquellas áreas que se queman repetidas veces. Entender la complejidad de los parches en los que el fuego se presenta en múltiples eventos y con variada severidad es un componente importante de la gestión del paisaje. En este estudio, investigamos el rol que la severidad inicial del fuego podría tener en la severidad posterior (en un área que se vuelve a quemar), para determinar si la distribución de parches de alta severidad sería impactada por las condiciones de quema iniciales. En nuestra área de estudio, el North Rim del Parque Nacional Grand Canyon de los EEUU, la distribución de los parches de severidad de un fuego tiene poca influencia en la distribución de la severidad de incendios posteriores, y la severidad en parches de lugares ya quemados estuvieron distribuidos en lo más alto de la escala de los primeros parches afectados por el fuego en una distribución prácticamente aleatoria. De todas las áreas que se quemaron dos veces entre 2000 y 2011 en el North Rim del Parque Nacional Gran Canyon, el 48 % se quemó con igual severidad, el 26 % con menor severidad, y el otro higher severity in the second fire. The majority of the agreement can be attributed to a similarity in the proportions of each severity class and not to a match in the spatial allocation of the equal severity patches on first and second entry fires. The distribution of high severity patches showed little change when comparing post-first entry and post-second entry distributions. The mean and the standard deviation of the high severity patch size did not change after a second fire entry. The total area of high severity did increase; this was due to both the addition of new patches as well the growth of existing patches. These findings can help to inform land managers about the roles that fire-on-fire events play on the landscape and how those interactions may impact management goals and decisions.

26% con una severidad más alta en el segundo incendio. La mayoría de las coincidencias pueden ser atribuidas a una similitud en las proporciones de cada clase de severidad y no debido a una coincidencia en la ubicación espacial de parches de igual severidad en los primeros y segundos eventos de fuego. La distribución de los parches de alta severidad mostró poco cambio cuando se compararon las distribuciones de los primeros y segundos eventos de fuego. La media y la desviación estándar del tamaño de los parches de alta severidad no cambiaron después del segundo evento de fuego. El área total de eventos de alta severidad se incrementó; esto se debió tanto a la suma de nuevos parches como al crecimiento de los parches existentes. Estos resultados pueden ayudar a informar a los gestores de recursos naturales sobre el rol que los incendios pueden tener en el paisaje, y como esas interacciones pueden impactar en los objetivos y decisiones de gestión.

Keywords: Arizona, Grand Canyon National Park, fire severity, fire-on-fire interactions, MTBS, spatial analysis, wildfire

Citation: Hoff, V., C.C. Teske, J.P. Riddering, L.P. Queen, E.G. Gdula, and W.A. Bunn. 2014. Changes in severity distribution after subsequent fires on the North Rim of Grand Canyon National Park, Arizona, USA. Fire Ecology 10(2): 48–63. doi: 10.4996/fireecology.1002048

INTRODUCTION

Spatial attributes of ecological processes, such as fire, are of interest to both researchers and land managers. The effects of fire vary greatly on both spatial as well as temporal scales (Morgan *et al*. 2001). With the increasing availability of spatial data, and an increase in the number of ways of consuming and analyzing that data, it is now possible to investigate spatial patterns on many scales. Quantitative information on the spatial and temporal diversity of fire can be helpful in qualifying and better understanding the effects of fire in an ecosystem (Conedera *et al*. 2009).

Fire severity is a qualitative indicator of the effects of fire on the above and below ground organic matter in an ecosystem (Keeley 2009). Quantifying the distribution of fire severity can highlight both the changes that fire brings to an area as well as the influences of initial change from a past fire on subsequent change from future fires. Strategic and tactical decisions in fire management are influenced by knowing what fires have done in the past and what fires can be expected to do in the future, especially regarding persistent changes to vegetation. In addition, the extent of high severity patches has ecological consequences for vegetation and wildlife dispersal and maintenance of landscape-scale diversity.

In a mixed severity fire regime, as is found in the complex structure of a mixed conifer forest type, the variability in patches can act as a filter for future fires (Agee 2005). Understanding the pattern of severity patches in a previous fire could aid in the determination of where and how fire burns next. Knowledge of the interaction of subsequent fires can help managers make decisions that will avoid unintended ecological outcomes such as habitat loss, decreased regeneration, and subsequent vegetation type conversion. The staying power or persistence of these changes varies widely. In some ecosystems, the effects are very short lived; in others, the results are visible or measurable for decades (Agee 1998). High severity patches tend to persist on the landscape (Lentile *et al*. 2005) and could become larger and more abundant with the occurrence of subsequent high severity fire. The patches become larger because new patches combine with old patches. This would also lead to a reduction in the number of total patches and a decrease in entropy: neighboring patches become more alike and the landscape more homogenous (Teske *et al.* 2012). Occasionally we also expect to see some new patches that are independent from first entry patches.

We measured the effects that the severity of an initial fire had on a subsequent fire. We hypothesized that severity of the initial fire influences the severity of a subsequent fire. A fire can influence a subsequent fire by either reducing the fuel load through consumption, or by increasing fuel loads by creating opportunities for biomass to grow and accumulate. This influence can manifest itself in the location, distribution, and severity of the patches in the mosaic created by each fire entry, as well as the intensity with which a fire burns, and could be examined by measuring the fire severity of the second entry fire. We were interested in determining if the proportion of second entry high severity patches was related to the distance the patch was removed from a first entry high severity patch. Simply, did second entry high severity patches occur more often close to first entry high severity patches? This is suggested by Tobler's first law of geography, which states that everything is related to everything else, but things near are more related than distant things (Tobler 1970).

METHODS

Study Area

Located on the Kaibab Plateau, the North Rim of Grand Canyon National Park, USA (Figure 1), is a relatively remote area in northern Arizona. The North Rim is the southernmost part of the Kaibab Plateau, on which fire occurs frequently (Table 1). The elevation ranges from 2200 m to 2800 m over a distance of about 35 km. Precipitation comes in the form of winter snow and summer monsoon rains, and the precipitation amount increases with increasing elevation (Halvorson 1972). This gradient has resulted in a range of vegetation types, from pinyon-juniper woodlands and ponderosa pine forests on the drier canyon rim to mixed conifer forests mid-slope and spruce-fir dominated forests at the highest elevations (Rasmussen 1941).

The ponderosa pine (*Pinus ponderosa var. arizonica* [Engelm.] Shaw) dominated forests occur at elevations from 2200 m to 2450 m, and occasionally have white fir (*Abies concolor* [Gord. & Glend.] Lindl. ex Hildebr.) encroachment (Fulé *et al.* 1997). Fire regimes in the ponderosa pine forests are generally high frequency and low severity (Fulé *et al.*1997). The primary carrier of fire is the fine dead surface fuel load (Grand Canyon National Park 2012).

In the mixed conifer forests, which occur at elevations of 2450 m to 2650 m, white fir and ponderosa pine are the dominant species, with Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and blue spruce (*Picea pungens* Engelm.) present (Mast and Wolf 2006). The historic fire regime was mixed, with a higher frequency and lower severity on drier sites, and a lower frequency and higher severity on moist sites (Swetnam and Baisan 1996).

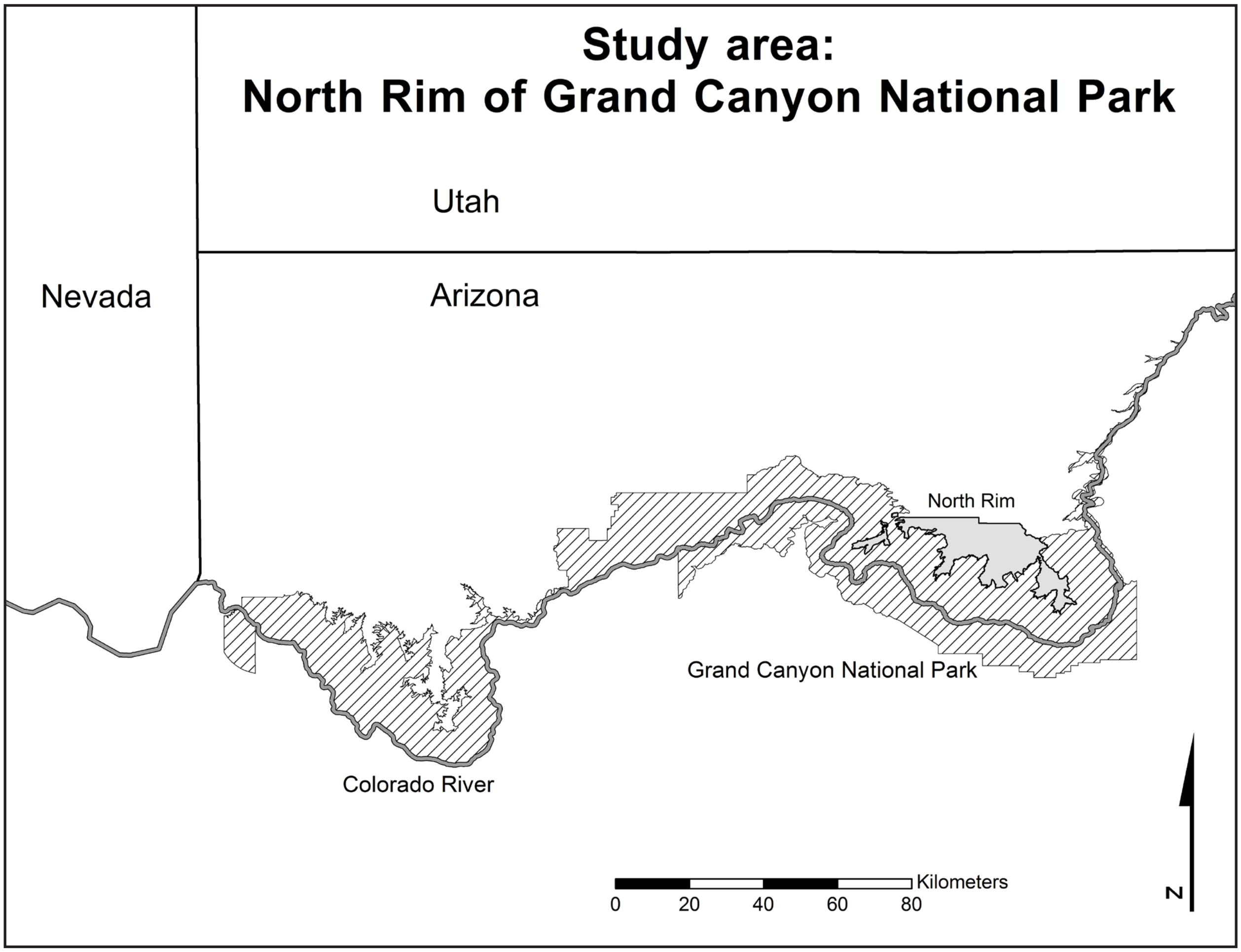

Figure 1. Study area on the North Rim of Grand Canyon National Park, Arizona, USA. The national park is shown by hatched lines and the North Rim is outlined in gray.

Table 1. Fire history summary of study area.

	Area (ha)
Area of North Rim of Grand Canyon National Park	38 401.5
Sum of all fires from 2000 to 2011	36 084.9
Area burned twice from 2000 to 2011	5 718.4
Total area affected by fire from 2000 to 2011	30 366.5

The fuel load is generally higher than in the pure ponderosa forests, with more logs and needles and less grass to carry the fire (Swetnam and Baisan 1996, Baker 2009).

The spruce-fir forests occur at the highest elevations (2650 m to 2800 m) of the Kaibab Plateau and are dominated by Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). Douglas-fir, white fir, blue spruce, and ponderosa pine are also present (Merkle 1962). Aspen (*Populus tremuloides* Michx.) frequently sprouts after fire and causes vegetation type conversion when larger patches are established. The suppression of fires might be factor in the lack of aspen and the dominance of conifers in some areas (Fulé *et al.* 2002). The low historic fire frequency in this forest type contributes to a heavy but compact fuel load, which leads to minimal surface fire spread and crown fire under dry and windy conditions (Touchan *et al.* 1996, Fulé *et al.* 2003).

Dataset

Grand Canyon National Park fire staff uses burn severity data to aid with fire management decisions. The source of the burn severity data is the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink *et al*. 2007). This national census dataset is available through a cooperation of the Forest Service's Remote Sensing Application Center (RSAC) and United States Geological Survey's Earth Resources Observation and Science Center (EROS). The fire severity data in this dataset are based on remotely sensed data from the Landsat sensors. In the western United States, every fire larger than 405 ha is mapped. The impact on the vegetation of each 30 m pixel has been calculated using the Normalized Burn Ratio (NBR; Key and Benson 2004). The difference in the pre-fire NBR and post-fire NBR can be interpreted as the severity with which a fire burned. These severity values are then categorized into five easily interpreted severity classes, using pre-defined threshold values for each class. For Grand Canyon National Park, fires larger than 60 ha occurring between 2000 and 2011 have been mapped by EROS. The minimum mapping unit of the severity classes within these fires is 30 m, and this patch size was used without smoothing for our study.

Grand Canyon National Park has improved these burn severity raster images by calibrating them using the Composite Burn Index (CBI; Key and Benson 1999, Key 2006) and creating severity polygons. The CBI is a metric designed to measure ground effects and define burn severity ecologically, which collectively provides a value that can be compared to a signal detected at moderate resolution by the Landsat Thematic Mapper (Key and Benson 2004). The CBI data were obtained in the field at 825 sample sites, covering 29 fires over a 12 year period, and used to adjust the remotely sensed data to the local conditions. The Grand Canyon fire staff adjusted the original MTBS default thresholds to match the CBI field data for each individual fire. A linear regression with the dNBR values versus the CBI field scores was done to assess the accuracy of the new thresholds. All fires had an r-squared value of 0.85 or greater. The resulting severity classes are the best available fire severity data for the study area. The fire severity data were reported in five classes: high severity, moderate-high severity, moderate-low severity, low severity, and unburned. The unburned class consists of patches that did not appear to burn, but are inside the fire perimeter. There were no locations where fire had occurred more than twice during our period of analysis, so we used only first and second entry patches.

Analyses

We used the spatial distribution of fire over the years 2000 to 2011 and analyzed what happened in areas that burned twice. We define the first time a fire burns in a particular location during the period 2000 to 2011 as the first entry. If fire occurs again in the same location, it is considered a second entry. We investigated the influence of the severity of the initial fire on the distribution of the severity caused by a subsequent fire by comparing two subsequent fire severities. Field visits have subjectively shown that, at least in some areas, a high severity patch is persistent and increases in size due to a second entry fire. This increase is a concern for managers. We quantified the distribution of subsequent fire severity utilizing a GIS and remotely sensed, field calibrated data, in which each patch could be as small as one Landsat pixel-based (i.e., 30 m) square polygon.

In order to evaluate fire-on-fire impacts, we looked at the relationship between first entry fire severity and second entry fire severity at patch level. We defined a patch as a contiguous area, as small as one 30 m pixel, with the same severity, surrounded by patches with different fire severities. These initial severity patches get combined with severity patches of second entry fires to create a landscape of unique combinations of first entry fire and second entry fire severities. We examined the distribution of these patches and analyzed them as a function of the three major forest types: ponderosa pine forest, mixed conifer forest, and spruce-fir forest. Finally, we calculated the agreement, the kappa coefficient, and the changes in severity for each of the three major forest types.

The fire severities of multiple fire entries were compared by intersecting the severity of first entry and second entry fires in locations common to both fires. Each unique, contiguous patch consisting of a combination of these two severity measurements became an individual feature. The severity of a second entry fire could be higher, lower, or identical to that of the first entry fire. We will refer to the commonality (in which severity matches in both occurrences) in subsequent fire severity as the agreement, a term chosen simply to assist in the explanation of results. Agreement matrices were created for each fire to see how much the severity of the subsequent fire was similar to the severity of the initial fire. A Cohen's kappa coefficient (Cohen 1960) was calculated to see how different the distribution of the second entry severity was from a random distribution. A kappa value close to zero indicates a chance agreement, while a kappa value close to 1 indicates near perfect agreement between the severity distributions of the first and second entries. A negative kappa indicates less than chance agreement. This method has frequently been applied to analyze remotely sensed data with the objective of calibrating the classification of a raster (Lillesand *et al.* 2004). Because the fire severity data for each fire has been calibrated with field CBI data by National Park Service fire scientists and matches the conditions in the field very well (r-squared ≥ 0.85), kappa was not used to assess the validity of the severity patch assignments. Rather, it was used to evaluate severity patch distribution versus a random distribution. Similarly, the agreement matrices were not used to find errors. They were used to find agreement between the first entry and second entry fires and evaluate whether the severities of subsequent fire entries could be defined as random or not.

We used three types of agreement to analyze how the first entry severity and second entry severity were related: quantity agreement, allocation agreement, and chance agreement (Pontius and Millones 2011).

- Quantity agreement is the amount of coincidence between first entry severity and second entry severity that is due to the similarity in the proportion of the severity classes.
- Allocation agreement is the coincidence due to an optimal match in spatial allocation of the severity classes, given the proportions of the severity classes on first and second entries.
- Chance agreement is the amount of coincidence due to chance. A five bin analysis, using the five severity classes, will reduce the influence of chance, and allocation agreement and quantity agreement will play a larger role, compared to a two bin analysis, when only high severity and low severity are compared.

The severities of an original fire and a subsequent fire were examined by looking at the agreement for each of the five severity classes: high, moderate-high, moderate-low, low, and unburned. In this context, agreement indicates what percentage of the twice-burned area showed the same severity on both first and second entry. The similarity in subsequent severities can be attributed to a combination of chance, the proportions of area in each severity class, and the spatial allocation of the areas that burned with the same severity. The difference in subsequent severities can be attributed to the difference in area in each severity class on first and second entry, and to the different spatial arrangement of these severity classes. Because all severity re-burn data for the study period were used, the matrix is unbiased (Pontius and Millones 2011).

We also quantified the changes in severity from first to second entry, according to both the number of patches and to the amount of area burned. The five severity classes were given a coded domain of 0 for unburned, to 4 for high severity. We classified the direction of change of second entry fire severity into higher, identical, or lower severity (than the first entry fire severity). By subtracting the initial (coded) severity value from the subsequent (coded) severity value, a delta-severity was calculated. This delta-severity symbolized the change in severity from first to second entry and provided a direction of the severity change for both area and patch count. The change could be as high as 4 for a patch that burned with a high-on-unburned severity (i.e., high severity minus unburned, 4 – 0 = 4), or as low as –4 for a patch that did not burn on second entry after a high severity first entry fire (i.e., unburned minus high severity, 0 – 4 = –4). Any patch that burned with the same severity twice had a value of zero.

To analyze the distance relationships of severity patches we created concentric buffers (Figure 2) around first entry high severity patches, at both a 15 m interval for the first 90 m, and a 90 m interval out to 990 m. We intersected the buffers with the fire severities from fires that created the second entry patches. The proportion of high severity was calculated for the area covered by each 15 m and 90 m buffer.

To investigate whether high severity fire patches increase in size, we evaluated how often second entry patches burned into first entry patches, as well as the distribution of the final patches. Multi-polygon patches were converted into single polygon features. Each original patch was spatially joined to second entry patches only if the boundaries of those patches touched. A high fire severity on first entry adjacent to a high fire severity patch on second entry may cause both the total area of high severity to grow on the landscape and the high severity patch to increase in size (Figure 3).

RESULTS

Distribution of Fire-on-Fire Severity Interaction

There were 31 individual fire-on-fire interactions in the period of study. The severity distribution shows how the 5719.3 ha burned and re-burned by these fires are distributed in each combination of first entry severity and second entry severity class (Table 2). We found that on second entry, 25.9% of the twice-burned area burned with a higher severity, 26.2% burned with a lower severity, and 47.8% burned with the same severity in the second fire. The patches in which low severity fire followed an initial low severity fire account for the largest amount of area (2341.6 ha, or 40.9% of the total area re-burned). The severity distribution of second entry patches is close to a random distribution, as indicated by the kappa of 0.08 (Table 3). The value of kappa varies among the forest types, but each individual forest type has a kappa value that is lower than the value of the kappa for the total area (Table 3). When each pair of overlapping fires was analyzed separately, agreement ranged from 21.2% to 79.90%, and kappa values ranged from –6.6% to 42.9%, with a mean of 3.3% and a standard deviation of 8.5%.

Like the kappa value, the agreement (and the proportion of allocation and quantity agreement) varies among forest types (Table 4). In each forest type, 20.0% of the agreement is attributable to chance for a five-class severity bin. In the ponderosa pine forest type, 33.1% of the twice-burned area has the same severity both times, which is due to the pro-

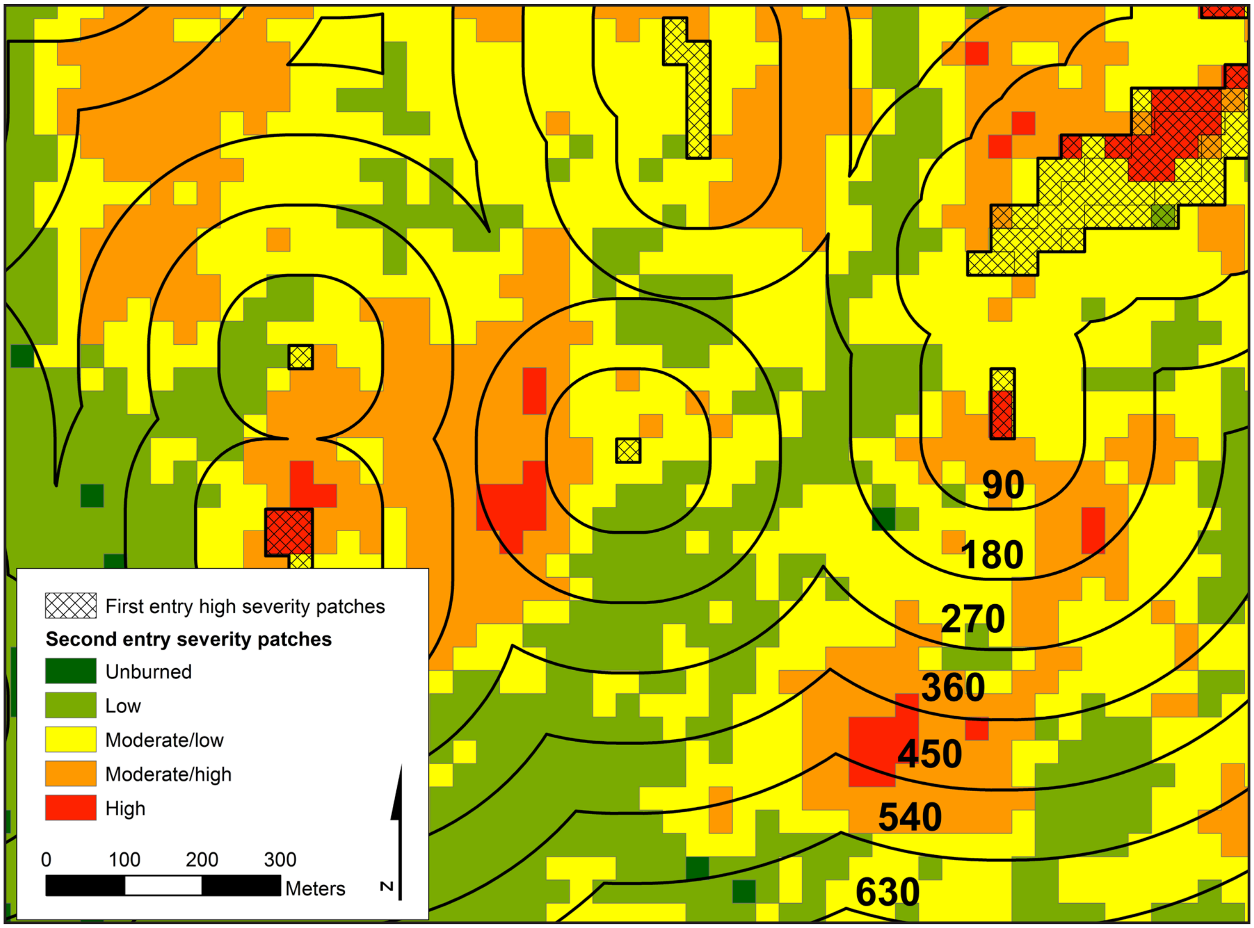

Figure 2. Example relationship between first entry high severity patches (cross-hatched areas) and the severity of second entry patches.

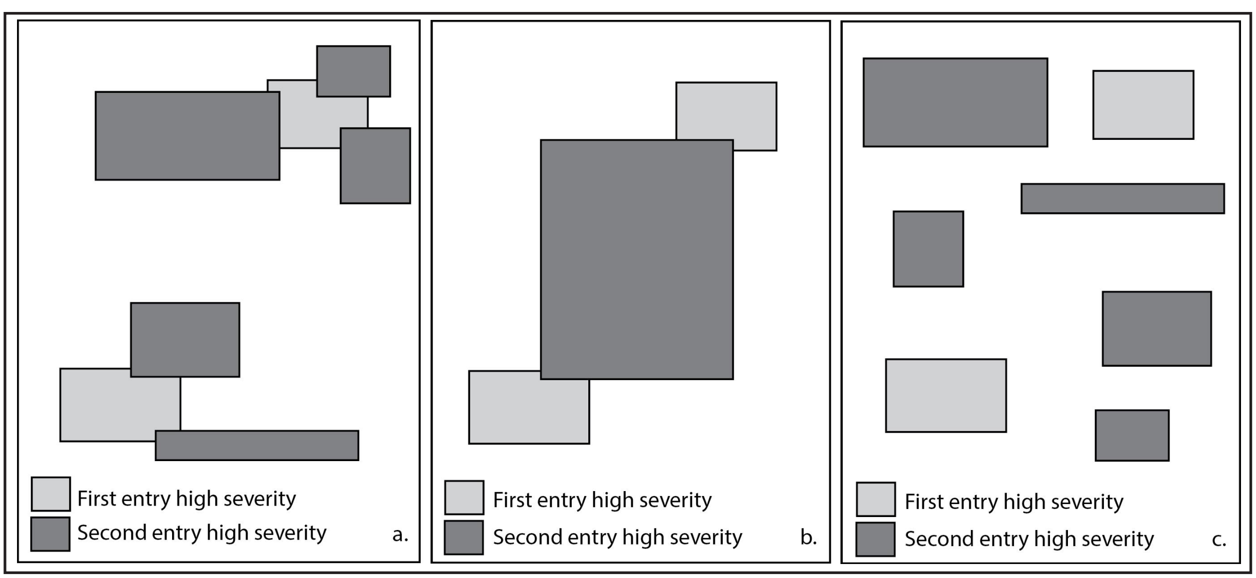

Figure 3. Potential spatial distribution of high severity patches following two fires (all figures represent equal area of high severity fire). a) two small patches become two larger patches; b) two small patches become one large patch; and c) many small patches distributed across the landscape.

Table 2. Area in hectares (and proportion, %) of the severity of first entry fires burned by second entry fires. Each of the values in the diagonal line of cells, shown in bold from top left to bottom right, is the area that burned with the same severity in both the first and second entries, and represent those areas that we are calling "in agreement." The sum of these values is the agreement between initial and subsequent fire severity as the proportion of the area that burned twice.

Second entry	First entry					
	High	Moderate-high	Moderate-low	Low	Unburned	Total
High	**16.4 (0.3)**	25.4 (0.4)	28.2 (0.5)	47.0 (0.8)	4.2 (0.1)	121.2 (2.1)
Mod.-high	18.5 (0.3)	**32.2 (0.6)**	118.8 (2.1)	232.4 (4.1)	20.6 (0.4)	422.5 (7.4)
Mod.-low	43.5 (0.8)	94.8 (1.7)	**287.9 (5.0)**	645.5 (11.3)	73.7 (1.3)	1145.4 (20.0)
Low	27.6 (0.5)	80.9 (1.4)	543.7 (9.5)	**2341.6 (40.9)**	286.8 (5.0)	3280.6 (57.4)
Unburned	12.0 (0.2)	32.9 (0.6)	117.9 (2.1)	529.0 (9.2)	**57.8 (1.0)**	749.6 (13.1)
Total	118.0 (2.1)	266.2 (4.7)	1096.5 (19.2)	3795.5 (66.3)	443.1 (7.7)	5719.3 (100.0)

Table 3. Changes in severity proportion (%) with subsequent fire entries in ponderosa pine, mixed conifer, and spruce-fir forests.

	Ponderosa	Mixed conifer	Spruce-fir	All 3 forest types
Higher severity	27.1	20.0	53.7	26.2
Equal severity	54.0	39.5	27.2	47.8
Lower severity	18.9	40.5	19.1	25.9
Total	100.0	100.0	100.0	100.0
Kappa	0.020	0.068	0.062	0.080

Table 4. Agreement and disagreement (percent) of subsequent fire severity in ponderosa pine, mixed conifer and spruce-fir forests.

	Ponderosa	Mixed conifer	Spruce-fir	All 3 forest types
Chance agreement	20.0	20.0	20.0	20.0
Quantity agreement	33.1	15.1	2.4	23.2
Allocation agreement	0.9	4.4	4.8	4.6
Total agreement	54.0	39.5	27.2	47.8
Allocation disagreement	36.8	41.6	51.6	43.1
Quantity disagreement	9.2	18.9	21.2	9.1
Total disagreement	46.0	60.5	72.8	52.2
Agreement + disagreement	100.0	100.0	100.0	100.0

portion of area in each severity class on first and second entry (i.e., quantity agreement). Only 0.9% of the distribution of severity classes of the area that burned twice can be attributed to the spatial coincidence (i.e., allocation agreement). The proportion of total agreement decreases, when going up the elevation gradient, from ponderosa pine forests to spruce-fir forests (Table 4).

Changes in Severity

A small majority of patches burned with a lower severity in the second entry than in the previous entry (Figure 4). Even though the number of patches in the unchanged category is small, the patches in this category contributed a larger area relative to the other two classes (Figure 5). Only a few second entry patches burned with a much higher severity (positive values) or much lower severity (negative values) than the first entry fire, and many patches burned with a similar or identical severity. Frequently, the magnitude of change was small in either direction.

The largest 11 patches (out of a total of 24 521 patches) that burned twice are in the mixed conifer vegetation type and burned with low severity both on first and second entry. These eleven patches cover 23% of the total area that burned twice between 2000 and 2011. This helps to explain the low number of unchanged patches compared to the high number of unchanged hectares. Overall, small changes in subsequent severity (+1 or –1) occurred frequently, but in small patches, which contributed a relatively small area.

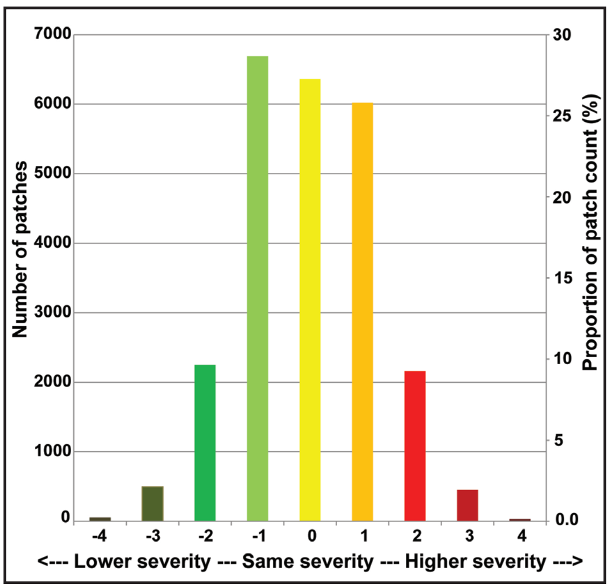

Figure 4. Magnitude of the delta-severity value by frequency for re-burned locations. The bars with negative values indicate the number of patches burned with a lower severity on second entry, while the bars with positive values indicate the number of patches burned with a higher severity on second entry. The number of patches in each class is displayed on the left vertical axis. The proportion in each category of change is displayed on the right vertical axis. The '0' column represents areas that burned with the same severity in both the first and second entry.

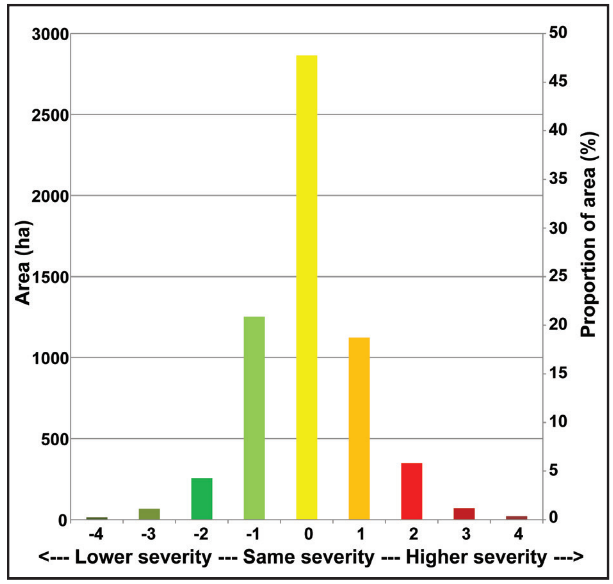

Figure 5. Magnitude of the delta-severity value by area for re-burned locations. The bars with negative values indicate the area burned with a lower severity on second entry, while the bars with positive value indicate the area burned with a higher severity on second entry. The area for each class is displayed in hectares on the left vertical axis. The proportion in each category of change is displayed on the right vertical axis. The '0' column represents areas that burned with the same severity in both the first and second entry.

Location of High Severity Patch Size Increase

The first entry high severity class contained 3647 individual patches across the entire study area (Table 5). The second entry high severity class contained 645 individual patches. When the second entry patches burned into first entry high severity patches, larger patches were formed; additionally, new patches were formed that do not burn into oth-

Table 5. Area (ha) of severity patch distribution.

	First entry	Second entry	Aggregate post-second entry
Count	3647	645	3907
Maximum area	1299	122	1343
Sum of patches	6164	599	6660
Mean area	1.69	0.93	1.70
Standard deviation area	28.11	5.48	27.94

er patches. Post-second entry, the area had 3907 high severity patches, which is less than the sum of each entry because some patches burned together. The size distribution of these patches changed significantly when multiple entries of high severity patches grew together.

The proportion of area classified in high, moderate-high, and moderate-low severity decreased slightly over the first 450 m away from an initial high severity patch (e.g., from 3.0% to 1.5%, from 28.2% to 22.5%, and from 13.1% to 8.7%, respectively). The proportion of area in the low severity class increased slightly, from 43.8% to 54.6%, in the first 450 m away from an initial high severity patch. The proportions of area in each severity class did not change much as distance increased away from the initial high severity patch. When examining the first 990 m around an initial high severity patch, the most significant changes were the increase in the proportion of area classified as low severity and the decrease in the proportion of area classified as moderate-low severity, with the sum of these two classes staying almost constant (Figure 6). The proportion of area classified as high severity changed very little in the 990 m surrounding an initial patch.

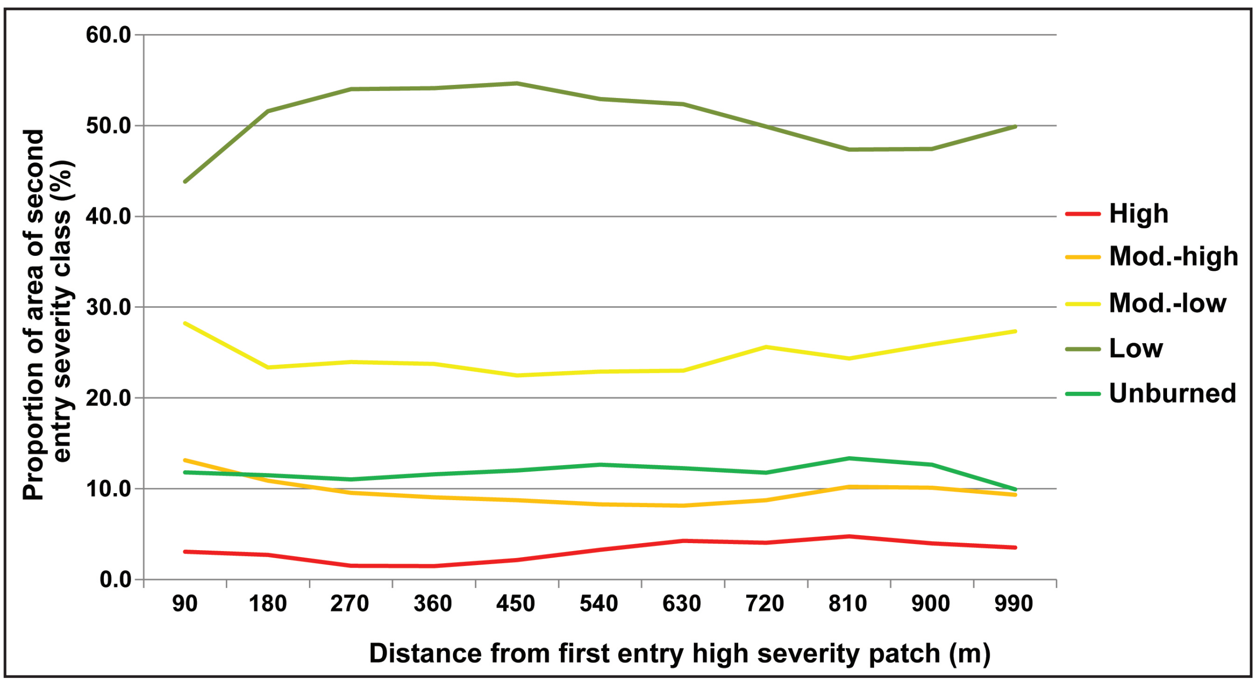

Figure 6. Proportion of area covered by each severity class on second entry, in independently measured, concentric buffers, around first entry high severity patches.

On first entry, many high severity patches were very small. There were 2784 out of 3647 patches that were smaller than 0.5 ha. This caused the mean patch size to be 1.69 ha, even though there was a 1299 ha high severity patch. The standard deviation of 28.1 for the first entry and the standard deviation of 5.48 for the second entry indicate that second entry had patches that were more alike in size. The distribution of the first entry and the combined first and second entry high severity patches were very similar.

High severity patches that were created on initial entry may have gotten aggregated with subsequent patches, resulting in fewer, larger patches than was seen in the original high severity areas. For example, one 91 ha high severity patch in our dataset connected 19 high severity patches from previous fires, and thus created one high severity patch that was 187 ha in size. The number of patches went down, but the area of high severity increased with subsequent fire entry. In a different scenario, a single 42 ha patch connected five patches from a previous fire, but the final patch was only 43 ha. It is unlikely that these five very small (sum = ~1 ha) patches influenced the occurrence of the single 42 ha patch. The increase in area of high severity varied greatly, but was usually small. For example, the largest patch of high severity measured 1299 ha, and the increase in contiguous high severity was 168 ha, due to the subsequent fires.

DISCUSSION

It is important to understand the spatial and temporal scales that are used when doing fire severity analysis. We were constrained in precision by the resolution of the 30 m pixels of the MTBS data, spatially by the administrative boundaries of the North Rim, and temporally by the availability of field calibrated fire severity data (i.e., CBI data for this study are only available from 2000 to 2011). These constraints helped us obtain quality data over an elevation gradient, and they gave us focus, but a longer analysis period would have allowed for stronger temporal inferences. This is especially true in the lower frequency fire regimes, which occur in the higher elevation vegetation types.

We hypothesized that fire severity would affect subsequent fire severity. When we compared the ratios between severity classes, there was evidence that there was less high severity in second entry fires than in first entry fires. This has also been observed in other research (Miller *et al.* 2012, Parks *et al.* 2013). The second entry severity distribution was much like what can be expected from a random patch severity distribution. The quantity agreement and allocation agreement did change along the elevation gradient. These two indices for quantifying the agreement between two maps are currently the standard for comparing spatial datasets. The kappa coefficient has received scrutiny, because it has frequently been used inappropriately (Pontius and Millones 2011). For quality assessment of a map or raster image, a random baseline, which the kappa coefficient is based on, might not be appropriate. But for the comparison of subsequent fire severity, randomness can be used as a baseline, because fire could theoretically occur with a random distribution of severity patches. The low kappa value in this study indicated that the distribution of second entry patches on top of first entry severity patches was close to random. The agreement for the whole study area supported this.

When all forest types were analyzed in one group, close to half of the patches burned with the same severity and the other half was split in close to equal parts between higher and lower severity. This level of agreement was partly a function of the scale of the analysis. When we analyzed the agreement per forest type, different distributions of changes in subsequent severity became evident. The lower agreement found, when going up the elevation gradient, could be caused by the difference in fire regimes found in the ponderosa pine, mixed conifer, and spruce-fir forest types. Differences in vegetation type, which are related to the fire regimes, can help explain changes in severity patch distribution (Collins *et al*. 2007). The large influence of quantity agreement, which is due to the high proportion of low-on-low severity patches, in ponderosa pine forest indicated a low severity fire regime. A high frequency, low severity fire regime has been historically found in this forest type (Covington and Moore 1994, Swetnam and Baisan 1996). In a mixed fire regime, which is found in the mixed conifer and spruce-fir forest types, a lower agreement indicated that fewer patches burned with the same severity on second entry. This can be caused by the greater variation in the distribution of forest structure patches, both temporally and spatially (Agee 2005). A patch that burned with low severity the first time, when mostly surface fuels were consumed, would have unburned fuels that are above the surface, which could be available for consumption during a second entry fire, for example, when the relative humidity is lower or winds are higher. The lower agreement in the spruce-fir forest left more room for disagreement. Here, 59% of the area that burned twice burned with a higher severity. Because the total area that burned twice in 12 years was very small, we cannot infer that this is a trend. In this low frequency fire regime, a longer analysis period would allow for more fire-on-fire interactions and thus a larger dataset to analyze.

The large areas of low-on-low severity patches in both ponderosa pine and mixed conifer forests indicate that low severity fires perpetuate low severity fires (Holden *et al.* 2010, van Wagtendonk *et al.* 2012). The areas of disagreement, caused by the somewhat rare conditions in which high severity occurred on either the first or second entry, are more frequently found in the higher elevations. These forests have a fuel structure that will support high severity fire, but only if conditions are right. These conditions include low relative humidities, high winds, and dry fuels. The variability of these conditions leads a wide spectrum of possible outcomes for fire-on-fire interactions (Collins *et al*. 2007, Teske *et al*. 2012).

The increase in size of high severity patches is a concern for fire managers. If initial high severity patches frequently grow larger due to a more high severity close to the initial patch, unintended ecosystem changes could occur. The proportion of high severity fire from a second entry fire did not appear to be influenced by a high severity patch from an earlier fire. This was indicated by the lack of change in the proportions of high severity on second entry with increasing distance from first entry high severity patches. The threat of increasing patch size does exist, but only happens when conditions for high severity fire are met, and when the fire burns near an existing high severity patch. Without these conditions (e.g., dry, windy, high Energy Release Component), the area surrounding existing high severity patches does not burn at high severity more frequently than places away from these high severity patches.

The initial high severity patches themselves did have slightly more high severity from a second entry than did the surrounding patches, which is similar to the findings of Holden *et al*. (2010). This can be caused by more available fuels in the form of grasses and shrubs that populate an area after an initial high severity fire, such as indicated by van Wagtendonk *et al*. (2012) in Yosemite National Park where chaparral increased after subsequent high severity fires. But this more frequent high severity fire did not extend beyond the initial patches, suggesting that vegetation type conversion is more likely to happen within these patches, but is not more likely to happen in areas surrounding these patches, than elsewhere on the landscape. This is supported by the low allocation agreement, which indicates that high severity on second entry does not depend on the location of high severity on first entry.

The analysis of high severity patches of different entries growing together to form fewer larger patches of high severity supports this as well. Possible causes of this lack of high severity patches growing could include the increase of fuels near the edge of an area that burned with high severity, due to increased availability of nutrients, water, and light. The fuels near the edge could also be drier due to increased wind, higher temperatures, and lower relative humidity. These factors are more important in a mixed conifer forest, where the canopy is likely more dense in areas that burned with a low severity. In ponderosa pine forests, the tree spacing is greater, the canopy less dense, and the micro climate less varied. Thus, the influence of high severity patches on surrounding vegetation is likely greater. Out of the 452 patches of second entry high severity that touched patches of first entry high severity, only 40 patches were larger than 1 hectare. This seems to indicate that, while patches do grow together, the additional area of high severity is small. The second entry makes some patches larger, but also adds smaller patches that do not connect to larger patches. This does not change the overall distribution of high severity patches. High severity patch growth due to subsequent fires is a powerful influence on the landscape, but only in a limited number of areas. While the overall high severity distribution did not change post-second entry fire, infrequent cases of a substantial increase on the individual patch level may contribute to stand-scale changes.

The results from this study can be added to a growing body of literature that investigates the impacts of fire-on-fire interactions in the western US. While the focus of these studies is similar (re-burn), results sometimes differ between study areas or studies. For example, van Wagtendonk *et al*. (2012) found that the proportion of high severity fire increased in reburned areas in Yosemite, while this study showed that the amount of high fire severity in re-burned areas did not increase significantly, overall, on the North Rim of the Grand Canyon. Parks *et al*. (2013) found moderating effects of previous fires on subsequent severity over a 22 year period in the Gila-Aldo Leopold Wilderness Complex in New Mexico, USA, and the Frank Church-River of No Return Wilderness in Idaho, USA. We found this to be true in ponderosa pine forests, but not in higher elevation spruce-fir forests, where higher severities on second entry occurred more frequently. The interaction of multiple fires over space and time is a complex problem, as illustrated by this research and that of others—scientists and managers alike can benefit from the research progress being made in this arena.

ACKNOWLEDGEMENTS

The authors would like to thank the National Center for Landscape Fire Analysis at the University of Montana, and the Grand Canyon National Park fire staff for contributing resources and ideas. We are also grateful to the two anonymous reviewers whose suggestions helped improve the final version of this paper.

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