RESEARCH ARTICLE

BURN SEVERITY OF AREAS REBURNED BY WILDFIRES IN THE GILA NATIONAL FOREST, NEW MEXICO, USA

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ABSTRACT

We describe satellite-inferred burn severity patterns of areas that were burned and then reburned by wildland fire from 1984 to 2004 within the Gila Aldo Leopold Wilderness Complex, New Mexico, USA. Thirteen fires have burned 27 000 hectares across multiple vegetation types at intervals between fires ranging from 3 yr to 14 yr. Burn severity of reburned areas showed sensitivity to the severity of the initial fire. The severity of reburned areas also varied by vegetation type and time elapsed between fires. Initial fires that burned at low severity tended to reburn at low severity, while reburned areas where initial fire was severe showed higher probability of reburning at high severity. Our analysis also suggests that there may be thresholds in the severity of an initial burn above which the severity of the subsequent fire is likely to increase. Because the spectral index used primarily reflects changes in vegetation relative to pre-burn conditions, a large relative change in post-fire vegetation (e.g., shrubs and small trees), as inferred from remotely sensed spectral data, is likely at sites that previously burned at high severity. Field data are needed to fully assess the reburn severity issue, in order to demonstrate that severe reburns may be a relatively new phenomenon occurring outside the historical norm, with potential long-term ecological significance.

Keywords: burn severity, Gila Wilderness, New Mexico, wildland fire use

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INTRODUCTION

Millions of dollars are spent annually in the United States on fuels reduction treatments aimed primarily at reducing the intensity and severity of wildfires. Mechanical thinning, prescribed burning, and both in combination are used to reduce tree densities and decrease surface fuel loading that have increased in many forest types as a consequence of land use changes and decades of fire exclusion. Annual area burned has increased on forested lands in the western US (Westerling *et al*. 2006), a trend that could increase if projected warming and drying of the southwestern US occurs.

The size and extent of ecologically significant wildfires makes extensive, detailed ground-based assessments of post-fire ecological effects difficult or impossible (Lentile *et al*. 2006). Landsat satellite imagery is often employed as a tool for mapping post-fire effects and area burned. Spectral indices known as the differenced Normalized Burn Ratio and the Relative differenced Normalized Burn Ratio (Miller and Thode 2007) are commonly used for assessing the magnitude of fire-induced ecological change using pre-fire and post-fire images. Moderate and coarse-resolution sensors, which scan from above, are limited in their ability to detect below-canopy change in forested environments. Thus, while Landsat-derived vegetation indices often capture overstory changes in live vegetation quite well, their ability to quantify fire effects on understory and soils is less certain and may depend on pre-fire and post-fire canopy cover. Throughout this study, we use the term burn severity to indicate the magnitude of change in overstory vegetation one year post-fire relative to pre-fire conditions. This clarification is particularly important in the evaluation of reburned areas where the quantity and type of vegetation at burned sites, in the absence of field data, are uncertain.

An overarching goal within the fire science and management community is to restore natural fire regimes, where feasible, to forests in which the fire regime has degraded due to land use change and fire exclusion. Such restoration is particularly important in the southwestern US, where frequent surface fires, once a dominant ecological process in many southwestern vegetation types, have been significantly disrupted by decades of fire suppression (Allen *et al*. 2002). Beginning in the early 1970s, some wilderness areas began managing some fires under a program whereby naturally ignited fires were allowed to burn when human life and property were not threatened and adequate resources were available should fire suppression be required (van Wagtendonk 2007). The terminology describing such fires has evolved considerably over the last few decades (van Wagtendonk 2007); for convenience, we use Wildland Fire Use (WFU) throughout this paper. Fires have burned extensive areas repeatedly throughout the twentieth century in the Gila Aldo Leopold Wilderness Complex (GALWC) within the Gila National Forest (GNF), including hundreds of fires since 1974, making this area a rich source of information on the ecological effects of past fires as well as trends in fire extent and severity patterns over time. As of 2010, extensive areas of the GNF have burned and reburned, allowing us to ask if those areas have burned more or less severely as inferred from the time series of Landsat satellite images.

In wilderness areas, where mechanical treatments are generally prohibited, the question of how wildfires interact with past ecological processes (e.g., insect outbreaks and past wildfires) is an important and emerging topic in fire ecology and management. The spatial distribution and patterns of fire on the landscape could serve to limit the spread and intensity of subsequent wildfires. However, few studies have examined the ecological effects or severity of repeated wildfires (Holden *et al*. 2008, Collins *et al*. 2009). The objective of this study was to quantify the extent and severity of areas that have reburned from 1984 through 2004. In this descriptive analysis, we explored how the severity of an initial burn influences the severity of subsequent fires, and how vegetation type and length of time between fires influence interactions between the initial burn and reburns. Insights gained into these questions using historical satellite imagery can help guide needed field assessments to better elucidate the long-term ecological consequences of severe reburns in the potentially changing fire regime of the southwestern USA.

METHODS

Study Area

Data for this study come from the 200 000-hectare GALWC, located within the GNF, New Mexico, USA (Figure 1). The GNF supports diverse vegetation types ranging from pinyon (*Pinus* L.)-juniper (*Juniperus* L.) woodlands between 1500 m and 2000 m in elevation, to mixed-conifer and spruce (*Picea* A. Dietr.)-fir (*Abies* Mill.) forests that occur between 2600 m and 3300 m in elevation. Many of the fires included in this study burned in the central and northern portion of the GALWC, where extensive stands of ponderosa pine (*Pinus ponderosa* C. Lawson) and mesic ponderosa pine-Douglas-fir (*Pseudotsuga menziesii* [Mirb] Franco) forests occur on broad, flat mesas (Rollins *et al*. 2002). Historically, these vegetation types tended to burn frequently (on average every 3 yr to 11 yr [Swetnam 1983]). Fires occurred less frequently in higher elevation mixed-conifer and spruce-fir forests (Abolt 1996). Precipitation is bimodal in the southwestern USA, falling as snow in the winter in upper elevations, and as summer monsoonal rain that arrives, on average, around the first week of July (Sheppard *et al*. 2002).

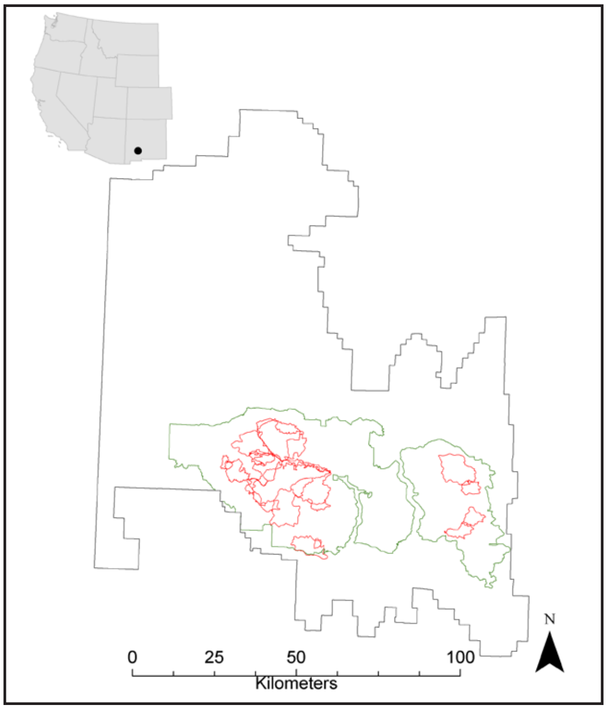

Figure 1. The Gila National Forest boundary (black), the Gila-Aldo Leopold Wilderness Complex boundary (green), and areas of overlapping fires (red).

Satellite Imagery Data

We used pre- and post-fire satellite imagery and the Relative differenced Normalized Burn Ratio (RdNBR) (Miller and Thode 2007) to map 114 fires on the GNF from 1984 through 2004. The RdNBR is a modified version of the differenced Normalized Burn Ratio (Key and Benson 2005) that accounts for the relative amount of pre- to post-fire change by dividing the dNBR by the pre-fire NBR value. Ten different fires burned in the GALWC that were subsequently reburned by six different wildfires 3 yr to 14 yr later (Table 1), with a total of 27 000 hectares reburned. We identified areas of overlap between first and second fires and extracted RdNBR pixels from one-year post-fire images. Each pixel was assigned a “time since fire” value based on the number of growing seasons that elapsed between fires.

We used both unclassified and classified RdNBR data to describe patterns of reburn severity relative to the initial burn severity. Classification of continuous RdNBR required somewhat subjective calls about where to define thresholds between burn severity classes.

Table 1. Name and year of first and second wildfires 1984 through 2004, with the proportion of the first fire reburned by the second fire and years elapsed between those fires.

	First fire		Second fire		
Percent area reburned	**Name**	**Year**	**Name**	**Year**	**Years between fires**
100	Mogollon	1984	Lookout	1996	12
100	Shelley	1989	Unknown	1997	8
23	Divide	1989	Morgan	2003	14
100	Unknown	1992	Cub	2002	10
40	Brushstraw	1993	Lookout	1996	3
18	Brushstraw	1993	Lilley	1997	4
39	Brushstraw	1993	Dry Lakes	2003	10
12	Pigeon	1994	Dry Lakes	2003	9
100	Granite	1995	Dry Lakes	2003	8
24	Lookout	1996	Dry Lakes	2003	7
10	Langstroth	1997	Cub	2002	5
16	Langstroth	1997	Dry Lakes	2003	6
09	Lilley	1997	Dry Lakes	2003	6

Following methods described by Holden *et al*. (2009), RdNBR pixels were grouped into low, moderate, and high severity classes using Composite Burn Index field data to define breakpoints between classes. The RdNBR values of less than 225 were classified as low severity, and RdNBR values 665 or greater were classified as high severity. Because the percentages of unburned, low, moderate, and high severity classes necessarily sum to unity, these are not independent classes. For this reason, and for brevity, we focus our interpretation of the results on the high severity (severe) class.

Data Analysis

The data we used in this natural experiment represented all reburned 30 m pixels during the 20 yr period from 1984 to 2004. We treated the data as a census rather than sampling the data, and presented frequency histograms of reburn severity stratified by vegetation type, severity class of initial burn (low, moderate, and high), and time since fire. We stratified reburn severity data using a potential vegetation type (PVT) layer developed specifically for the GNF by Keane *et al*. (2000). The PVT is a classification of sites named for the vegetation likely to occur on a site in the absence of fire. Eight PVT classes were initially produced for the GNF. These included riparian, grassland, shrub, pinyon-juniper, ponderosa pine, Douglas-fir, mixed conifer, and spruce-fir. We excluded all non-forested vegetation types. We then combined data for ponderosa pine and Douglas-fir PVT types together and mixed conifer and spruce-fir types together. This was done to increase the sample size of pixels included in each PVT group, which were very low for the Douglas-fir and spruce-fir PVT types.

Conditional probability (CP) plots were generated using classified binary RdNBR grids (i.e., low vs. other, moderate vs. other, and high severity vs. all other severity classes). We used CP plots to describe the probability of a previously burned area reburning at a given severity, conditional on the severity of the first fire (Aspinall 1992). Reburned pixels were first separated into three classes of low, moderate, and high (reburn) severity. Then, the initial burn severity of fires within each of the three reburned groups was classified into 20 equal interval classes of the RdNBR. The CP plots provided a means of addressing the question: Given the proportion of area reburned in which initial fire severity burned at a particular severity, what is the conditional probability of that area reburning as low, moderate, or high severity?

RESULTS

Histograms of RdNBR pixels in reburned areas stratified by initial burn severity class and PVT type are shown in Figure 2. The percentage of reburned areas classified as high severity and stratified by PVT and initial fire severity class are listed in Table 2. Reburn severity showed some sensitivity to the severity of the initial wildfire. Low severity reburns were more likely when the prior fire had burned with low severity, while the RdNBR distribution shifts toward high severity when the initial fire severity was high (Figure 2). High severity reburn occurred with greater frequency in moist vegetation types (Figure 2). High severity reburn also occurred with greater frequency in moist vegetation types when there were more years between reburn and prior burn (Figure 3). Low severity reburn was more likely than expected when the severity class of an initial fire was low (Figure 4A). The probability of moderate and high severity reburn was higher than expected when the initial fire burned with a moderate or high initial severity (Figures 4B and 4C), with high severity reburn being more likely than expected when the initial RdNBR was 407 or greater (Figure 4C).

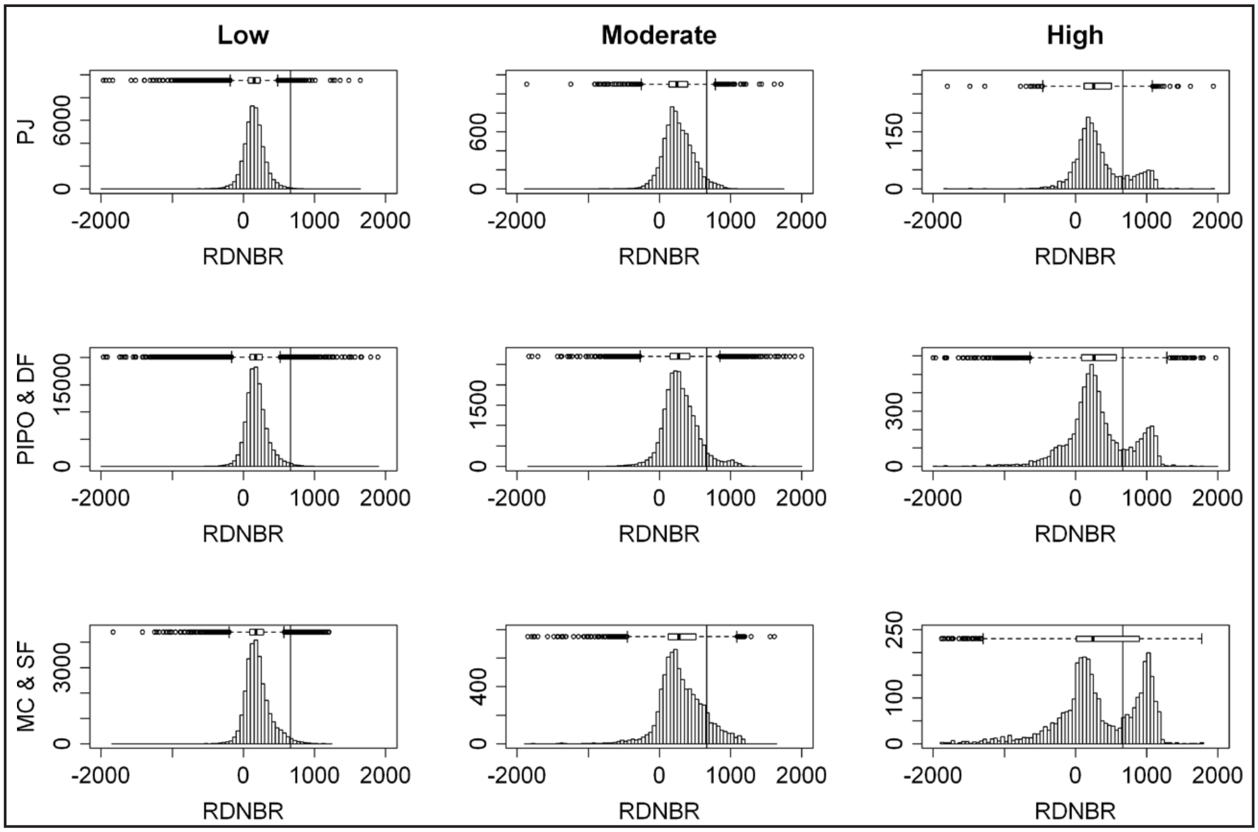

Figure 2. Reburn severity distributions stratified by low, moderate, and high burn severity of previous fire. Distributions are shown by PVT group along the y-axis. PJ denotes pinyon-juniper PVT. Ponderosa pine and Douglas-fir (PIPO & DF) are grouped together. Mixed-conifer and spruce-fir (MC & SF) PVTs are grouped together. Vertical line in each plot represents high severity threshold (RdNBR = 665).

Table 2. Percent of reburned area classified as high severity stratified by initial burn severity class and by PVT. Total % (all classes) indicates the total area reburned as high severity across all initial burn severity classes within each PVT.

	Low	**Moderate**	**High**	
Initial severity	**Percent severe reburn by class**			**Total % (all classes)**
Pinyon – juniper	0.004	0.17	0.19	0.035
Ponderosa pine – Douglas-fir	0.011	0.06	0.22	0.047
Mixed conifer – spruce-fir	0.019	0.13	0.35	0.085

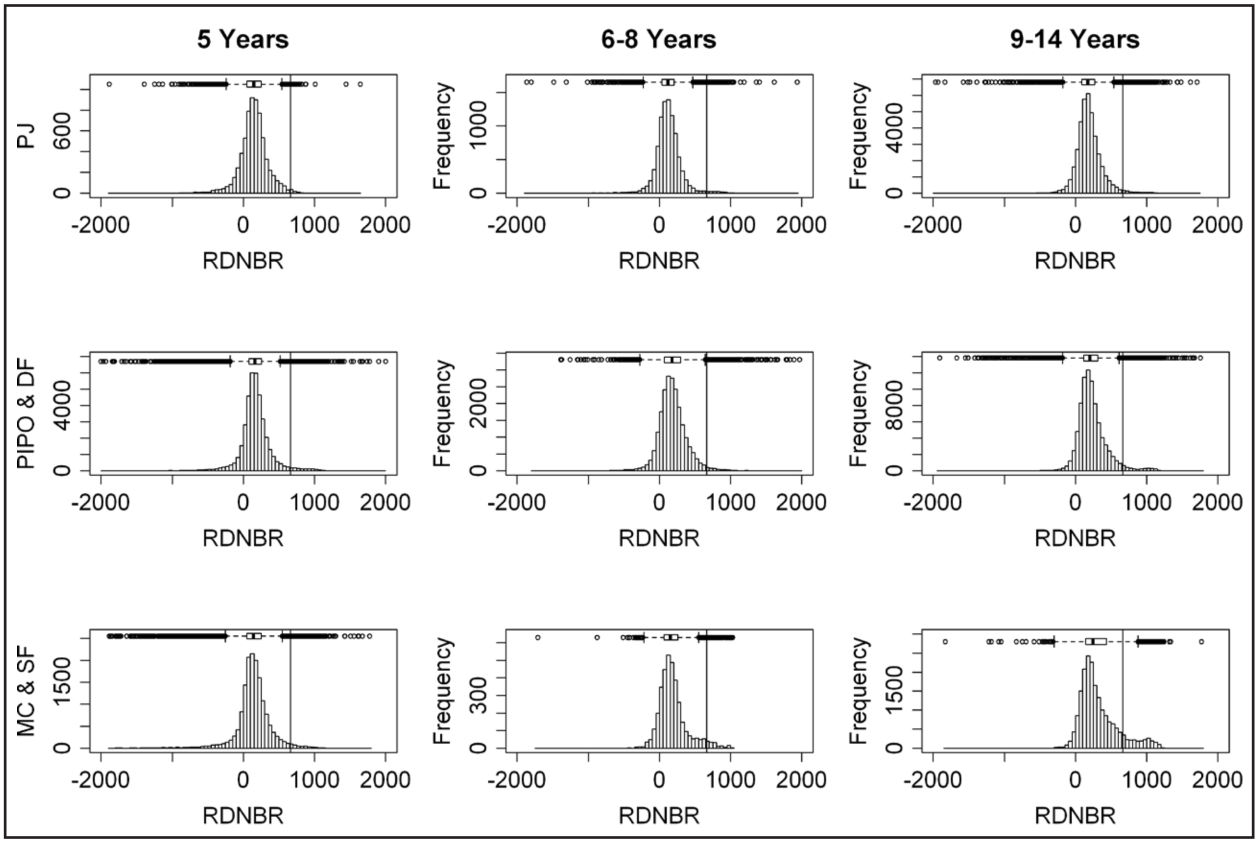

Figure 3. Reburn severity distributions stratified by years between initial burn and reburn. Distributions are shown by PVT groups along the y-axis. Ponderosa pine and Douglas-fir (PIPO & DF) are grouped together. Mixed-conifer and spruce-fir (MC & SF) are grouped together. Vertical line in each plot represents high severity threshold (RdNBR = 665).

DISCUSSION

During field visits in 2003 and 2004, we observed that some reburns were dominated by grass and forbs with patchy ponderosa pine regeneration at some sites, while others were dominated by Gambel oak (*Quercus gambelii* Nutt.). When these areas reburn, shrubs, grasses and forbs are likely to be top-killed by fire. With enough vegetation accumulation following the initial stand-replacing fire, the relative change in vegetation caused by the second burn would be sufficient to be classified as high severity by the RdNBR. Although the relative magnitude of change inferred from the difference in the post-fire dNBR relative to the

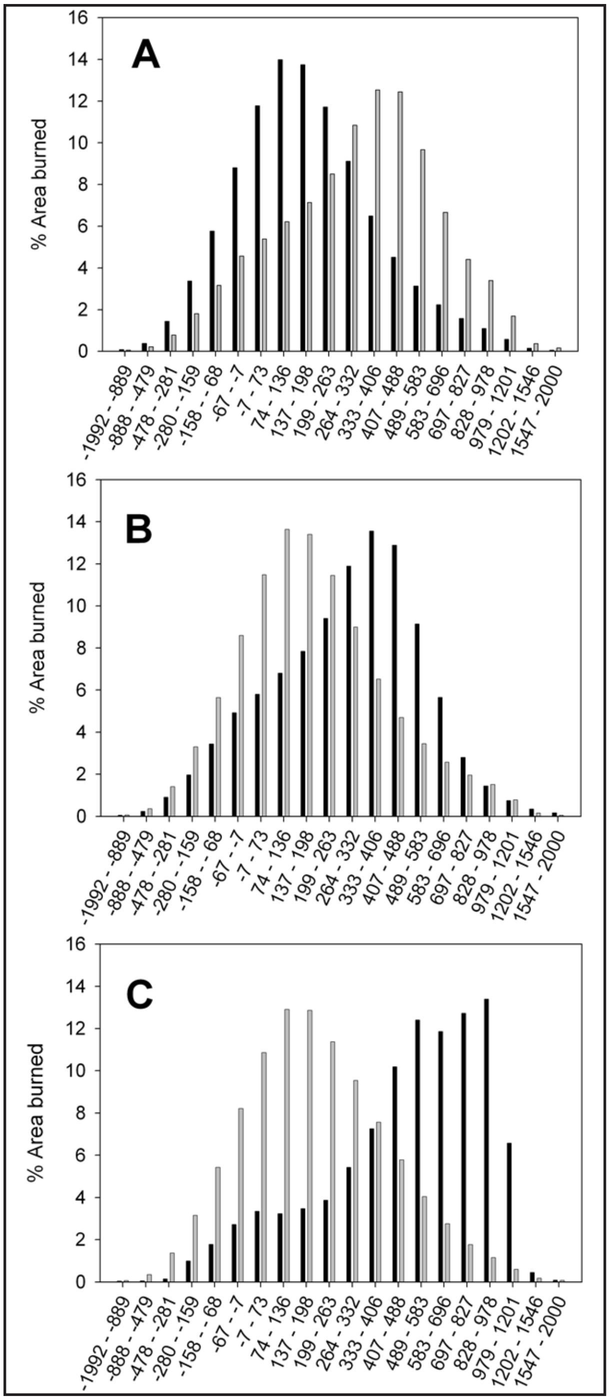

Figure 4. Conditional probability plots showing probability of (A) low severity reburn (B), moderate severity reburn, and (C) high severity reburn relative to 20 initial burn severity classes of RdNBR. Black bars represent the proportion of reburned area in a given reburned class (e.g., severe reburn in figure 4C) relative to the total area burned within an initial burn severity class (represented by gray bars). Where black bars are higher than gray bars, the probability of reburn is greater than expected, given the amount of that initial burn severity class present.

pre-fire dNBR could be high, it is difficult to infer much about magnitude of ecological change associated with that second fire. Heavy fuel loading associated with tree mortality in the initial fire could heat the soil during a second wildfire, although these effects would be difficult to infer using the spectral indices employed here because they are likely less spectrally detectable.

Reburn potential is likely limited by fuel and vegetation consumption by an initial fire and, secondarily, by the accumulation of surface fuel and vegetation prior to reburning. These factors in turn are driven by the amount of time between burns and site productivity. In the assembly of this dataset, we observed several places where fires appeared to burn out when they encountered another recent fire, presumably because of insufficient surface fuel accumulation since the initial fire.

Overall, these results suggest that low severity wildfires in the GALWC tend to maintain low-severity surface fire characteristics in the reburned areas evaluated during the 20 yr period of this analysis. This is consistent with what is known about fire regimes in dry forest types in the Southwest (Allen *et al*. 2002). Even areas for which initial severity was classified as moderate or high using satellite imagery data tended to reburn at predominantly low severity. However, these results also suggest the potential for wildfires to create fuel loading and vegetation characteristics that promote moderate and high burn severity characteristics when subsequent wildfires occur. Precise mechanisms for these changes are impossible to infer without extensive field data. However, we speculate that crown scorch could increase surface fuel loading that would in turn increase potential for a severe reburn, while tree mortality could create ladder fuels that would increase crown fire potential.

In conclusion, we described patterns in satellite-inferred measures of burn severity in areas burned and then reburned by wildfires in the Gila National Forest, New Mexico, USA.

High severity reburn occurred more frequently where the severity of a first fire was high, and in mesic high-elevation forest types. The length of recovery time and site characteristics that influenced moisture availability also influenced the satellite-inferred severity of reburned areas. However, burn severity data inferred from satellite imagery must be interpreted carefully. Because spectral indices like the dNBR and RdNBR are mainly sensitive to fire-induced vegetation change, the amount of vegetation that is present and then removed largely determines the RdNBR value, and hence the "burn severity" inferred at that location. Field-based studies combined with analysis of post-fire trends in satellite indices will be needed to improve our understanding of the potential ecological changes at locations that experience multiple burns.

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LITERATURE CITED

Abolt, R.A. 1996. Surface and crown fire histories of upper elevation forests via fire scar and stand age structure analyses. Thesis, University of Arizona, Tucson, USA.

Allen, C.D., M. Savage, D.A. Falk, K.F. Suckling, T.W. Swetnam, T. Schulke, P.B. Stacey, P. Morgan, M. Hoffman, and J.T. Klingel. 2002. Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12(5): 1418-1433. doi: 10.1890/1051-0761(2002)012[1418:EROSPP]2.0.CO;2

Aspinall, R. 1992. An inductive modelling procedure based on Bayes' theorem for analysis of pattern in spatial data. International Journal of Geographical Information Systems 6(2): 105-121. doi: 10.1080/02693799208901899

Collins, B.M., J.D. Miller, A.E. Thode, J.W. van Wagtendonk, and S.L. Stephens. 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

Holden, Z.A., P. Morgan, and S.J. Evans. 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

Holden, Z.A., P. Morgan, M.G. Rollins, and K.K. Kavanagh. 2008. Effects of multiple fires on stand structure in two southwestern wilderness areas, USA. Fire Ecology 3(2): 18-33. doi: 10.4996/fireecology.0302018

Keane, R., S.A. Mincemoyer, K.M. Schmidt, D.G. Long, and J. Garner. 2000. Mapping vegetation and fuels for fire management on the Gila National Forest complex, New Mexico. USDA Forest Service General technical Report GTR-RMS-046, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Key, C.H., and N.C. Benson. 2004. Landscape Assessment (LA) sampling and analysis methods. Pages LA1-LA55 in: D.C. Lutes, R.E. Keane, J.F. Caratti, C.H. Key, N.C. Benson, S. Sutherland, and L.J. Gangi. 2006. FIREMON: Fire effects monitoring and inventory system. USDA Forest Service General Technical Report RMRS-GTR-164CD, Rocky Mountain Research Station, Fort Collins, Colorado, USA.

Lentile, L.B., Z.A. Holden, A.M.S. Smith, M.J.Falkowski, A.T.Hudak, P. Morgan, S.A. Lewis, P.E. Gessler, and N.C. Benson. 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. International Journal of Wildland Fire 15: 319-345. doi: 10.1071/WF05097

Miller, J.D., and A.E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ration (dNBR). Remote Sensing of Environment 109: 66-80. doi: 10.1016/j.rse.2006.12.006

Rollins, M.G., P. Morgan, and T.W. Swetnam. 2002. Landscape-scale controls over twentieth century fire occurrence in two large Rocky Mountain (USA) wilderness areas. Landscape Ecology 17: 539-557. doi: 10.1023/A:1021584519109

Sheppard, P.R., A.C. Comrie, G.D. Packin, K. Angersbach, and M.K. Hughes. 2002. The climate of the US Southwest. Climate Research 21: 219-238. doi: 10.3354/cr021219

Swetnam, T.W. 1983. Fire history of the Gila wilderness, New Mexico. Thesis, University of Arizona, Tucson, USA.

van Wagtendonk, J.W. 2007. The history and evolution of wildland fire use. Fire Ecology 3(2): 3-17. doi: 10.4996/fireecology.0302003

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increases western US wildfire activity. Science 313: 940-943. doi: 10.1126/science.1128834