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Fire season precipitation variability influences fire extent and severity in a large southwestern wilderness area, United States

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[1] Despite a widely noted increase in the severity of recent western wildfires, this trend has never been quantified. A twenty-year series of Landsat TM satellite imagery for all forest fires on the 1.4 million ha Gila National Forest suggests that an increases in area burned and area burned severely from 1984–2004 are well correlated with timing and intensity of rain events during the fire season. Winter precipitation was marginally correlated with burn severity, but only in high-elevation forest types. These results suggest the importance of within-season precipitation over snow pack in modulating recent wildfire size and severity in mid-elevation southwestern forests. **Citation:** Holden, Z. A., P. Morgan, M. A. Crimmins, R. K. Steinhorst, and A. M. S. Smith (2007), Fire season precipitation variability influences fire extent and severity in a large southwestern wilderness area, United States, *Geophys. Res. Lett.*, *34*, L16708, doi:10.1029/2007GL030804.

1. Introduction

[2] Wildfires burned more than 3.9 million hectares in the United States in 2006, the largest area since records began in 1960, highlighting a recent trend toward increasing fire activity in the western US (http://www.nifc.gov). Despite a widely perceived increase in the severity (generally defined as the magnitude of ecological change caused by a fire) of fires in the western US, we have previously lacked datasets describing burn severity trends and their association with regional and global climate patterns. Understanding the causes and consequences of severe fires is particularly important in the southwestern US, where disruption of natural fire cycles in dry forests and land use change have altered their structure and resulting fire behavior and effects [*Allen et al.*, 2002; *Covington*, 2000]. Severe, stand-replacing fires may lead to high post-fire erosion [*Cannon and Reneau*, 2000], alter ecosystem function and are difficult to manage or suppress [*Pyne et al.*, 1996].

[3] Numerous studies have described general relationships between regional climate patterns and historical fire extent in the western US. Dendroecological studies of surface fire regimes in dry pine forests in the northern Rocky Mountains and the southwestern US have noted that fewer and relatively smaller fires are detected during regionally wet years, and more larger fires are detected during dry years [*Heyerdahl et al.*, 2002; *Schoennagel et al.*, 2004]. Historically, wet winters and springs followed by dry years may have increased fine fuel production necessary to carry large fires [*Swetnam and Betancourt*, 1998, 1990]. More recently, fire occurrence databases have been used to establish links among early, warm spring temperatures, timing of snow melt and the recent increase in forest fire extent across federally managed lands in the western US [*Westerling et al.*, 2006].

[4] In the southwestern United States, weather patterns vary widely across annual and multi-decadal time scales and strongly influence the southwestern US fire season. Multi-year to interdecadal regional droughts have been shown to be associated with the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) from the 1900s to present [*McCabe and Dettinger*, 1999; *McCabe et al.*, 2004]. Based on these historical patterns, climatologists predict that alignment of the negative (La Niña) phase of the ENSO and a positive phase of the PDO may create a prolonged period of intense drought in the southwestern US [*McCabe et al.*, 2004]. Climate models predict increasing aridity across the southwestern US as global climate warming alters patterns of the North American monsoon [*Seager et al.*, 2007]. Both of these studies highlight potential climate patterns that will likely influence fire activity in the southwestern US. However, we lack a thorough understanding of the role of natural climate variability as well as the potential role of current and future climate change on fire activity in this region.

[5] Here, we present the first temporal analysis of satellite-derived trends in burn severity for 114 fires that burned 195,600 ha within 1.4 million ha encompassing the Gila Aldo Leopold Wilderness Complex and surrounding National Forest (Figure 1). This un-logged wilderness area has been ungrazed for the last 60 years and is an ideal area in which to study fire patterns, where many large, naturally ignited fires have been allowed to burn with a minimum of management or suppression activities. The term burn severity has been used to describe a variety of post-fire ecological effects, and can therefore be misleading [*Lentile et al.*, 2006]. To avoid such confusion, we define severity specifically as the magnitude of change in overstory vegetation measured one year after a fire relative to the pre-burn conditions.

[6] This unique data set, while sub-regional in scale, provides spatially explicit information about fire perimeters and the post-fire ecological effects within burned areas. Importantly, this data can be combined with archives of seasonal weather patterns to understand linkages between intra-annual climate and fire. In this study, we compared

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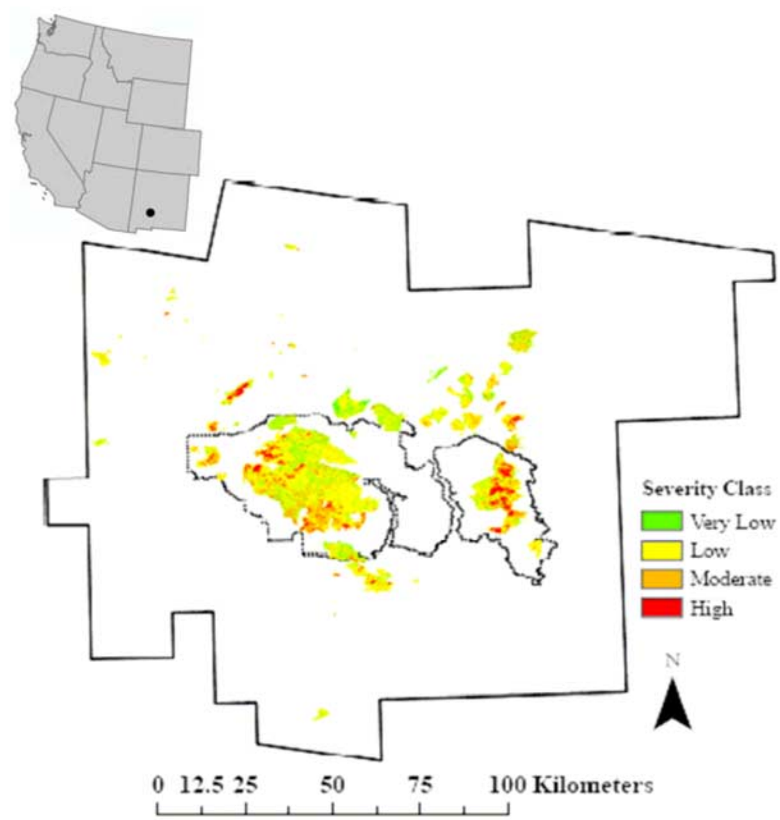

Figure 1. Burn severity atlas of 114 fires and 195,600 ha burned (1984–2004) on the Gila National Forest. Outer perimeter delineates the Gila NF boundary, inner perimeter the Gila and Aldo Leopold wilderness complex.

annual area burned and area burned within four severity classes with snow pack and precipitation metrics from a snow pack telemetry (SNOTEL) site and a daily surface climate station located within the Gila NF.

2. Methods

[7] A time series (1984–2004) of summer Landsat 5 Thematic Mapper (TM) satellite images were used to create burn severity maps for all fires greater than 40 ha on the Gila National Forest, NM (Figure 1). Hundreds of fires have burned as wildland fire use fires (WFU) in the Gila Aldo Leopold Wilderness Complex, New Mexico (GALWC) and surrounding National Forest since the program was implemented there in 1974. Pre and post-fire satellite images for 114 fires (total area burned = 195,600 ha) were processed using the Relative Differenced Normalized Burn Ratio (RdNBR) [*Miller and Thode*, 2007]. The RdNBR is a variant of the Differenced Normalized Burn Ratio (dNBR) [*Key and Benson*, 2006], devised to improve performance in open vegetation types by dividing the dNBR by a pre-fire NBR value. Perimeters of each fire were manually digitized using both the RdNBR index image and the reflectance-corrected Landsat images.

[8] 109 ground based Composite Burn Index (CBI) plots [*Key and Benson*, 2006] were collected in 2004 on the 2003 Dry Lakes Fire Complex in the Gila Wilderness. The CBI is a measure that combines 23 ocular estimates, including overstory and understory vegetation consumption, scorch and fuel consumption. We refined our final CBI estimates for each plot by removing several measures (e.g. change in soil color) that were too subjective to be accurately estimated post-fire. Linear correlations between ground plots and the RdNBR image of that fire ($r^2 = 0.78$) were used to define severity thresholds for all fires from 1984–2004 on the Gila NF. A classification of "severe" was assigned to areas where 75% or more of overstory vegetation was removed. RdNBR index images for each fire were classified into 4 classes (very low, low, moderate and high severity), which were used in subsequent analyses.

[9] Three, six and twelve month instrumental Palmer Drought Severity Index (PDSI) data [*Cook et al.*, 2004] and historical precipitation data from the Gila Hot Springs climate station (Elevation 1768 m; central to areas where most fires have occurred) were obtained from the National Climate Data Center (http://www.ncdc.noaa.gov). Daily precipitation data from each station were used to calculate the total number of days without rain (TNR), the maximum consecutive number of days without rain (MNR) and total

Table 1. AIC Model Selection Results for MANOVA Models

Model	AIC	ΔAIC
Y ~ PVT + PCP + SWE	9508	179.4
Y ~ PVT + MNR + TNR	9423	94.4
Y ~ PVT + MNR + TNR + PRCP	9370	41.4
Y ~ PVT + MNR + TNR + PCP + PDSI6 + SWE	9332.6	4.0
Y ~ PVT + MNR + TNR + PCP + SWE	9328.6	0

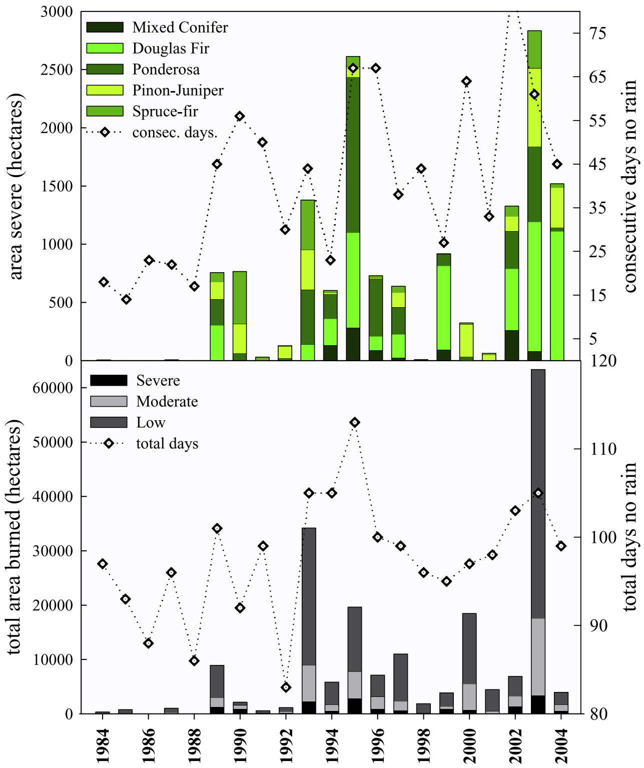

Figure 2. (top) Annual area burned as severe grouped by Potential Vegetation Type and (bottom) total area burned in all severity classes. The dotted lines represents the maximum number of consecutive rain-free days and the total rain free days from 01 April to 15 July.

precipitation (PCP) from 1 April to 15 July from 1984–2004. Snow water equivalent data from February–April (SWE) were obtained from the Lookout Mountain snow pack telemetry (SNOTEL) site located within the Gila NF.

3. Data Analysis

[10] Multiple analysis of variance (MANOVA) was used to evaluate the influence of climate variables on total area burned in each burn severity class. Area burned as very low, low, moderate and high severity was calculated from classified burn severity maps for all fires by year. Residuals of burn severity data were normally distributed. Area burned in each severity class was treated as a multivariate response variable. TNR, MNR, PCP, SWE and three month, six month and annual instrumental Palmer Drought Severity Index data were used as independent variables. Potential Vegetation Type (PVT), defined as the dominant vegetation expected at a site after long periods without any disturbance, was included as an independent blocking variable. The PVT layer used in this study was developed by *Keane et al.* [2001] after extensive field data collection and ground validation. The Akaike Information Criteria (AIC) was used to select statistical models that best explained variation in area burned in each severity class [*Akaike*, 1974] (Table 1). Canonical analysis was used to evaluate the relationship between the original dependent variables and the canonical variates [*Johnson and Wichern*, 2002].

4. Results

[11] Total area burned and total area burned severely increase over the 20-year period for which imagery are available (Figure 2). Because this is a short time series that begins during a relatively wet period, we interpret any apparent trends with caution. Annual area burned and area severely burned are best explained by variability in the frequency and intensity of springtime rain events (Figure 3). Area severely burned each year is well correlated with TNR and MNR, which together explain 63% of the variability. Linear models of area severely burned within individual Potential Vegetation Types (PVT) show that SWE is only a marginally significant predictor in upper elevation spruce-fir forest types ($p = 0.055$) and mixed conifer forest types ($p = 0.062$) but not in lower elevation Douglas fir, ponderosa pine, and Pinyon-juniper vegetation types.

5. Discussion and Conclusions

[12] Variability in timing and intensity of precipitation (days without rain and maximum consecutive days without rain) during the fire season in the southwestern US strongly influences the extent and severity of fires across the Gila NF. Canonical analysis reveals that while the significance of TNR (a measure that describes the overall dryness of the spring and early summer fire season) is related to area burned in all severity classes (including the very low and low classes which contain more than 90% of the area burned), MNR is related mainly to area burned severely. This intuitive result suggests that longer rain-free periods may increase the likelihood that a fire will burn as a high severity crown fire, a reflection of increasingly dry live and dead fuels. However, while many of the fires analyzed in this study were allowed to burn as wildland fire use fires with minimal suppression, management decisions from year-to-year (e.g. whether to suppress some fires) likely influenced the annual area burned, and as a consequence, area within each severity class.

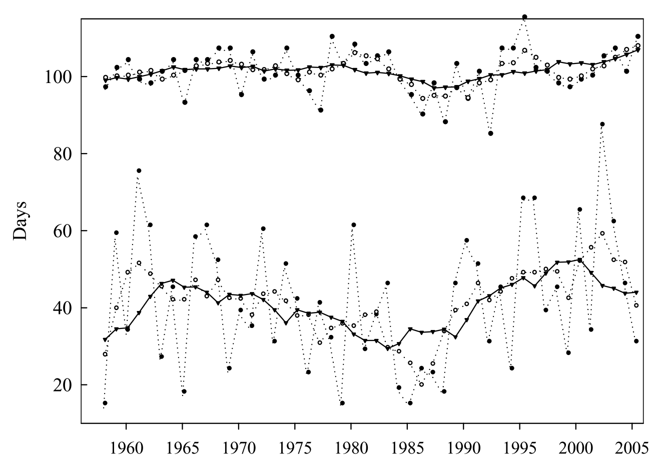

Figure 3. Annual, 5 and 10 year running average maximum number of consecutive days without rain (bottom line) and total number of days without rain (top line) from 01 April to 15 July for Gila Hot Springs (1958–2005).

[13] While snow-pack is a significant variable in statistical models, univariate analysis of extent and severity within the individual vegetation types reveal that snow pack in this study only marginally influences fire extent and severity in upper elevation (spruce-fir and mixed conifer) forest types but lacks significance in other forest types. SNOTEL station data shows that snow rarely persists after March below 2600 m, where most fires in this area have occurred, suggesting that burning in mid-elevation ponderosa pine and pinyon-juniper vegetation types during the last 20 years occurred independently of winter precipitation. This is most likely due to the climatologically warm and dry conditions that persist across the region each spring [*Sheppard et al.*, 2002]. Winter precipitation patterns across the Southwest are known to be influenced by the El Niño -Southern Oscillation (ENSO) with the cold phase (La Niña) favoring drier-than-average conditions while the warm phase (El Niño) favors wetter-than-average conditions [*Sheppard et al.*, 2002]. Several dry winters associated with La Niña events followed by increased burning in spruce-fir and mixed-conifer forest types are observed within the study period, but the overall relationship between winter precipitation and fire extent and severity is very weak.

[14] The causes and consequences of stand-replacing wildfires have been the subject of intense scientific and political debate [*Allen et al.*, 2002]. Such high severity fires were thought to have been relatively uncommon historically in ponderosa pine forests of the southwestern US, which cover 29% of the area burned during the 20 years included in this study. Land management and climatic trends have both been proposed to explain the recent increase in fire activity in the western United States [*Running*, 2006; *Westerling et al.*, 2006]. Our results suggest that an alternative mechanism to early snowmelt may play a role in the observed trend toward larger more severe fires in ponderosa pine forests of the southwestern US. Our analysis of fire season precipitation patterns shows increasingly dry springs during last 20 years, including an increase in the total and consecutive number of days without rain, which provide longer periods of weather favorable for fire activity. Whether this variability is associated with trends in the Pacific Decadal Observation (PDO) [*Mantua et al.*, 1997], Pacific and Atlantic SST teleconnections, or shifting precipitation patterns associated with global climate warming [*Seager et al.*, 2007] is unclear. Further analysis using regional datasets will be necessary to determine how spring precipitation patterns vary across the Southwest and whether its influence on fire activity is a regional rather than just a localized phenomenon. However, preliminary analysis of climate station data from other parts of Arizona and New Mexico shows similar patterns in spring dryness during the last two decades. These data also reveal similar increases in spring precipitation variability during past dry periods, suggesting that the localized variability in precipitation observed in this study might be a natural oscillation related to regional and global climate patterns (Figure 3). Therefore, controls on transitional springtime and early summer precipitation patterns in this region warrant further study.

[15] Previous fire history studies based on tree ring data have shown the importance of winter precipitation associated with ENSO [*Swetnam and Betancourt*, 1990]. While it is difficult to compare short satellite-based records with longer but non-spatially explicit tree ring studies, our results may contradict these earlier findings. Precipitation limits productivity in arid ecosystems and it is likely that winter snow pack, typically a much larger component of the annual water budget in the Southwest, masks any signal in tree growth associated with springtime precipitation. In our study, snow pack influenced the extent and severity of fires burning in upper elevation forest types. Such conditions (dry winters coupled with dry springs) would have promoted the regionally extensive fire years observed in these earlier studies, though we can say little about how severe these fires may have been.

[16] We can also speculate that the recent trends in fire activity described in our study reflect the changes that fire regimes have undergone during the last century across much of the southwestern US. Prior to suppression and exclusion, fires burned synchronously across extensive areas of the Southwest during regional dry periods. Given consecutive years of regionally widespread fire activity, lack of fine fuels would have become the primary factor limiting fire spread. While the importance of antecedent climate on fine fuel production and fire activity will vary by vegetation type, dry pine forests in the Southwest today are generally not fuel limited. With tens of millions of hectares unburned for decades, fine fuels are abundant. Some dense forests with thick layers of needles and duff no longer maintain grassy understories and hence do not produce abundant fine fuels in response to wet antecedent conditions. Only dry fuels and ignition are necessary for fires to burn under these conditions. Given these changes, it seems likely that precipitation rather than fine fuels and biomass production now influence fire activity in dry pine forests in the southwestern US. Further research is needed to evaluate the degree to which patterns in spring season dryness observed during the last 20 years can be observed in the tree ring record. Similar analyses of burn severity time series data for other areas will elucidate the extent to which recent climate warming versus natural climatic variability may be influencing recent burn severity in the western US.

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