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Climate relationships with increasing wildfire in the southwestern US from 1984 to 2015

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ABSTRACT

Over the last several decades in forest and woodland ecosystems of the southwestern United States, wildfire size and severity have increased, thereby increasing the vulnerability of these systems to type conversions, invasive species, and other disturbances. A combination of land use history and climate change is widely thought to be contributing to the changing fire regimes. We examined climate-fire relationships in forest and woodland ecosystems from 1984 to 2015 in Arizona and New Mexico using 1) an expanded satellite-derived burn severity dataset that incorporates over one million additional burned hectares when compared to MTBS data, and 2) climate variables including temperature, precipitation, and vapor pressure deficit (VPD). Regional climate-fire relationships were assessed by correlating annual area burned, area burned at high and low severity, and percent high severity with fire season (May-August) and water-year (October-September) climate variables. We also analyzed relationships between climate and high-severity fire at the scale of the individual fire using a hurdle model. We found that increasing temperature and VPD and decreasing precipitation were associated with increasing area burned regionally, and that area burned at high severity had the strongest relationships with climate metrics. The relationship between climate and fire activity in the Southwest appears to be strengthening since 2000. VPD-fire correlations were consistently as strong as, or stronger than, temperature or precipitation variables alone, both regionally and at the scale of the individual fire. Notably, at the scale of the individual fire, temperature and precipitation were not significant predictors of fire activity. Thus, our results support the use of VPD as a more integrative climate metric to forecast fire activity. We suggest that the strong relationship between VPD and fire activity may be useful to assess the likelihood of high-severity fire occurrence through continued development of the high-severity fire threshold model we present. The link between increasing aridity and increasing wildfire activity suggests a future with more fire in Southwest forests and woodlands with projected warming, underscoring the urgency of restoration in dry forests to reduce the likelihood of uncharacteristic, large high-severity fires.

1. Introduction

Fire is a vital ecosystem process in dry forests of the southwestern United States (Southwest; Arizona and New Mexico). Fire shapes the composition and structure of vegetation and is crucial to maintaining ecosystem function and diversity (Abella and Denton, 2009; Swetnam and Baisan, 1996; Van Horne and Fulé, 2006). Grazing, logging, and over a century of fire suppression have led to increased tree densities and excess fuel accumulation in many dry forest ecosystems, thereby increasing the severity of wildfires and shifting the fire regimes of these ecosystems (Covington and Moore, 1994). Large, high-severity fires, historically uncharacteristic to dry forests in the Southwest increase the potential for long-term forest loss through conversion to grass or shrubs (Guiterman et al., 2018). It has become increasingly clear that in addition to increased fuels, climate change is also a driver of changing fire regimes across the western US (Abatzoglou and Kolden, 2013; Abatzoglou and Williams, 2016; Littell et al., 2009; Westerling et al., 2006). Understanding climate-fire relationships is key for better projecting when and where fire will occur and how severely they will burn, thereby allowing for more informed management and better planning

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of resources in the effort to increase the resilience of dry forests of the Southwest in a warming climate.

The history of fire and fire management in the Southwest has been well documented (Covington and Moore, 1994; Swetnam and Baisan, 1996). Prior to European settlement in dry-forest ecosystems, such as madrean, ponderosa pine, or xeric mixed-conifer forests, frequent, low-severity surface fires kept forest conditions open and surface fuel loads low (Swetnam and Baisan, 1996). Starting in the late 19th century, this frequent-fire regime was interrupted by the introduction of grazing, logging, and active fire suppression, resulting in numerous missed fires (Covington and Moore, 1994; Swetnam and Baisan, 1996). The lack of surface fires allowed surface fuels and tree densities to increase, which is an important driver of increasingly severe fires (Covington and Moore, 1994; Stephens et al., 2013).

Over the past several decades, there has been a well-documented increase in the number of fires (Dennison et al., 2014; Singleton et al., 2019), fire-season length (Westerling et al., 2006), total area burned, and area burned at high severity (Dillon et al., 2011; Littell et al., 2009; Singleton et al., 2019) in forest and woodland ecosystems across the Southwest. These increasing trends in fire activity are occurring across multiple forest and woodland vegetation types (Singleton et al., 2019). Furthermore, there are signs of a shift toward an increase in fire activity starting in 2000 across the West (Abatzoglou and Williams, 2016; Dillon et al., 2011), as well as a potential upward shift in high-severity fire in the Southwest (Singleton et al., 2019) that has yet to be quantified.

Climate is an important driver of variability in wildfire activity in the western U.S. at centennial to seasonal time scales (Littell et al., 2009; Margolis et al., 2017; Marlon et al., 2012; Swetnam and Betancourt, 1990). Climate variables such as precipitation and temperature drive the regional water-balance, which affects fire occurrence, spread, and severity through influences on fuel moisture, and at longer timescales, fuel abundance. Concurrent with the increase in fuel loads over the last century, changes in climate, including warming temperatures, are driving an earlier onset of snowmelt, increasing the length of the fire season, and reducing fuel moistures, which is making large portions of the landscape flammable for longer periods of time (Hoerling et al., 2013; Westerling et al., 2006).

Although temperature and drought have been shown to be important drivers of annual area burned (Kitzberger et al., 2017; Littell et al., 2009; Westerling, 2016), fire responds to the combined effects of temperature and moisture. Vapor pressure deficit (VPD) is a metric that measures the difference between the amount of moisture in the air and the potential moisture holding capacity of the air, thereby capturing the effects of temperature and moisture, including precipitation, on the driving force of water loss from vegetation (Seager et al., 2015; Williams et al., 2014). Both periods of high temperatures and/or reduced precipitation can result in high VPD values. During extended periods of high VPD the evaporative demand in the atmosphere rapidly depletes moisture from live vegetation, dead fuels, and soil via evapotranspiration, thereby increasing flammability. Likewise, integrative climate-based and fire-danger metrics are frequently used to quantify the combined impacts of weather and climate on the probability of fire ignition, spread, and behavior and are highly useful for predicting a variety of aspects of fire activity (Riley et al., 2013). However, Williams et al. (2014), using Monitoring Trends in Burn Severity (MTBS) data, found that VPD was strongly correlated with high and moderate severity annual area burned in the Southwest, more so than temperature alone or several other commonly used climate-based or fire-danger metrics, such as the Palmer Drought Severity Index, Keetch-Byrum Drought Index, the Standardized Precipitation–Evaporation Index, or the Energy Release Component.

Despite some limitations, prior climate-fire studies have extensively used MTBS products to examine a variety of temporal and spatial aspects of burn severity. The MTBS project has mapped the burn severity of all fires greater than 404 ha in the West since 1984 and created remotely sensed continuous burn severity mosaics for these fires (Eidenshink et al., 2007). There are however limitations and inconsistencies in the MTBS data (Kolden et al., 2015; Singleton et al., 2019). For example, large fires that occur predominantly in grasslands and shrublands are typically analyzed as initial assessments (IA), where the post-fire image is acquired less than six months after the fire, even if they include significant area of forest and woodland. Initial assesments may overestimate fire severity because they only capture immediate post-fire effects while disregarding resprouting or recovery of live vegetation and because ash cover, which decreases with time since fire, often increases the reflectance values resulting in increased measures of high severity (Miller and Quayle, 2015). Previous studies of trends in fire severity (Dillon et al., 2011) and climate-fire relationships (Abatzoglou and Williams, 2016; Parks et al., 2014; Williams et al., 2014) in the Southwest exclusively utilize data from MTBS, which includes large burned areas analyzed as IAs. Dillon et al. (2011) chose to eliminate IAs from their trend analysis of fires in the Southwest to remove this limitation. By reanalyzing MTBS IA fires as extended assessments (EAs, where post-fire images are acquired > 6 months after the fire), Singleton et al. (2019) doubled the number of fires and area burned of the EA dataset for forests and woodlands in the Southwest. They added 803 fires and 1,051,354 ha of burned area, including 82,206 ha of fire burned at high severity.

The Singleton et al. (2019) analysis documented increases in total area burned and percent area burned at high severity since 1984 using the most comprehensive burn severity dataset of large fires in the Southwest. We expanded on this study by examining climate-fire relationships potentially driving these trends. Furthermore, most climate-fire relationship studies spatially average climate variables across large regional areas or look at the relationship between seasonal or annual climate and area burned to measure and relate patterns of key drivers of fire activity (Abatzoglou and Williams, 2016; Littell et al., 2010; Williams et al., 2014); although, Birch et al. (2015) analyzed daily weather effects on burn severity of 42 fires in Montana and Idaho. Nevertheless, climate is not uniform across Arizona and New Mexico with local climate variability influencing fire activity. Furthermore, fires are managed locally and individually; therefore, we also looked at the climate relationships with fire at the scale of individual fires. Here, we analyze climate-fire relationships on 1130 individual fires to assess how regional climate-fire relationships persist at the local scale.

Our objectives were to (1) use the most comprehensive fire dataset available in the Southwest to test the hypothesis that increases in annual area burned, area burned at high and low severity, and percent area burned at high severity from 1984 to 2015 are related to regional climate variation and trends; and (2) analyze the relationships between climate variables and burn severity at the individual fires level. Do we see the broad-scale relationships hold at the scale of the individual fires? We anticipated that trends in precipitation, temperature, and vapor pressure deficit across the Southwest correlate with increasing trends in total area burned and fire severity at both scales of analysis.

2. Methods

2.1. Study area

The study area included all area burned in forested and woodland vegetation types for fires greater than 404 ha (ha) in Arizona and New Mexico from 1984 to 2015 (Fig. 1). Forests and woodlands were defined by the Wahlberg et al. (2014) Ecological Response Units (ERU) vegetation framework, which describes areas with ≥10% tree canopy cover. We used 12 of the 13 ERUs that were classified as forest or woodland. The Bristlecone pine ERU was excluded due to the limited area burned over the period of the study.

The climate of the Southwest is semi-arid, with a bimodal precipitation regime (Sheppard et al., 2002). Cool-season precipitation, which often falls as snow, occurs from October to April and is strongly

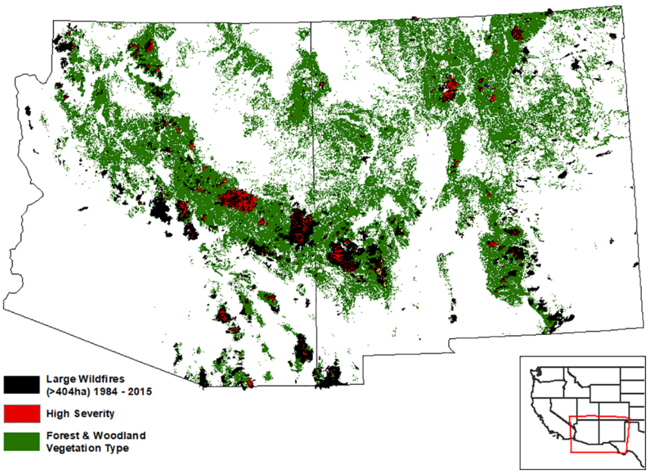

Fig. 1. Wildfires (black) and high-severity fire (red) in forests and woodlands from 1984 to 2015 in the southwestern U.S. (n = 1130 fires). Vegetation is from the US Forest Service Ecological Response Units. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

influenced by the El Niño-Southern Oscillation. Warm-season precipitation associated with the North American Monsoon occurs between July and September and is characterized by convective storms that provide up to 50% of the annual precipitation (Sheppard et al., 2002; Notaro et al., 2010). Mean winter temperatures ranged from 0 °C to14.3 °C and mean summer temperatures ranged from 17.7 °C to 33.5 °C during the study period (NOAA, 2018).

2.2. Burn severity data

We used the ERU layer to determine the vegetation type for each burned pixel and only used burn severity data for those pixels mapped as forest and woodland ERU vegetation types (see Singleton et al., 2019). To reduce direct human influences, we removed prescribed fire and fires managed for resource objectives. Resource objectives fires were identified as those managed with strategies other than full suppression, and that either used resource objective terminology within fire management reports (SIT-209, 2018), or were designated as fuel reducing treatments in the United States Forest Service, Accomplished Activities database (USDA Forest Service, 2018; Young et al., 2019). Prescribed fires were identified either directly from the MTBS database or the Wildfire Perimeters database for the Southwestern Region from the Forest Service Region 3 (MTBS, 2014; USDA Forest Service, 2017).

Burn severity was derived for each fire using the continuous Relativized differenced Normalized Burn Ratio (RdNBR; Miller and Thode, 2007), which is a variant of the differenced Normalized Burn Ratio (dNBR; Key and Benson, 2006). The RdNBR looks at the change between pre-fire and post-fire images while taking into account pre-fire vegetation cover. This provides a more stable definition of severity across space and time and can be used to draw comparisons between different fires, especially in low-density vegetation types typically found in the Southwest (Miller and Thode, 2007).

To capture a more complete assessment of area burned, Singleton et al. (2019) used the Event Mapper Tool plugin for QGIS developed by the MTBS project (MTBS, 2014). This tool was used to reanalyze all of the available initial assessments that had pixels mapped as forests and woodlands, as extended assessments, and map any missing large fires in the Southwest. Pre-fire Landsat images were selected ≤ 2 years prior to the fire, while post-fire effects images were selected 6–24 months post-fire (Dillon et al., 2011; Singleton et al., 2019). RdNBR data were classified based on thresholds field tested in the Southwest (high-severity threshold value ≥643 and low severity threshold value (< 308) (Singleton et al., 2019).

We analyzed the expanded Singleton et al. (2019) burn severity data set, which includes annual area burned, area burned at high severity, and percent high severity. We also included area burned at low severity (excluding unburned area) because we were interested in understanding the effects of climate on both the low and high end of burn severity. All regional-scale area burned variables were calculated by summing the total pixels of area burned for each year across all fires, and annual totals were log-transformed to stabilize the variance in the datasets. Percent high-severity was calculated for each year by dividing the summed pixels of high-severity fire by the total burned forested pixels of all fires. This data was arcsine-square root transformed to stabilize the variance of the dataset. We also derived area burned at high severity and the percent high severity of each fire individually.

2.3. Climate data

Monthly climate variables were obtained from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) group at Oregon State University (Daly et al., 2004). These data are gridded at a 4 km resolution and averaged monthly. Our analysis included mean, minimum and maximum temperature, minimum and maximum vapor pressure deficit, and total precipitation. We analyzed only those climate pixels that intersected burned area within the fire perimeters. Additionally, we derived the monthly climate anomaly at each pixel for each climate variable for the regional analysis of climate-fire relationships. These anomaly grids were created by subtracting climate variables for each year by the 30-year normal (1981–2010).

The climate data were averaged over two time periods, the fire season and the water year. The fire-season climate was defined as May through August, since these are the months when 90% of fires occurred and area burned annually from 1984 to 2015. To assess potential effects of prior moisture on area burned we also used water-year climate variables (prior October to current September).

2.4. Regional correlation analyses of fire and climate variables

To assess regional correlations between fire and climate we used a time-series framework. Within this framework, (weak) stationarity is a key assumption, where the mean, variance and autocorrelative structure of a data series do not depend on the time at which the series is observed (Box and Jenkins, 1976). We observed autocorrelation (persistence) and non-stationary trends within many of our fire and climate data series, which can increase the likelihood of spurious correlations (Podobnik and Stanley, 2008). To account for this, we modeled and removed the autocorrelation and trend from each fire and climate variable time series separately (Table 1) using an autoregressive integrated moving average (ARIMA) model with an integration term of one (Box and Jenkins, 1976). The best AR and MA model processes were selected using the Akaike Information Criterion (AICc; Shumway and Stoffer, 2010). While most fire and climate variables were best fit with an MA process of one that accounted for interannual variability (Appendix A, Table A1), mean temperature was best fit with an AR process of two that accounted for autocorrelation.

After fitting an ARIMA model to each of our fire and climate data series, we obtained the model residualof each detrended series (with autocorrelation and trend removed) to compute correlations between each fire and climate variable (Podobnik and Stanley, 2008). We calculated the Pearson's correlation coefficient between the residual of each fire variable time series model and the residual of each climate variable time series model to test for potential climate-fire relationships. Each climate variable was modeled separately to enable comparisons between the variables and because of the strong correlations between them (Appendix B, Table B1).

Based on previous literature that suggests a notable upward shift in fire activity starting in 2000 across the West (Abatzoglou and Williams,

Table 1
Predictor and climate response variables considered for each analysis and the temporal scale of each variable across all area burned in large fires (> 404 ha) in Arizona and New Mexico. *Forest cover percent is based on 2014 ERU vegetation layer.

Response Variables	Scale	Predictor Variables	Scale
Regional Correlation Analysis			
Total Area Burned	Total annual (Jan–Dec)	Mean Temp	Water year average (prior Oct–Sept) Fire season average (May–August)
Area Burned at High Severity		Max Temp	
Percent High Severity		Min VPD	
Area Burned at Low Severity		Max VPD	
		Total Precip	
Individual Fires Hurdle Model Analysis			
Area Burned at High Severity	Total of each individual fires	Mean Temp	Month of the fire ignition date
Percent High Severity		Max Temp	
		Min Temp	
		Min VPD	
		Max VPD	
		Total Precip	
		Forest and woodland Cover	Percent cover of each individual fire

2016; Dillon et al., 2011), we also tested for a potential change in area burned at high severity and percent high severity beginning in the year 2000. To assess if there was a structural shift, we used truncated negative binomial models to test for structural breaks (fixed effects) in the median area burned at high severity and the median percent high severity (Chow, 1960). We assessed the significance of structural breaks with a Huber-White sandwich estimator, which accounts for heteroscedastic variance. Independent observations were supported by the lack of autocorrelation in area burned, and the highly stochastic processes of fire occurrence, fire weather (Finney et al., 2011), and fire management team assignments.

2.5. Individual fires hurdle model analysis

In addition to the regional analysis, we analyzed the relationship between climate and high-severity fire at the scale of the individual fire. Generally, larger fires tend to have an absolute greater area of high-severity fire even when fire weather is not extreme (Cansler and Mckenzie, 2014; Miller et al., 2012, 2009); therefore, we looked at both the area burned at high severity and the percent high severity for each fire individually. Temperature, precipitation, and VPD climate variables used in the regional analysis were analyzed further in the individual fires analysis (Table 1). We analyzed each climate predictor variable from the month of the recorded ignition date of the fire, because the ignition date was consistently available across the Southwest, instead of limiting our data to only those fires with reliable progression data or containment dates. These climate data were averaged over the area of each individual fires. Untransformed values for the climate variables were used instead of climate anomalies for interpretability. Finally, because fires generally burn at higher severities in more dense forests and woodlands, we included percent forest and woodland cover of each fire as a covariate in the model.

Preliminary analysis of the influence of climate on the count of pixels burned at high severity at each fire indicated that the dataset contained many zeros and was overdispersed. That is, many fires did not have pixels that burned at high severity, and a few fires had very high numbers of pixels that burned at high severity. Therefore, we used a hurdle model designed to handle zero-inflated count data that originated from a single data generating process (Rodriguez, 2013). The hurdle model fits the data in two steps: the first step is a binomial generalized linear model (GLM) that is used to assess the odds of whether or not a fire had any pixels burn at high severity (odds of surpassing the "hurdle"), and the second step is a log-normal linear model that is used to evaluate the number of pixels burned at high severity for only those fires that had pixels that burned at high severity. Because the model requires the response variable to be an integer, we set the "hurdle" for the area burned at high-severity model to one pixel categorized as high severity and we set the "hurdle" for the percent high-severity model to one percent of the pixels categorized as high severity. To further address the overdispersion in the data, the positive count process of the hurdle model was fit with a negative binomial regression parameter. The overdispersion parameter in the model (log (theta)) was significant, confirming that the negative binomial improved the fit of the model.

2.5.1. Developing a high-severity threshold model

Finally, hurdle models allowed us to estimate the probability of the percent odds of high-severity fire occurrence in an individual fire based on known values of a climate variable. Due to VPD's strong correlation with high-severity fire, we calculate the odds of surpassing a given percent of high-severity fire based on given values of VPD, and the percent of fire classified as either a forested or woodland area. We assessed model predictions at the median of 64.5% forested and woodland cover. (See Appendix C, Tables C1 and C2 for predictions at 10% and 90% forest cover). The vegetative and topographic distribution of high-severity data used in this analysis is briefly described in Section 2.2 and in Appendix D, Table D1. Using this model to analyze these odds at multiple values, or thresholds, of percent high-severity fire introduces a conceptual design that could be used to inform decisions about high-severity fire risk when assessing when and where to use fire to reach desired landscape effects.

3. Results

3.1. Trends in area burned, burn severity and climate variables 1984–2015

Large fires from 1984 to 2015 have burned over 2.5 million hectares of forests and woodlands in the Southwest, which equates to about 14% of these ecosystems. At least 300,000 ha have burned at high severity (15% of total area burned). All fire variables had a positive trend (Fig. 2). Total area burned increased at a rate of 9.5% annually or an average increase of 4298 ha per year. The rate of increase for area burned at high severity was 17.3% or 826 ha annually. Regionally, percent high severity increased at a rate of 0.35% annually (Appendix A, Table A1). Area burned at low severity also increased at a rate of 9% annually (1204 ha per year).

All water-year climate variables had a trend toward increasing aridity. Temperature and VPD had a significant positive trend, while precipitation had a significant negative trend (Fig. 3 and Appendix A, Table A1). Three of the five climate variables trended toward increased aridity during the fire season (Fig. 4). Fire-season precipitation and maximum temperature did not have a significant trend.

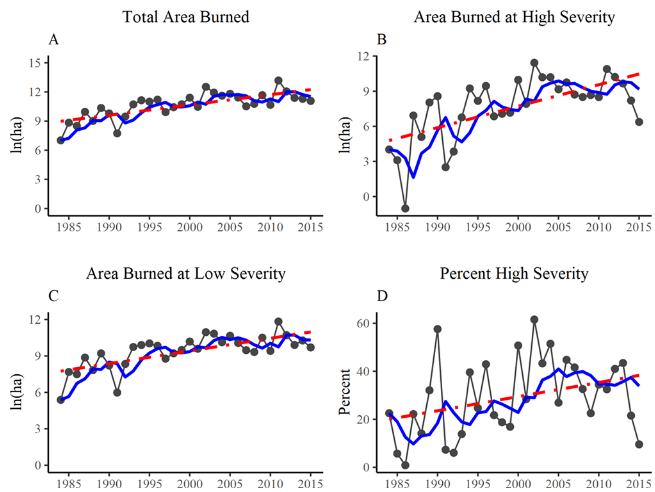

Fig. 2. ARIMA time series models (blue) and temporal trends (red) for fire variables in forest and woodland ecosystems in the Southwest from 1984 to 2015. Change in area burned is the average annual increase of the trend for all large fires (> 404 ha). Panels A, B, and D are modified from Singleton et al. (2019) with prescribed and managed fires removed. Note that the y-axis in panel A is different than panels B and C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

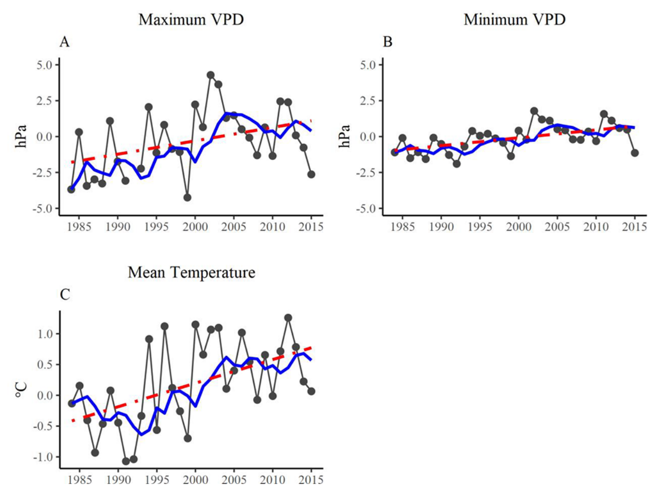

Fig. 4. ARIMA time series models (blue) and temporal trends (red) for fire-season (May – August) climate variable anomalies in forest and woodland ecosystems from 1984 to 2015. Climate anomalies are based on the PRISM 30-year normal dataset for the climatological period from 1981 through 2010. Variables with no significant trend, fire-season maximum temperature and total precipitation are not shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

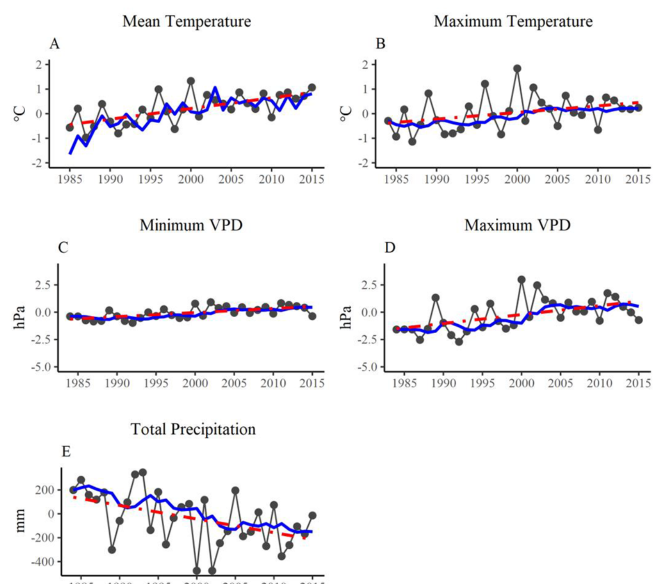

Fig. 3. ARIMA time series models (blue) and temporal trends (red) for water-year (prior October – current September) climate variable anomalies in forest and woodland ecosystems in the Southwest from 1984 to 2015. Climate anomalies are based on the PRISM 30-year normal dataset for the climatological period from 1981 through 2010. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. Regional climate-fire relationships

The regional climate-fire correlation analysis (with trends removed) indicated that both water year and fire-season climate were significantly correlated with inter-annual variability in wildfire activity (Table 2).

Fire-season VPD had the strongest correlations with fire activity, and fire-season precipitation had the weakest. All temperature variables were significantly associated with inter-annual variability in fire activity, with water-year mean temperature being the strongest. Total area burned had the strongest associations with climate and area burned at low severity had the weakest.

Total area burned – Fire-season VPD had the strongest correlation with total area burned (minimum VPD, r = 0.64; maximum VPD, r = 0.71), but water-year temperature was similar (r = 0.60). Fire-season precipitation was the only climate variable not significantly correlated with total area burned (r = −0.32).

Area burned at high severity – All climate variables except fire-season precipitation and water year mean temperature were significantly correlated with area burned at high severity and fire-season minimum VPD was the strongest (r = 0.69).

Percent high severity – Water-year precipitation and minimum VPD had the strongest correlations with percent of area burned at high severity (r = −0.63 and 0.63, respectively) and fire-season VPD correlations were weakest with this fire variable.

Area burned at low severity – Fire-season minimum VPD had the strongest correlation (r = 0.64) with area burned at low severity.

Total precipitation – Fire-season precipitation was not significantly correlated to any fire variables, yet water-year precipitation was significantly correlated with all fire variables (r = −0.37 to −0.63) (Table 2).

The test for a structural break at the year 2000 found that median area burned at high severity increased by a factor of 7.93 (Incidence Rate Ratio = IRR, $p < 0.01$) from 2492 ha (1984–1999) to 19,773 ha (2000–2015) and median percent high severity increased by a factor of 2.25 (IRR, $p < 0.01$) from 5.8% (1984–1999) to 15.4% (2000–2015; Fig. 5). We further tested other potential structural breaks at three years on each side of the year 2000 but did not find any to be of greater significance. Correlations between area burned at high severity and minimum VPD increased from 0.60 (95% CI: 0.15–0.74) to 0.91 (95% CI: 0.77–0.97) after the year 2000 (Fig. 6), and there was a similar increased correlation with maximum VPD and area burned at high severity from 0.51 to 0.80, although the shift was not significant (95% CI: 0.02–0.80 and 95% CI: 0.63–0.95, respectively).

Table 2
Pearson's correlation coefficients between fire variables (left) and climate variables (top). Water year includes data from prior October through September. Fire season includes data from May through August. Precip. represents the time period total precipitation. All temperature and VPD variables represent the time period averages.

	Water Year					Fire Season				
	Total Precip	Mean Temp	Max Temp	Min VPD	Max VPD	Total Precip	Mean Temp	Max Temp	Min VPD	Max VPD
Total Area Burned	−0.48*	0.60*	0.46*	0.63*	0.60*	−0.32	0.45*	0.40*	0.71*	0.64*
Area Burned at High Severity	−0.56*	0.35†	0.39*	0.66*	0.61*	−0.34	0.48*	0.43*	0.69*	0.62*
Percent High Severity	−0.63*	0.35*	0.47*	0.63*	0.61*	−0.28	0.51*	0.49*	0.59*	0.56*
Area Burned at Low Severity	−0.37*	0.55*	0.36*	0.53*	0.51*	−0.30	0.40*	0.36*	0.64*	0.60*

* Indicates significance ($p < 0.05$). †Not significant due to rounding.

3.3. High-severity climate-fire relationships for individual fires

Maximum and minimum VPD were significant predictors of whether individual fires would burn at high severity, as well as the percent of high-severity fire when accounting for the percent of the fire with forest or woodland cover. The results for the hurdle model were divided into the area burned at high severity for a fire (the area model), and the percent high severity for a fire (the percent model; Table 3 and Fig. 7). In the area model, for an increase of one unit (hPa) in maximum VPD, the odds that a fire contains high severity (at least one pixel categorized as high severity) increased by 4.4% (see odds ratio, Table 3). For those fires that contained high-severity fire, a one unit increase in maximum VPD increased the area burned at high severity by 7.1% (see rate ratio, Table 3). In the percent model, for an increase of one unit (hPa) in maximum VPD, the odds that a fire contained at least 1% of high severity (at least one percent of pixels categorized as high severity) increased by 5.1% (see odds ratio, Table 3). For those fires that contained at least 1% of high-severity fire, a one unit increase in maximum VPD increased the area burned at high severity by 1.8% (see rate ratio, Table 3).

Maximum and minimum VPD were significant predictors of the odds of a fire containing high-severity fire and had a positive relationship with area burned at high severity in both the area and percent models (Table 3). Precipitation was significantly related to the change in area burned at high severity for those fires that contained high severity in the count model only and a significant predictor of the odds of a fire containing high-severity fire in the percent model. Temperature was not a significant predictor in the area or percent models.

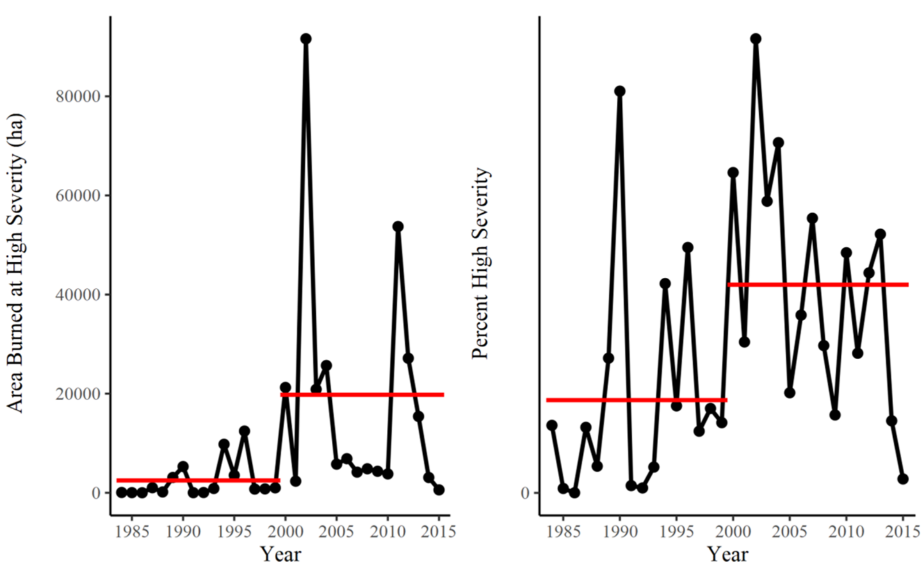

Fig. 5. Total area burned and area burned at high severity in the southwest U.S. from 1984 to 2015. The horizontal bars represent the median area burned at high severity and percent area burned from 1984 to 1999 (2492 ha and 6.8%, respectively) and from 2000 to 2015 (19,773 ha and 15.4%, respectively). We used truncated negative binomial models to test for a significant structural break (fixed effects) at the year 2000 in the median area burned at high severity (IRR = 7.93, $p < 0.01$, truncation = 0 ha) and median percent high severity (IRR = 2.25, $p < 0.01$, truncation = 0 ha; Chow, 1960). Results indicated a significant increase in area burned after the year 2000.

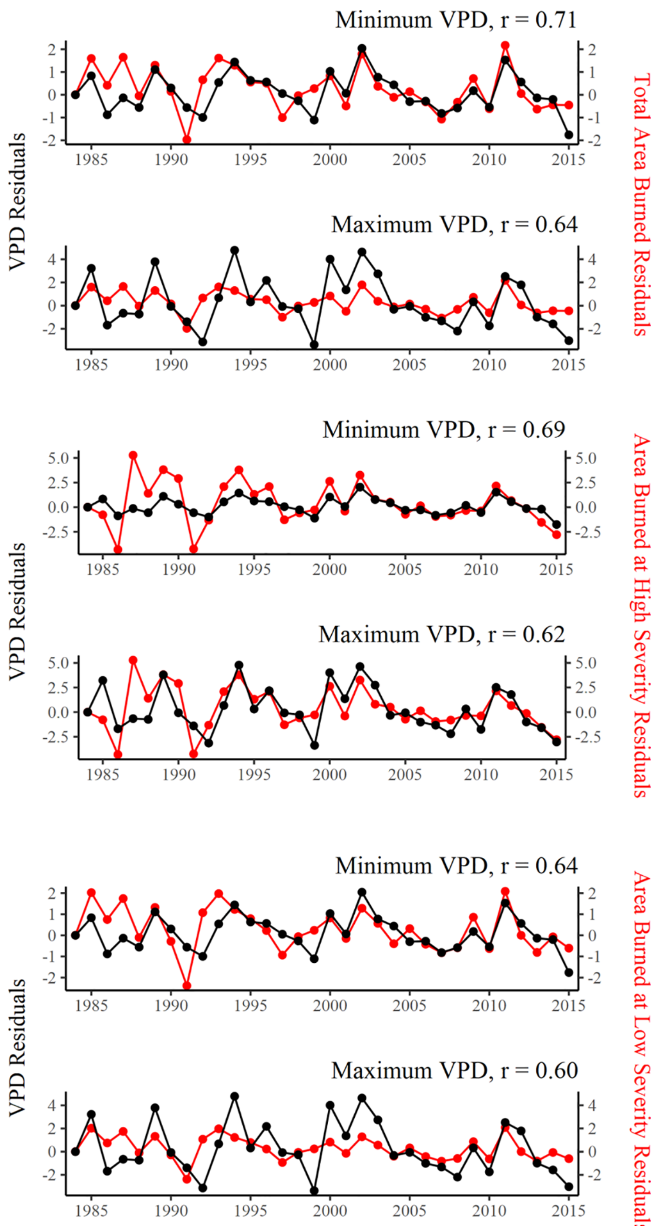

Fig. 6. Inter-annual climate-fire relationships between annual area burned at high severity (red) and mean fire-season vapor pressure deficit (VPD, black) in the southwest U.S (1984 – 2015). All time series are residuals from the ARIMA models with trend and autocorrelation removed to meet the assumptions of the correlation tests. Note the significant increased association between minimum VPD and area burned at high severity after 2000. Pearson's correlation coefficients for 1984 to 1999 and 2000 to 2015 are r = 0.60* (95% CI: 0.15 to 0.74) and r = 0.91* (95% CI: 0.77 to 0.97). *Indicates significance ($p < 0.05$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Fixed effects estimates for negative binomial logit hurdle model for the area burned at high severity (# of pixels) and the percent area burned at high severity (% of pixels). The zero-hurdle part of the model is a binary logistic regression model that estimates the odds of a fire burning with high severity as a function of the climate variable and percent forest and woodland cover. The count part of the model estimates for those fires that have high severity, what is the effect of the climate variable and percent forest and woodland cover. All climate variables were modeled separately due to the strong correlation between the variables (Appendix B, Table B1). The conversion to percent change of odds and rate ratio for values > 1 is ((Ratio – 1) * 100); odds and rate ratio for values < 1 is ((1-Ratio) * 100). Coef. = model coefficients. * indicates significance ($p < 0.05$).

	Zero Hurdle			Count		
	Coef. zero part (climate)	Odds Ratio	Coef. zero part (forest)	Coef. count part (climate)	Rate Ratio	Coef. zero part (forest)
Area Model – Area Burned at High Severity						
Max VPD	0.043*	1.044	0.029*	0.069*	1.071	0.012*
Min VPD	0.116*	1.123	0.116*	0.139*	1.149	0.014*
Mean Temp	0.016	1.016	0.025*	−0.031	0.969	−0.003
Min Temp	0.019	1.019	0.026*	−0.062	0.940	−0.002
Max Temp	0.015	1.015	0.026*	−0.011	0.989	−0.002
Total Precip	−0.005	0.995	0.026*	−0.027*	0.973	0.003
Percent Model – Percent High Severity						
Max VPD	0.050*	1.051	0.023*	0.018*	1.018	0.005*
Min VPD	0.120*	1.127	0.022*	0.076*	1.079	0.008*
Mean Temp	0.022	1.022	0.019*	0.025	1.025	0.005
Min Temp	0.021	1.021	0.019*	0.025	1.025	0.005*
Max Temp	0.018	1.018	0.019*	0.024	1.024	0.005
Total Precip	−0.005*	0.995	0.019*	−0.006	0.994	0.003

3.3.1. High-severity threshold model

Based on the results of this model we produced a table indicating the probability of exceeding a percent of high-severity threshold within an individual fire for a given value of VPD with percent forest and woodland cover held at the median, 64.5% (Table 4). The probabilities ranged from 88% chance of > 1% high-severity fire at a maximum VPD of 70, to < 1% chance of > 50% high-severity fire at a VPD of 0. The effect of VPD increased with increasing percent forest and woodland cover (Appendix C, Table C1 and C2).

4. Discussion

Our results indicate that trends toward a warmer and drier climate over the last three decades (1984–2015) in the Southwest are strongly associated with observed increases in fire activity. Since 2000, median fire activity has increased and relationships between seasonal climate (VPD) and high-severity fire have strengthened. Abatzoglou and Williams (2016) found similar results for the western U.S. and concluded that nearly half of the recent increase in area burned was attributed to human-caused climate change. These trends have important implications for the ecology and management of dry conifer forests in the Southwest, many of which are experiencing uncharacteristically large patches of high-severity fire. These increasingly large and more-severe fires are expected to increase with projected warming (Williams et al., 2014), increasing the potential to transition dry conifer forests to grass and shrublands that could persist for decades or longer (Davis et al., 2019; Guiterman et al., 2018).

4.1. Trends in regional fire and climate variables 1984–2015

We analyzed a burn severity data set that contains > 1,000,000 ha not included in MTBS and found that total area burned, area burned at low and high severity, and percent high severity are increasing in forest and woodlands of the Southwest (1984–2015). Singleton et al. (2019) found similar results using a similar analysis to specifically detect trends, although they included acreage burned as managed or prescribed fire. They found that total area burned and area burned at high severity were increasing annually by an average of 10.7% and 17.8%, respectively. Despite removing the managed and prescribed fires, we found similar rates of increase (average annual increases of 9.5% and 17.3%, respectively). Williams et al. (2014) found that combined annual moderately and severely burned area increased at a rate of 10.2% on average per year (1984–2013) with a more rapid increase in higher-elevation forested areas. Not surprisingly, area burned at high severity has been correlated to total area burned, and has increased concomitantly with increasing fire size as seen in these studies and others (Cansler and Mckenzie, 2014; Dillon et al., 2011; Miller et al., 2009; Singleton et al., 2019, Williams et al., 2014). We also found that area burned at low severity has also increased annually on average by 10.5% since 1984. This can be viewed as a step toward restoring the historical low-severity fire regime in dry conifer forests, since these forests have "missed" many fires over the past century. Despite the variation in methods and the addition of the extended assessment burn severity data, there is strong evidence that fire activity has increased regionally in the Southwest over the past three decades.

We also found a trend toward a warmer and drier climate in forests and woodlands of the Southwest, which is likely a significant driver of the observed increases in fire activity (Abatzoglou and Williams, 2016). Temperature and VPD increased and precipitation decreased regionally since 1984. Forecasted increased temperatures will further increase VPD exponentially so that by 2050 the current extreme VPD values are expected to become the mean (Williams et al., 2013, 2014). This suggests that fire activity will continue to increase in the Southwest until at some point fuels become limiting. In our analysis, only fire-season maximum temperature and fire-season precipitation did not have trends since 1984, suggesting that relatively consistent summer rains associated with the North American Monsoon may be having a stabilizing effect on summer climate in the region.

4.2. Regional climate-fire relationships

VPD was consistently highly correlated to area burned and area burned at high severity (Table 2). VPD has been established as a strong indicator of fire activity, including annual area burned at moderate and high severity (Seager et al., 2015; Williams et al., 2014), and fire ignition and spread (Sedano and Randerson, 2014). Specifically, Williams et al. (2014) analyzed mean monthly VPD. When we analyzed average monthly minimum and maximum VPD separately, we unexpectedly found minimum VPD to have the highest correlations with fire activity. Minimum VPD, which generally occurs overnight, has significant effects on vegetation (fuel) moisture recovery (Kurpius et al., 2003). Diurnal changes in fuel moisture allow fuels to regain moisture nightly when humidity increases and temperature decreases. High minimum VPD values reflect periods of low fuel moisture recovery, resulting in increasingly dry and flammable fuels (Collatz et al., 2000; Lauritsen and Rogers, 2012) and therefore potentially explaining the stronger correlation of minimum VPD with fire activity.

Likewise, other water balance metrics such as actual evapotranspiration and climatic water deficit have also been shown to relate well to fire severity (Kane et al., 2015; Littell et al., 2010; Parks et al., 2014). This result is not surprising since climate variables that track water balance are generally better related to vegetation flammability

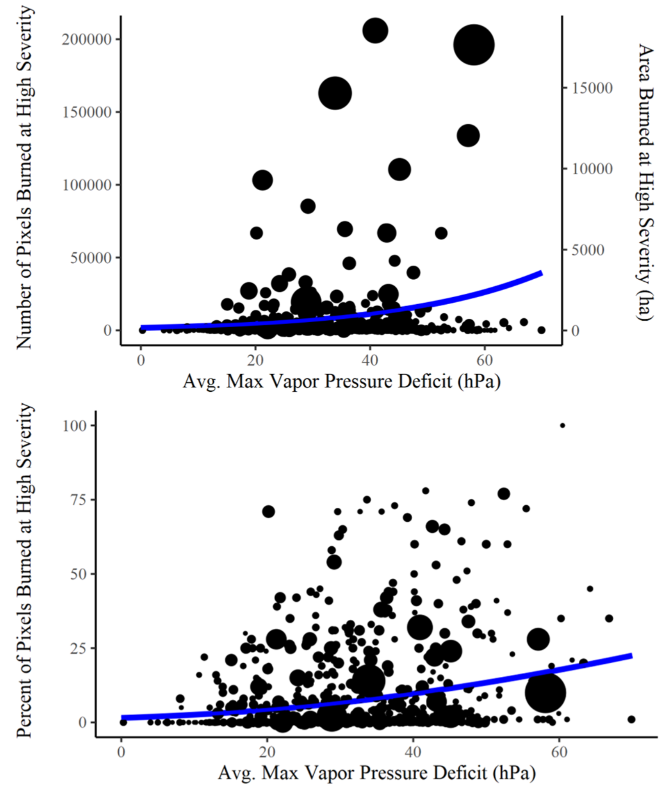

Fig. 7. Scatter plots of the number of pixels burned at high severity (top) and the percent of pixels burned at high severity (bottom), versus the monthly average maximum vapor pressure deficit for the month that each fire started. The blue line represents the conditional predicted hurdle model (full model). Each point represents one fire. Size of points represents the relative size of the total forested area of the fire. The data contain an excess of zeros, or fires that did not burn with any area at high severity. Note the 2002 Rodeo-Chediski Fire was used in this analysis, however, it is not displayed in top figure for visual aesthetics. It burned 1,899,764 pixels of which 822,526 pixels burned at high severity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Abatzoglou and Kolden, 2013). Plants respond to the increase in atmospheric dryness by regulating the exchange of water through their stomata so that an initial increase in VPD may actually correspond to a decrease in water loss because of stomatal closure (Massmann et al., 2019; Rico et al., 2013). However, there are limits to plant water conservation strategies, and as VPD increases, so does atmospheric water demand, which eventually will overwhelm the ability of plants to reduce transpiration and water loss, increasing flammability at the ecosystem scale (Massmann et al., 2019; Will et al., 2013). Not surprisingly, higher-than-normal warm-season VPD in recent decades have already been linked to increased forest drought stress, tree mortality and increased fire hazard (Will et al., 2013; Williams et al., 2013).

Correlations between temperature and fire activity were weaker than with VPD, though often still significant. The strongest correlation between temperature and total area burned was r = 0.60 (water year mean temperature) whereas the strongest correlation between VPD and total area burned was r = 0.71 (fire season minimum VPD). This is not surprising, because VPD is an integrated measure of temperature and moisture, responding to feedbacks in both temperature and precipitation and is highly correlated to both (Appendix B, Table B1). For example, at a constant humidity, VPD will increase with increasing temperature. An increase in VPD can be expected under warmer temperatures, driven by the exponential relationship between the saturated vapor pressure and temperature, as warmer air has a higher moisture holding capacity (Seager et al., 2007; Williams et al., 2014). In addition, Holden et al. (2018) found that across much of the western

Table 4
Model predictions of the probability of surpassing a percent high-severity threshold within a fire based on the value of average maximum monthly VPD with percent forest and woodland cover held at the median, 64.5% (i.e. when maximum VPD = 50, the probability of a fire burning > 10% high severity (surpassing the threshold) is 35%). The table does not indicate the amount of severity to expect based on VPD, only the probability of crossing a designated threshold. New thresholds were created by resampling the population where those fires that did not meet the assigned threshold were reassigned a value of '0'. The total number of fires is 1,130.

	Percent High-severity Threshold (>)					
	1%	10%	20%	30%	40%	50%
Max VPD						
0	18%	7%	3%	0%	0%	0%
10	26%	10%	5%	1%	1%	0%
20	37%	14%	7%	2%	2%	1%
30	49%	19%	12%	5%	3%	1%
40	61%	26%	18%	11%	7%	4%
50	72%	35%	26%	21%	13%	9%
60	81%	44%	37%	38%	25%	20%
70	88%	54%	49%	57%	41%	40%

U.S., there has been a significant decline in precipitation during the fire season and an increase in the length of consecutive days without rain since 1979. These long dry spells result in an increase in sunlight being converted to heat at the surface, leading to further drying of vegetation. This is important because the observed warming trend is projected to continue (Seager et al., 2007; USGCRP, 2017). Decreasing trends in precipitation across the western U.S. are also expected to continue over the next century, although with less certainty than temperature (Holden et al., 2018; Seager et al., 2007; Cubash and Meehl, 2001; USGCRP, 2017). Accordingly, these trends in increasing temperature and decreasing precipitation are likely to result in a substantial increase in VPD and associated wildfire activity.

Precipitation had the weakest relationships with fire activity. Fire-season precipitation was not significantly correlated with any fire variables. This is possibly a function of the spatial variability of summer rains and the limitation of monthly climate data versus daily data. Fire season included May – August, which captured 90% of area burned. July and August are usually two of the wettest months of the year, but they are also characterized by highly localized convective storms, in contrast to cool-season precipitation that is more widespread (Sheppard et al., 2002). Therefore, a year could have a regionally wet August, but still have locations dry enough to burn. In addition, many fires burned in the early portion of July, which was likely dry, but was followed up by mid-to-late July precipitation. Data with finer temporal resolution are necessary to resolve this limitation. In contrast to fire-season precipitation, water-year precipitation had significant correlations with fire activity, including the highest correlation with percent of area burned at high severity ($r = -0.63$). This suggests an important longer-term influence of cool-season moisture prior to the fire season on high-severity fire. Reduced overall winter precipitation can lead to low fuel moistures (fuel conditioning), which favor fire spread (Abatzoglou and Kolden, 2013). Conversely, high winter precipitation increases soil moisture, especially when snowpack is persistent into late winter, deferring the onset of fire season; although, abundant soil moisture may also support increased fine fuel production ("green-up") which may support larger and more severe fires in some vegetation types (Abatzoglou and Kolden, 2013).

Differences, as well as similarities, between the climate-fire relationships of water-year versus fire-season climate could provide insights into climate-fire dynamics, and also have management value. Water-year temperature was better correlated with area burned than fire-season temperature. Climate variables like this, which have lagging relationships may be valuable for forecasting fire activity months prior to the fire season. Other climate variables, like VPD, generally had little change in the climate-fire relationship between water year and fire season, and if they did, the relationship generally improved with fire-season climate. This suggests that VPD is tuned to the short-term (fire-season) changes in water balance directly affecting the fire and that the climate window of the months leading up to the fire season may not provide added value to predictions. Low-severity fire generally burns 1- and 10-hr surface fuels, which are highly responsive to short-term changes in the moisture balance, therefore it is logical that fire-season climate would have higher correlations than water year. In contrast, the climate variables that were notably stronger in the water year (e.g., precipitation) were associated with high-severity fire metrics. This suggests that short-term dry conditions during the fire season are less likely to override prior, cool-season wet conditions as they relate to high-severity fire. This is supported by regional tree-ring climate-fire analyses indicating that historically widespread high-severity fires were related to extreme cool-season drought prior to the fire season (Margolis and Swetnam, 2013).

4.3. Post-2000 shift

Post-2000, there was a significant shift toward greater annual area burned at high severity and a greater percent of fires burning at high severity in the Southwest. These trends have also been observed in other studies (Abatzoglou and Williams, 2016; Dillon et al., 2011; Singleton et al., 2019). Eight of the top ten years with the largest area burned at high severity occurred since 2000. The median percent of high severity since 2000 was two-and-a-quarter times greater than the median from 1984 to 1999. For the area burned at high severity, the median since 2000 was almost eight times greater than the median area burned from 1984 to 1999 (Fig. 5). Abatzoglou and Williams (2016) observed a shift in aridity beginning in 2000 across four fire-danger metrics and four drought metrics, which they linked to increasing climate-driven fire activity across the western U.S. This coincides with a similar shift in the trends of the climate variables in this study.

In addition, the relationship between climate and fire in the Southwest strengthened after 2000. The correlation between minimum VPD during the fire season and area burned at high severity increased from 0.60 to 0.91 since 2000 (Fig. 6). This represents a relatively short period of time but may be further evidence of a shift in climate and fire regimes in the region (Birch et al., 2015; Singleton et al., 2019). As longer-term data become available, future research may determine the extent to which climate is driving this shift in fire activity.

4.4. Climate-fire relationships for individual fires

Our results support prior research that VPD correlates strongly with regional area burned metrics, yet it was unknown whether these results apply at the scale of the individual fires. We found that both minimum and maximum VPD significantly predict the odds of a fire burning with high severity, as well as the percent of high severity within a fire across all vegetation types (Table 3; Appendix D, Table D1). Kane et al. (2015) tested for the effects of climate and fire weather along with biophysical variables on a single fire, the 2013 Rim Fire in Yosemite National Park. They showed that actual evapotranspiration (AET) helped predict burn severity on the Rim Fire, but not in the absence of other biophysical variables. They proposed that the drought conditions prior to and during the Rim fire dried locations that typically had higher productivity and therefore higher fuel loads, resulting in patches of high severity. Our study does not take into account biophysical variables; however, the above study agrees that there is a relationship between water-balance and burn severity that is tied to short- and long-term variation in climate. This also supports the idea that climate can synchronize availability of fuels across a range and reduce the threshold effects of biophysical variables at the scale of an individual fire (Kane et al., 2015).

Notably, temperature was not able to predict the odds of a fire containing high-severity fire for either the area or percent models, or the change in area burned at high severity. Although greater fire severity may often occur when temperatures are high in the Southwest, temperature can be highly variable, especially at the local level and is only indirectly associated with vegetation moisture conditions (Abatzoglou and Kolden, 2013; Seager et al., 2015; Williams et al., 2014). Precipitation was also not a predictor of the odds of a fire burning with high severity for either model, but this is likely because in the Southwest precipitation has high temporal variability. Since the PRISM data are the monthly total for the month of the start of the fire, the temporal mismatch between precipitation and fire occurrence may be adding noise to this relationship. Finally, our analysis does not include vegetation type, although we did account for the percent forest and woodland cover. In essence, fire severity would be weighted by the origin of the high severity with regards to ecological type. Future work is needed to parse out the effects of vegetation on fire severity.

4.4.1. High-severity threshold model

Finally, we developed a high-severity threshold model describing the probability of surpassing a given percent high-severity threshold of fire relative to maximum VPD (Table 4). For example, when maximum VPD is 50 hPa, the probability of a fire containing > 10% high severity, or surpassing the threshold, is 35% when percent forest and woodland cover is held at the median, 64.5% (Table 4). These percentages increase with increasing percent forest and woodland cover. For the same conditions, the probability of a fire containing > 10% high-severity fire when percent forest and woodland cover is 90% is 48%, while a forest with 10% cover would have a 14% probability of surpassing the same threshold (Appendix C, Tables C1 and C2). It should be noted that these are monthly-averaged VPD values and our models do not explicitly account for variability in other variables (e.g. vegetation type or topography). However, this presents a concept that could be used with other variables in the future, and ideally, similar models could be developed with daily values. Using threshold models, based on risk tolerance, values, resources and other factors, managers could decide the percent of acceptable high severity and then identify the corresponding maximum VPD "window" that would give them the best chance to achieve those outcomes. For example, at a maximum VPD of 10 hPa, a fire will not likely (10% chance) include more than 10% high severity, and most of the area burned will most likely be low severity. At a maximum VPD of 30 hPa, however, a fire is more likely (12% chance) to include > 20% high severity, but such a fire will also include more moderate severity fire and therefore consume more fuels. Projecting the potential risk of high-severity fire based on current climate conditions can inform the decision of when and where fire can be used to reach desired fire effects.

5. Conclusions and management implications

Our study used the most comprehensive burn severity dataset available to assess contemporary climate-fire relationships for the Southwest (1984–2015). We observed the strongest relationships between annual area burned and area burned at high severity with VPD, which is an integrated measure of both temperature and moisture. Still, uncertainty in future climate-fire relationships remains, and the variability in the strength of climate-fire relationships may be due to additional factors. First, changes in fire activity are complicated by changes in human land use, land cover, and human ignitions (Hessl, 2011). It continues to be a challenge to disentangle the contributions of climate change from past forest management and fire suppression practices and their influence on the trends in area burned and fire severity. Moreover, although large-scale satellite datasets have proven to be useful tools for detecting change in climate and fire activity, we may still lack a sufficient timespan to distinguish between natural variability versus climate change-induced trends. Furthermore, estimates of future fire activity do not include potential negative feedbacks of fire and climate on vegetation (i.e. persistent drought can reduce plant growth and thus biomass (fuel) production, which paradoxically can reduce fire spread) (Krawchuk and Moritz, 2011).

Still, the results of our analyses and that of others (e.g., Singleton et al., 2019) indicate that area burned, and fire severity have increased over the past three decades and that these trends are strongly correlated to climate. Specifically, an upward trend in VPD has become apparent over the past three decades driven by increases in temperature concurrent with decreases in precipitation amount and increases in the length of rain-free periods (Holden et al., 2018; Jolly et al., 2015; Seager et al., 2015). The exponential relationship between temperature and VPD indicates that continued warming in the Southwest will drive exponential increases in VPD even if precipitation does not change, thereby exacerbating drought conditions (Will et al., 2013) and increasing fire potential (Williams et al., 2013, 2014; Abatzoglou and Williams, 2016). Similarly, a continued decrease in precipitation and the increase in associated fire-season aridity will increase fire potential either directly through its effects on fuel moisture or indirectly via feedbacks to VPD (Holden et al., 2018; Jolly et al., 2015). Therefore, this study and others (e.g. Seager et al., 2015; Williams et al., 2013, 2014) suggest that VPD, which integrates moisture supply and demand, may more directly simulate the local response of climate variability on fire activity than other climate-based or fire-danger metrics (Abatzoglou and Kolden, 2013; Littell et al., 2016; Williams et al., 2014).

Given the forecasted increase in temperatures and VPD and decrease in moisture, observed increasing trends in fire activity will likely continue, until fuels become limiting. There is currently a fire deficit in the region (Parks et al., 2015), and this could pose an opportunity for restoration of historical low- and moderate-severity fire regimes in dry conifer forests that collapsed in the late 1800s. We found that low-severity fire is increasing 10% annually, some of which should represent a restored fire regime, but high-severity fire was also increasing, at an annual rate of 17.3%. To benefit from the continued increase in wildfire, managers will need to find "fire windows" or the right conditions that maximize low and moderate severity fire while minimizing large patches of high-severity fire in most ecosystems. Our high-severity threshold model could be a useful first step in identifying these windows based on maximum monthly VPD. These models can further create opportunity to assist in risk-based wildfire management, potentially allowing for increased fire use based on management tolerance for high-severity fire risk. A better understanding of climate-fire relationships can provide opportunities to restore the historical fire regimes that shaped Southwestern forests and woodlands and will continue to do so in the future.

CRediT authorship contribution statement

Stephanie E. Mueller: Conceptualization, Formal analysis, Data curation, Writing - original draft. **Andrea E. Thode:** Conceptualization, Writing - review & editing, Supervision. **Ellis Q. Margolis:** Conceptualization, Writing - review & editing. **Larissa L. Yocom:** Conceptualization, Writing - review & editing. **Jesse D. Young:** Formal analysis, Methodology, Writing - review & editing. **Jose Iniguez:** Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

See Table A1

Table A1
Table of ARIMA time series model selection and descriptive statistics for fire variables (top) and climate variables (bottom) in forest and woodlanded vegetation (1984 – 2015). Trends are present in all of the fire variables and all but two of the climate variables. Water year is prior Oct – current Sept; fire is May–August. Precip. represents the time period total precipitation. All temp and VPD variables represent the time period averages. All p-values for model fit are significant ($p < 0.05$). Change in area burned is the average annual increase of the trend for large fires (> 404 ha). Mean annual rate of change is equal to drift * 100.

	ARIMA (p,d,q)	RMSE	P-value	Drift	Mean Annual Increase
Fire Data					
Total Area Burned	0,1,1	1.07	0.002	0.0947	4298 ha
Area Burned at High Severity	0,1,1	2.23	< 0.001	0.1729	826 ha
Percent High Severity	0,1,1	0.15	< 0.001	0.0063	0.35%
Area Burned at Low Severity	0,1,1	1.11	0.007	0.09	1204 ha
Climate Data					
Water Year Variables					
Total Precip	0,1,1	8.47	< 0.001	−0.4544	
Mean Temp	2,1,0	0.56	< 0.001	0.0487	
Max Temp	0,1,1	0.68	< 0.001	0.0273	
Min VPD	0,1,1	0.46	< 0.001	0.0378	
Max VPD	0,1,1	1.31	< 0.001	0.0813	
Fire Season Variables					
Total Precip					
Mean Temp	0,1,1	0.62	< 0.001	0.0377	
Max Temp					
Min VPD	0,1,1	0.83	0.005	0.0531	
Max VPD	0,1,1	2.24	< 0.001	0.1032	

Appendix B

See Table B1

Table B1
Pearson's correlation matrix of PRISM climate variables. Many of the climate variables are highly correlated to each other. *Indicates correlation was not significant ($p > 0.05$).

	Fire Season						Water Year					
	Precip	Mean Temp	Max Temp	Min Temp	Min VPD	Max VPD	Precip	Mean Temp	Max Temp	Min Temp	Min VPD	Max VPD
Fire Season												
Precip	1											
Mean Temp	−0.50	1										
Max Temp	−0.66	0.91	1									
Min Temp	−0.22*	0.89	0.62	1								
Min VPD	−0.79	0.80	0.79	0.64	1							
Max VPD	−0.82	0.86	0.92	0.62	0.94	1						
Water Year												
Precip	0.47	−0.74	−0.68	−0.64	−0.73	−0.75	1					
Mean Temp	−0.32*	0.68	0.51	0.73	0.59	0.60	−0.74	1				
Max Temp	−0.24*	0.75	0.67	0.67	0.57	0.62	−0.87	0.79	1			
Min Temp	−0.18*	0.65	0.34*	0.85	0.53	0.46	−0.56	0.86	0.62	1		
Min VPD	−0.55	0.84	0.73	0.78	0.91	0.84	−0.86	0.73	0.79	0.68	1	
Max VPD	−0.53	0.86	0.80	0.74	0.83	0.85	−0.92	0.78	0.90	0.63	0.95	1

Appendix C

See Tables C1 and C2

Table C1
Model predictions of the probability of surpassing a percent high-severity threshold within a fire based on the value of average maximum monthly VPD with percent forest and woodland cover of 10%. The table does not indicate the amount of severity to expect based on VPD, only the probability of crossing a designated threshold.

	Percent High-severity Threshold (>)					
	1%	10%	20%	30%	40%	50%
Max VPD						
0	6%	2%	1%	0%	0%	0%
10	9%	3%	2%	0%	0%	0%
20	14%	5%	3%	1%	1%	0%
30	22%	7%	4%	2%	1%	0%
40	31%	10%	7%	3%	2%	1%
50	43%	14%	11%	7%	5%	2%
60	56%	20%	17%	15%	10%	5%
70	67%	27%	25%	28%	20%	13%

Table C2
Model predictions of the probability of surpassing a percent high-severity threshold within a fire based on the value of average maximum monthly VPD with percent forest and woodland cover of 90%. The table does not indicate the amount of severity to expect based on VPD, only the probability of crossing a designated threshold.

	Percent High-severity Threshold (>)					
	1%	10%	20%	30%	40%	50%
Max VPD						
0	28%	11%	5%	1%	1%	0%
10	39%	16%	7%	2%	1%	0%
20	51%	22%	12%	4%	2%	1%
30	63%	29%	18%	9%	5%	3%
40	74%	38%	26%	18%	10%	7%
50	82%	48%	37%	32%	20%	16%
60	88%	58%	49%	52%	35%	34%
70	93%	67%	61%	71%	53%	58%

Appendix D

See Table D1

Table D1
Distribution of burned area by vegetation type (ERU fire regime type) and slope (degrees) by percent area of total area burned and area burned at high severity.

Vegetation Type (ERU Fire Regime Type)	Total Area Burned	Area Burned at High Severity
Ponderosa Pine	34.13%	32.43%
Mixed Conifer Frequent Fire	15.97%	23.32%
Mixed Conifer with Aspen/Spruce Fir	7.70%	14.79%
PJ Grass/PJ Juniper Grass	16.03%	8.91%
PJ Sagebrush/PJ Woodland	5.90%	7.98%
Madrean	12.35%	6.96%
PJ Evergreen Shrub	7.92%	5.61%
Slope (degrees)		
≤15	62.92%	56.22%
16–30	29.56%	36.58%
31–45	7.27%	7.12%
46–60	0.23%	0.07%
60+	0.02%	0.00%

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