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Wildfire extent and severity correlated with annual streamflow distribution and timing in the Pacific Northwest, USA (1984–2005)

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ABSTRACT

Climate change effects on wildfire occurrence have been attributed primarily to increases in temperatures causing earlier snowpack ablation and longer fire seasons. Variability in precipitation is also an important control on snowpack accumulation and, therefore, on timing of meltwater inputs. We evaluate the correlation of total area burned and area burned severely to snowmelt-induced streamflow timing and total annual streamflow metrics across the Pacific Northwest region from 1984–2005. Principal component scores on total annual water year flow and date of 50th percentile flow (PC1T) in the Pacific Northwest were used as predictors of satellite-inferred area burned and area burned severely in forested settings. Both annual area burned and burned severely are significantly correlated with mean annual flow and streamflow timing. PC1T alone explains 24% of the variability in annual area burned. Path analysis suggests that a substantial amount of the variability in annual area burned, previously attributed solely to temperature effects on melt timing, may be primarily driven by trends in precipitation and total annual streamflow. Principal component analysis scores on mean annual streamflow explain as much as 46% of the variability in annual area burned from 1984–2005. Thus, although streamflow timing may be a better single correlate of annual wildfire activity, timing is, in turn, strongly dependent on precipitation. These results suggest that recent fire activity in forests of this region are influenced more by precipitation variability than temperature-induced shifts in snowmelt timing, with significant implications for our ability to predict wildfire activity in the future. Published in 2011. This article is a US Government work and is in the public domain in the USA.

KEY WORDS fire severity; burn severity; streamflow; climate change; annual area burned

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INTRODUCTION

Wildfires represent one of the most direct, visible and societally important natural phenomenon associated with climate and climate change. With recent intense efforts in global climate modeling and the growing availability of climate change projections for planning efforts, understanding the relative sensitivities of wildfire occurrence to temperature and precipitation-related changes is important for interpreting the implications of future climate for wildfire activity. Much of the effect of global climate change on streamflow timing has been attributed primarily to increases in winter temperatures causing reduced snowpack accumulation for a given amount of precipitation (Mote *et al*., 2005; Stewart *et al*., 2005; Knowles *et al*., 2006). However, variability in precipitation is also an important control on snowpack accumulation, and therefore, on timing (Mote *et al*., 2005; Stewart *et al*., 2005; Moore *et al*., 2007; Luce and Holden, 2009). The distinction in mechanism between warming-induced changes and precipitation-induced changes is important because global circulation models (GCMs) produce robust estimates of temperature changes with climate change, but are less reliable for predicting future precipitation patterns (IPCC, 2007).

The sensitivity of wildfires to climate forcing is well known. Dendroecological studies have linked historical forest fire frequency to both Pacific and Atlantic ocean sea surface temperature indices in the southwestern and western US (Kitzberger *et al*., 2007) and in the US northern Rocky Mountains (Heyerdahl *et al*., 2008). Digital maps of 20th-century fire occurrence or fire atlases have been used to show that years with synchronous, widespread fire tend to occur when warm, dry summers follow warm springs in forests of the US northern Rockies (Morgan *et al*., 2008). Littel *et al*. (2009) showed that area burned in the western US is strongly linked to climate in the antecedent and year of fire, and that these climate drivers of area burned vary by forest and other vegetation types. Westerling *et al*. (2006) showed correlations between increasing number of large fires and the early onset of spring. These and other studies implicate primarily recent warming trends while also acknowledging the role of natural climatic variation as a driver of trends in fire activity in the western USA. It is important that we understand the patterns and mechanisms driving variation in inter-annual fire activity, and the degree to which they

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are associated with climate warming versus precipitation changes, if we are to reliably predict future fire extent.

Although past studies have correlated wildfire area burned or fire frequency with past climate, little is known about how ecological effects, often termed burn severity, of those fires are related to climate. Given our growing sensitivity to the ecological importance of wildfires across nearly all forested ecosystems, it is these ecological effects that are ultimately of greatest concern. Although natural in many ecosytems, wildfire is often managed to reduce anticipated impact on what are seen as high value resources such as homes, endangered fish populations, or threats to water quality.

Recent fire activity is of particular interest in the northwestern USA, where significant climatic change has been observed during the last 50 years. Changes in temperature have been observed during recent decades relative to the last century (Mote, 2003b). Warmer temperatures have led to declining snowpack across much of the western USA (Mote, 2003a; Mote *et al*., 2005). Recent warming trends have also contributed to shifts toward early onset of spring (Cayan *et al*., 2001), a trend that is reflected in patterns of annual streamflow timing (Stewart *et al*., 2005). More recent work has identified trends in annual streamflow in the Pacific Northwest (PNW) (Luce and Holden, 2009; Clark, 2010; Fu *et al*., 2010), which could also play an important role in fire occurrence and severity trends. The shifts to earlier streamflow and the recent increases in the frequency of wildfires, wildfire area burned, and lengthening fire seasons (Westerling *et al.* 2006) are likely correlated because they are both driven by temperature and precipitation.

The influences of winter precipitation, snowpack, and spring temperatures on the resulting distribution and timing of streamflow are complex. Recent studies have pointed to the direct link between total annual streamflow and the date of 50th percentile flow (Moore *et al*., 2007; Luce and Holden, 2009). More winter precipitation produces deeper snowpacks, which produce more streamflow and take longer time to melt. Snow cover and spring air temperatures are correlated, making identifying causal mechanisms of snowmelt timing difficult. Luce and Holden (2009) noted declines in total annual streamflow and changes in the probability distribution of annual streamflow in the PNW 1948–2006. Trends in mean annual streamflow were observed at the majority of stream gage stations, and 72% of the gages they analyzed showed significantly declining trends in streamflow during years in the 25th percentile (i.e. low flow years). These results suggest that dry years are becoming drier in this region, a trend which could have major implications for a range of ecological responses, including wildfire activity. Because of the link between total streamflow and timing, as mediated through snow accumulation and melt, these trends in dry years suggest the possibility that historical trends in wildfire area burned resulted, at least in part, from trends in precipitation during the last half-century as opposed to or in addition to changes in streamflow timing attributable to warming winter and spring temperatures affecting snow accumulation and snowmelt timing. Low streamflow does not cause extensive fires, but the correlation can nonetheless be useful in explaining mechanisms of change. Although it has been noted that fire occurs in dry years as well as in early snowmelt years, that the two results are related is important for future prediction of forest fire extent. Although warming trends for the future have high certainty, regional precipitation forecasts for a changing climate are less reliable (IPCC, 2007).

In this study, we examined area burned and area burned severely during a 22-year period (1984–2005) relative to annual streamflow metrics in the PNW region of the USA. Because total annual streamflow is directly related to the timing of 50th percentile flow, we use path analysis to explore the relative contribution of total streamflow versus timing on annual wildfire area burned and area burned severely. We recognize that streamflow timing and total flow do not directly influence wildfire, but are proxies for watershed-scale unmeasured soil and fuel moistures, where early and low streamflows both reflect drier conditions. Although total runoff is essentially an independent function of total precipitation, it is the total precipitation combined with temperature during precipitation events that affects snow-to-water ratios in precipitation, depth of snowpack accumulation and ultimately timing, at least in snow-dominated regions. Thus, through its connection to total precipitation, we expect annual streamflow to be correlated with both streamflow timing and wildfire area burned. In contrast, streamflow timing is likely to have a previously noted influence on wildfire area (Westerling *et al*., 2006), but little mechanistic influence on total streamflow. By examining the relative contributions of timing and total streamflow on wildfire area, we can gain more insights about the relative role of temperature versus precipitation variation on wildfire extent.

METHODS

Study area

Our analysis encompassed fires that burned in the US PNW, a region that included Washington, Oregon, Idaho, western Montana, and northwestern Wyoming (Figure 1). This area is heterogeneous in terms of vegetation, topography, and climate (Miller and Goodrich 2007), it has experienced extensive fires historically (Heyerdahl *et al.* 2008) and in recent decades (Morgan *et al.* 2008), some of which have burned severely.

Fire extent and burn severity data

Data for wildfire area burned and area burned severely came from satellite-derived maps of fire extent and burn severity from the Monitoring Trends in Burn Severity (MTBS, www.mtbs.gov) project (Eidenshink *et al*., 2007). We used data from 1788 fires (1984–2005) that burned forests in the PNW region. A fuzzy C-means algorithm (Hartigan and Wong, 1979) was applied to the continuous relative differenced normalized burn ratio MTBS (Miller and Thode, 2007) burn severity data following the methods

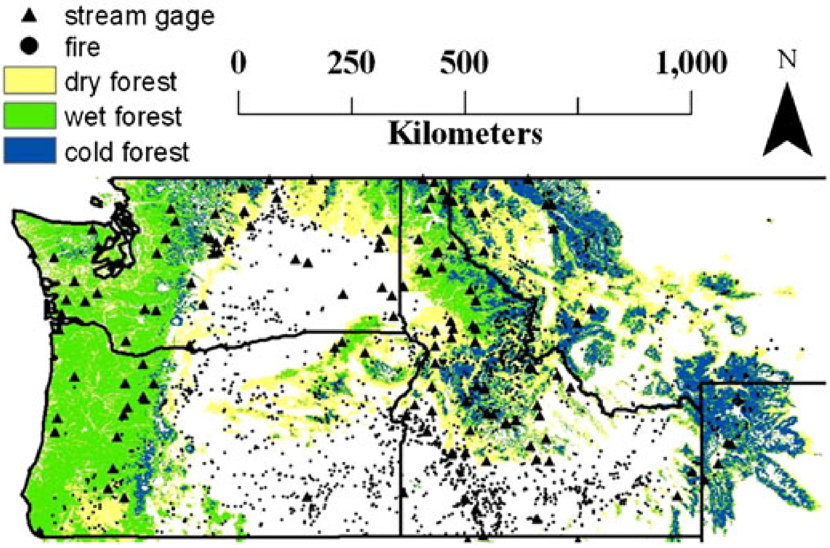

Figure 1. Study area extent with stream gage locations (triangles) and individual fire locations (points).

described by Holden and Evans (2010). Area burned and area burned severely were then summed by year and log-transformed, yielding a 22-year vector of two response variables (log-transformed area burned and log-transformed area burned as high severity). These data gave a short time series and represented only large ($>4\,\text{km}^2$) fires, but had several important advantages over previous data sources of fire activity (e.g. point record estimates of area burned and digital polygon atlases). Because the estimated area burned was derived from satellite images (rather than memory or hand-drawn field maps), they were consistent and likely spatially accurate depiction of burned areas, including unburned islands and complex fire perimeters. Second, these data allowed us to infer, based on changes in pre-fire and post-fire near-infrared and short-wave infrared reflectance, the magnitude of overstory vegetation change associated with each wildfire.

We contrasted fire-streamflow relationships by forested biophysical settings across the PNW using 30-meter landfire environmental site potential (ESP) data (www.landfire.gov). ESP named similar sites for the vegetation that would develop in long absence of disturbance. We grouped 89 ESP classes into seven coarse site classes (grassland, dry shrub, wet shrub, woodlands, dry forests, wet forests, and cold forests). Area burned by burn severity class (low, moderate, and high severity) within each ESP class was then calculated for each fire and summed by year. All non-forested ESP types were excluded from this analysis.

Principal components analysis and interpretation

PCA on mean annual flow. We used principal components analysis (PCA) to explore the spatial and temporal patterns in annual streamflow among 61 snowmelt-dominated streams using data from stream gage stations in the PNW region. Data from each stream gage were first weighted by the contributing basin area and then log-transformed. PCA on annual water year flow from 1984–2005 showed strong spatial loading patterns with three principal modes of variability that explain 90% of the variance in annual streamflow during this period (Figure 2). We interpreted PCA scores by examining correlations between them and seasonal to annual precipitation across 31 climate divisions using data from the NOAA National Climatic Data Center (http://www7.ncdc.noaa.gov/CDO/DIV_DESC.txt). The first principal component on annual streamflow (PC1F) explained 72% of the common variance in mean streamflow among all stations and was highly correlated to winter precipitation at climate divisions across the region (Figure 3). Interpolated PC1F loading surfaces showed strong regional coherence in annual flow among stations during this time period (Figure 2). The second PC loading (PC2F) on annual streamflow explained 14% of the variability in annual flow among stations and was correlated to July–September precipitation. An interpolated PC2F loading surface revealed a strong north–south gradient, likely reflecting sub-regional variation in convective storms along the Rocky Mountains (Figure 2). PC3F explains only 4% of the variability in regional annual streamflow and showed a correlation to May precipitation across the region (Figure 3), suggesting that spring precipitation may play a more important role in some basins compared with others.

PCA on 50th-percentile flow date. Following Westerling *et al.* (2006), we extracted the first principal component calculated on the date of 50th-percentile streamflow for 61 snowmelt-dominated streams using data from HCDN streamflow stations (1984–2005). Herafter, we refer to this variable as PCIT. The first principal component on date of 50th-percentile flow across 61 stream gages explained 45% of the variability among stations.

Statistical analyses

Regression models of fire-streamflow relationships. We evaluated statistical relationships of annual area burned and area burned severely (both natural log transformed) to

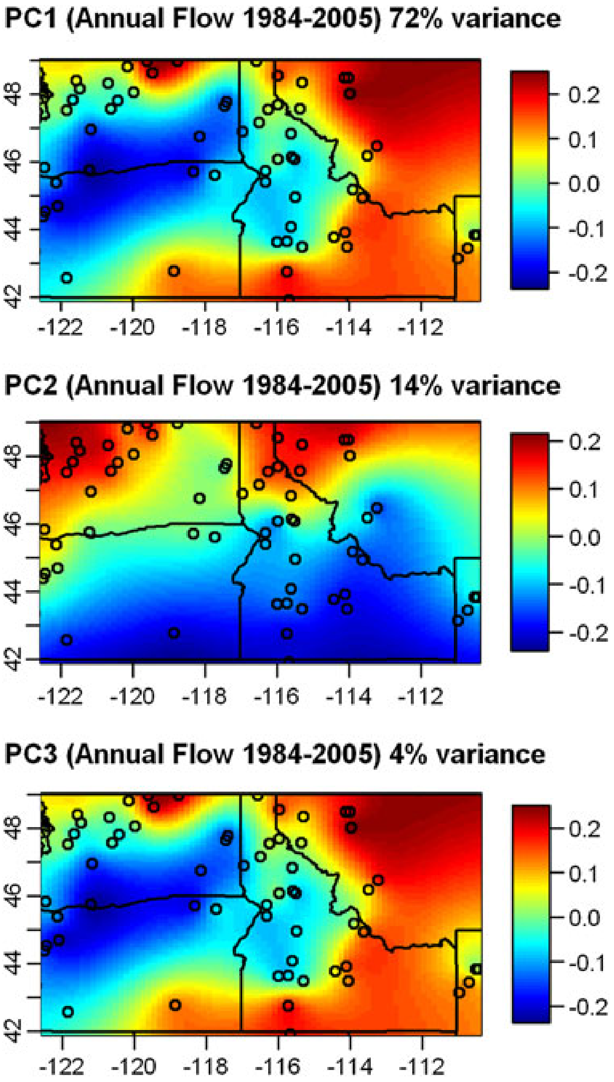

Figure 2. Surfaces interpolated from principal component loadings of mean annual streamflow across 61 stream gage stations (1984–2005). Colors represent from negative (blue) to positive (red) spatial loading patterns. PC1, PC2, and PC3 explain 72, 14, and 4% of the variance in mean annual flow, respectively.

principal component scores for both annual streamflow and streamflow timing.We compared a series of candidate models using different combinations of PC scores on mean annual streamflow (PC1F, PC2F, PC3F) and PC1T, using the Akaike information criteria (AIC) (Akaike, 1974) as a means of assessing model parsimony (Table I). Rather than select a single model, we presented coeffcients of determination, log likelihood and AIC values for six competing models to allow the reader to evaluate the significance values and the cost of including additional predictor variables at the expense of degrees of freedom in the model. Finally, we evaluated the relative sensitivity of area burned and area burned severely in different forest types to streamflow metrics, stratifying burn severity data by forest biophysical setting.

Path analysis

We examined the relationship between wildfire activity and total annual streamflow and streamflow timing using path analysis. Path analysis is an application of multiple regression that seeks to identify the underlying relationships among sets of correlated variables (Wright, 1934; Alwin and Hauser, 1975). Path analysis uses consideration of mechanisms through logical constructs to assess both direct and indirect effects of covariates on a process of interest (Wright, 1934; Alwin and Hauser, 1975). In this case, we were interested in relating area burned and area burned severely to underlying climate drivers as reflected in both streamflow timing and total streamflow.

For path analysis, we used a simple influence diagram with annual streamflow as an exogenous variable (X_1) with two endogenous variables: streamflow timing (X_2) and wildfire area burned (X_A) (Figure 4). Within this simple model, the effects of temperature on streamflow timing were lumped with all other external effects on timing not related to the direct influence of annual streamflow (X_u). Similarly, all other effects on wildfire area for a given year, including effects from fire suppression efforts, were treated as random effects (X_v). For this analysis, we assumed these other influences were correlated neither to each other nor to the measured variables to which they were not directly connected. This allowed for substantial simplification of the structural equations and interpretation of the decomposition (Figure 3):

$$X_A = p_{A1}X_1 + p_{A2}X_2 \tag{1}$$

$$X_2 = p_{21}X_{1,} \tag{2}$$

where the path coefficients p, are the direct effects between the subscripted variables. These effects can be directly estimated as the standardized reqression coefficients from the measured variables. The total effect of streamflow on wildfire area, q_{a1}, then is given as

$$q_{A1} = p_{A1} + p_{A2}p_{21} \tag{3}$$

where $p_{A2}p_{21}$ is both the indirect effect of streamflow on area burned and the spurious effect of timing on fire area because of correlation with annual flow.

RESULTS

The percentage of burned area classified as high severity varied from 16 to 32%, with a mean of 24% for the 1788 fires analyzed. No statistically significant relationships were found between the percentage of area burned as high severity and streamflow metrics. Annual area burned and area burned severely were strongly and positively correlated ($r^2 = 0.93$; Figure 5). Because area burned and area burned severely were so strongly correlated, and to be consistent with other studies, we focused here on total area burned in forested environments. However, analysis results were similar when area burned severely was used as a response variable. Regression model results using PC scores 1, 2, and 3 on annual flow and PC1T as predictors of

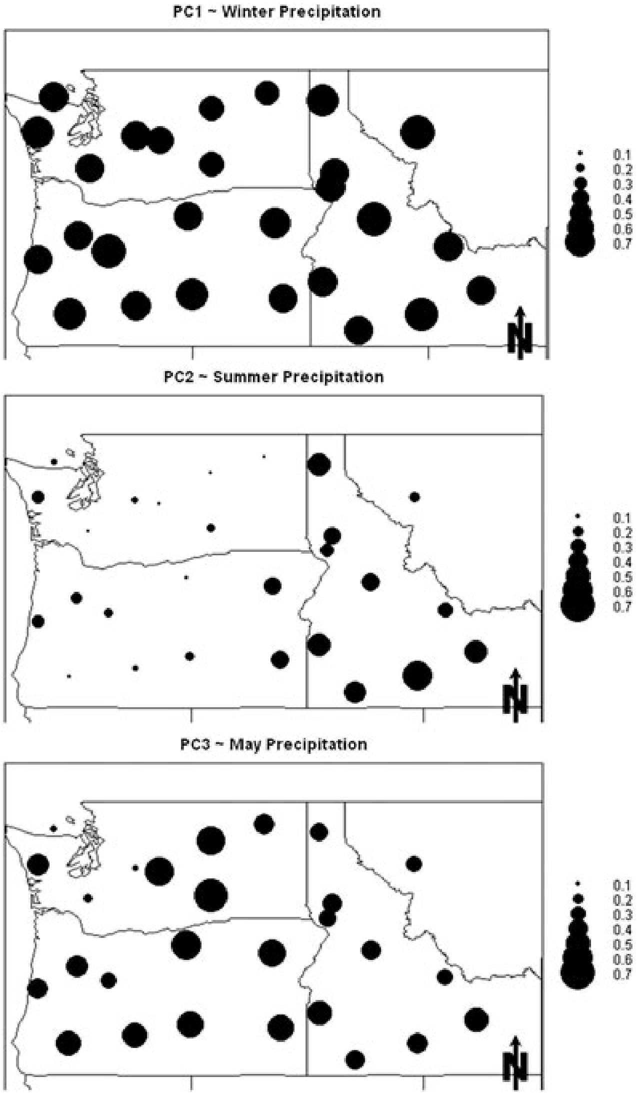

Figure 3. Pearsons correlations between winter (DJF), summer (JJA) and May precipitation for 31 climate divisions and PCA scores on mean annual streamflow across 61 stream gages.

Table I. Log likelihood (logLik) and Akaike information criteria (AIC) for linear models with area burned as a response and principal component scores on annual streamflow (1984–2005) as predictor variables. The two Best models are highlighted in bold. Six models are shown to allow the reader to evaluate tradeoffs between model significance and including additional variables in the model.

Model	logLik	AIC	ΔAIC	R^2 (adj.)
Area burned ~ PC1F + PC2F × PC3F	**−32.3**	**78.1**	**0.0**	**0.471**
Area burned ~ PC1F + PC2F × PC3F + PC1T	**−33.1**	**78.7**	**0.6**	**0.466**
Area burned ~ PC1F + PC2F + PC3F	−37.7	83.4	4.2	0.35
Area burned ~ PC1F + PC2F	−37.7	83.5	5.0	0.28
Area burned ~ PC1T	−38.6	83.1	7.2	0.24
Area burned ~ PC1F	−37.7	84.5	7.2	0.18

wildfire area burned are shown in Table I. Annual area burned was weakly, but significantly correlated with PC1F ($R^2 = 0.18$, $p = 0.03$). Annual area burned was weakly, but significantly correlated with PC1T on streamflow timing ($R^2 = 0.24$, $p = 0.02$). Three PC scores on mean annual streamflow explained as much as 46% of the variability in area burned (Table I). Area burned in dry forests was relatively insensitive to both streamflow timing and flow. Wet and cold forest types showed much greater sensitivity to both streamflow timing and annual flow (Table II). Although PC1T was more strongly correlated with wildfire area than PC1F, about half of this effect was through the influence of PC1F on PC1T. When these influences were accounted for, the relative importance of total annual streamflow was greater ($q = 0.49$) than timing alone ($q = 0.17$) to area burned (Figure 4).

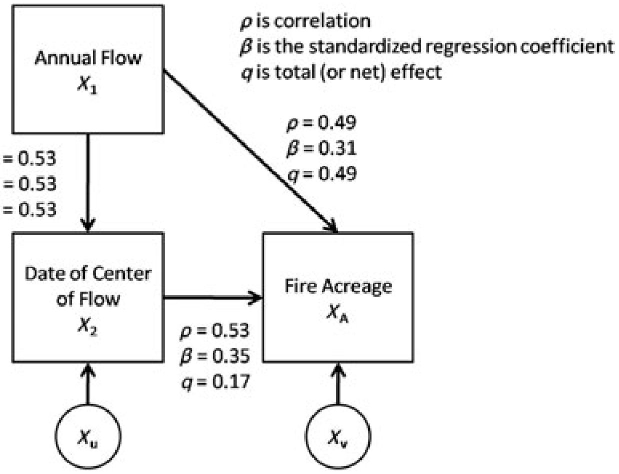

Figure 4. Causal pathway diagram for estimating the relative influence of total streamflow and timing of streamflow on wildfire area burned.

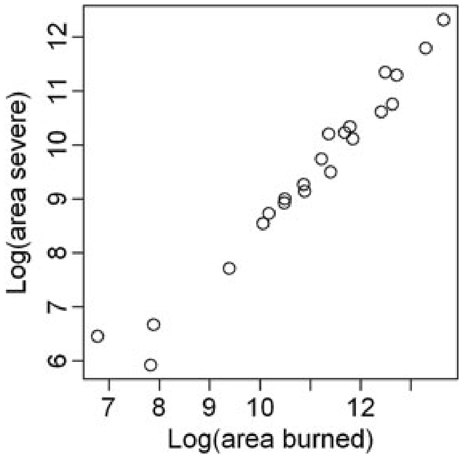

Figure 5. Annual forested area burned in the PNW region (1984–2005) and area burned as high severity are closely related, with a slope close to one indicating a relatively constant fraction burning severely each year.

Table II. Correlations (adjusted R^2 values) and p-values for linear models using PC scores on timing and annual streamflow as correlates of area burned in different forested biophysical settings. Significant correlations ($p \leq 0.05$) are highlighted in bold.

Predictor of area burned	PC1T	PC1F	PC1F + PC2F	PC1T + PC1F + PC2F
	R^2	R^2	R^2	R^2
Dry forests	0.09	0.04	0.11	0.09
Cold forests	**0.24**	**0.17**	**0.18**	**0.26**
Wet forests	0.07	0.12	**0.38**	**0.31**
Wet/cold forests	**0.21**	**0.16**	**0.30**	**0.35**

DISCUSSION

Recent discussion about the potential effects of climate change on wildfire activity have focused primarily on warming spring temperatures and early snowmelt timing as well as warm, dry summers (Running 2006; Westerling *et al.* 2006; Heyerdahl *et al.* 2008; Morgan *et al.* 2008). Our analyses suggest that precipitation, inferred from annual streamflow, significantly influenced area burned from 1984–2005. Furthermore, because the total volume of water passing a stream gage is mechanistically related to the date at which 50% of that water passes a gage, at least some of the influence of snowmelt and streamflow timing on recent fire activity can be attributed to nonstationarity in the probability distribution of annual streamflow, rather than timing alone. This has important implications to our ability to predict the impacts of climate warming on wildfire activity. Global climate model (GCM) estimates of the magnitude of projected temperature increase under various emmission scenarios all predict warming in the US northern Rocky Mountains over the next century. In contrast, there is tremendous uncertainty in predictions of future precipitation variability across this region, with some GCM's predicting decreases and some increases in annual precipitation over the next century. If recent trends in wildfire activity are influenced more strongly by precipitation variability rather than temperature, it may be harder to predict the consequences of climate change for future wildfire area burned and area burned severely than previously assumed. A warming climate will undoubtedly have impacts on the snow hydroclimatology and subsequently wildfire regimes of the PNW, but uncertainty in precipitation projections leaves room for suprises in future wildfire activity across the region.

That correlations between area burned and annual streamflow and streamflow timing are significant for wet and cold forest biophysical settings, but not for dry forest sites is consistent with the observation that relative to dry forests, wet and cold forest biophysical settings are less likely to burn (Schoennagel *et al.*, 2004). In both cold and wet forest biophysical settings, large areas burn only when it is very hot, dry and windy following long periods of drying, whereas dry forests are likely to burn under these as well as less extreme climatic conditions (Morgan *et al.* 2008). This is in part a reflection of our data, which are limited to larger fires, many of which have escaped initial fire suppression efforts because they are typically burning under relatively hot, dry, and windy conditions.

It is often difficult to confidently infer meaningful temporal patterns in short data time series. The correlations described here are somewhat weak. Area burned has likely been influenced by many non-climatic factors, including fire suppression efforts and management objectives, availability of fire fighting resources, as well as weather, terrain, and vegetation conditions unique to each fire. Such factors contribute significant noise to these data. Climate, topography, and vegetation distribution in the PNW region are all highly variable across space and through time. In addition, MTBS data include only fires greater than approximately 400 ha. Thus, it is possible that summarizing fire data across the entire region also introduces significant variation, as evidenced by the significant relationship between area burned and PC2 on annual streamflow. However, relationships between annual streamflow and fire extent and severity are strong enough to support the connections we found.

Although we focus here on terrestrial ecosystems and fire outcomes, there may be important implications of these findings for understanding climate change effects on aquatic ecosystems as well, in considering the interactions of fire effects with streamflow changes. Fires can significantly impact fish populations via a number of mechanisms (Gresswell, 1999; Bisson *et al.*, 2003); effects on habitat can be detrimental, neutral, or beneficial and may be different for short and long-term periods (Rieman *et al.*, 2010). Where fires burn more severely in riparian areas, water temperatures may increase leading to increased stress in fish populations (Dunham *et al.*, 2007; Isaak *et al*, 2010). Changes to the riparian vegetation also alter food supplies and woody material availability for habitat (Dwire and Kauffman, 2003). Where severely burned patches are very large on steep slopes near streams, the probability of post-fire debris flows increases (Istanbulluoglu *et al.*, 2002; Cannon *et al.*, 2010). Debris flows directly impact local fish populations, and at the same time, they are important for long-term development of gravels (Benda *et al.*, 2003; May and Gresswell, 2003). Consequently, changes in fire frequency and severity under a changing climate will have substantial effects on aquatic systems. If the effects of climate change on fire are treated independently of effects on streamflow changes in forecasts, we may inadequately capture the effects of co-ocurring fire and drought. In other words, if fires are expected to increase simply as a result of warming with an assumed stationary streamflow distribution, we develop a forecast where fires may be widespread in relatively mesic years and lose the context that the consequences of these fires are happening in drought years, when streams are warmest and aquatic populations are already most stressed.

One could take the line of logic offered by mating the GCM model output for the PNW (e.g. Elsner *et al.*, 2010) to our results to conclude that if precipitation is relatively stationary with respect to anthropogenic climate change, streamflow and wildfire should both just vary naturally with existing precipitation cycles. Although this would seem a logical extension, it misses an important point. What these results mean is that if we want to forecast the future of aquatic resources and the terrestrial and aquatic ecosystems that depend on them, we will need to better understand the influence of climate change on non-stationarity in the mean and, particularly, the variability of precipitation. The influence of precipitation variability on wildfire far outstripped the influence of temperature variability. Because GCMs perform poorly for precipitation, particularly in mountainous areas (IPCC, 2007), and because ensemble runs do not reliably represent inter-annual variability (Sperna Weiland *et al*, 2010), other approaches are needed to generate expectations for future assessments of ecological changes related to changes in water availability.

CONCLUSIONS

We explored relationships between wildfire area burned and annual streamflow in forested biophysical settings of the PNW region. Both annual area burned and area burned severely were weakly, but significantly correlated with metrics of total annual streamflow and streamflow timing ($r^2 = 0.18$ and 0.24 respectively). In dry forest biophysical settings, area burned is relatively insensitive to any streamflow metrics, suggesting that windows for burning in some forest types are generally available in any given fire year. In cold forest types and wet forest types, annual area burned showed greater sensitivity to streamflow timing and annual flow, respectively. The time-series of data are too short to evaluate temporal trends. However, these results suggest that if annual streamflow, an indicator of precipitation and water availability, continues to decline, wildfire area burned and area burned severely in forests of the PNW could continue to increase. Furthermore, because total annual streamflow strongly influences date of 50th-percentile streamflow, some of the influence of snowmelt timing on recent wildifre activity may be attributable to historical precipitation trends rather than to temperature trends alone. These results have important implications for our ability to predict the impacts of climate warming on future wildfire activity. MTBS data are valuable for understanding landscape and regional-scale variation in the extent and ecological effects of wildfires in the USA. Future work focused on the relative, interacting influences of climate, topography, vegetation, and land use on wildfire severity should enhance our understanding of wildfire ecology and management.

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