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Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003

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Abstract. The purpose of this paper is to quantify climatic controls on the area burned by fire in different vegetation types in the western United States. We demonstrate that wildfire area burned (WFAB) in the American West was controlled by climate during the 20th century (1916–2003). Persistent ecosystem-specific correlations between climate and WFAB are grouped by vegetation type (ecoprovinces). Most mountainous ecoprovinces exhibit strong year-of-fire relationships with low precipitation, low Palmer drought severity index (PDSI), and high temperature. Grass- and shrub-dominated ecoprovinces had positive relationships with antecedent precipitation or PDSI. For 1977–2003, a few climate variables explain 33–87% (mean = 64%) of WFAB, indicating strong linkages between climate and area burned. For 1916–2003, the relationships are weaker, but climate explained 25–57% (mean = 39%) of the variability. The variance in WFAB is proportional to the mean squared for different data sets at different spatial scales. The importance of antecedent climate (summer drought in forested ecosystems and antecedent winter precipitation in shrub and grassland ecosystems) indicates that the mechanism behind the observed fire–climate relationships is climatic preconditioning of large areas of low fuel moisture via drying of existing fuels or fuel production and drying. The impacts of climate change on fire regimes will therefore vary with the relative energy or water limitations of ecosystems. Ecoprovinces proved a useful compromise between ecologically imprecise state-level and localized gridded fire data. The differences in climate–fire relationships among the ecoprovinces underscore the need to consider ecological context (vegetation, fuels, and seasonal climate) to identify specific climate drivers of WFAB. Despite the possible influence of fire suppression, exclusion, and fuel treatment, WFAB is still substantially controlled by climate. The implications for planning and management are that future WFAB and adaptation to climate change will likely depend on ecosystem-specific, seasonal variation in climate. In fuel-limited ecosystems, fuel treatments can probably mitigate fire vulnerability and increase resilience more readily than in climate-limited ecosystems, in which large severe fires under extreme weather conditions will continue to account for most area burned.

Key words: adaptation; antecedent climate; climate; climate change; drought; ecoprovinces; ecosystem management; fire; forest; fuels; gamma distribution; resilience.

Introduction

The area burned annually by wildfire in the western United States influences policy decisions and future land use planning of public land management agencies. The nationwide area burned on federal agency lands increased since the mid-1970s (Agee 1997, Kasischke and Turetsky 2006, Westerling et al. 2006), capped by a string of years with large areas burned between 2000 and 2004 (NIFC 2005). Suppression costs incurred by all agencies have approached or exceeded one billion dollars (US$) per annum in recent years (Calkin et al. 2005, NIFC 2005). These trends have led to speculation that fire suppression caused increasing fire area by producing unprecedented fuel accumulations across the West. However, fire extent and frequency are products of interacting factors other than suppression operating at multiple spatial and temporal scales (Keeley et al. 1999, Johnson et al. 2001, Bridge et al. 2005, Cumming 2005, Stephens 2005). It is possible, for example, that other factors, not just suppression, led to the recently observed increase in area burned (Stephens 2005). Among these factors, climate appears to be an

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important driver of fire area (Stephens 2005) and frequency (Westerling et al. 2006). The importance of understanding the causes of the increase in fire area burned during the late 20th century is underscored by the cost associated with fire suppression and the ecological effects that land managers must confront. Even if the predominant factor influencing increased area burned across the West is changes in fuel structure and composition, the role of climate must be understood in order to weigh the relative importance of mitigating the risk associated with increased fuels via fuels treatments and/or adapting to future fire regimes via changes in management policy.

From an ecological standpoint, the annual area burned by fire across the western United States has little meaning because a diversity of natural fire regimes, vegetation types, and fire severities produces a broad range of ecological responses to a given area burned. It is therefore difficult to assign terms such as "unprecedented," "catastrophic," or "unnatural" to fire years based on area burned without a meticulous accounting of the ecological severity (sensu Romme 1980, Agee 1993) and ecosystem context (vegetation type, natural fire regime, fire suppression history, and impact on ecosystem services) of each fire contributing to the annual total. It is also likely that not all ecosystems with increasing trends in wildfire area burned (WFAB) have increases in fuel accumulation caused by fire exclusion, especially when the time frame of effective fire exclusion approximates or is less than the range of return intervals characteristic of fire regimes (Johnson et al. 2001, Schoennagel et al. 2004).

Fire history evidence from diverse climate regimes and forest types suggests that fire regimes were strongly controlled by climate prior to Euro-American settlement and subsequent fire exclusion and fire suppression (Swetnam 1990, Larsen 1996, Barrett et al. 1997, Swetnam and Betancourt 1998, Veblen et al. 2000, Brown and Shepperd 2001, Heyerdahl et al. 2002, 2008, Taylor and Skinner 2003, Weisberg and Swanson 2003, Hessl et al. 2004, Brown et al. 2005). These presettlement fire histories demonstrate a strong correlation between low precipitation and years of widespread fire, consistent with a regional depletion of soil moisture that leads to low moisture in foliage or in fine, dead surface fuels and ultimately, the potential for widespread fire (Swetnam and Betancourt 1998). Some fire histories in the American Southwest also demonstrate a lagged relationship with above-average antecedent precipitation (Swetnam and Betancourt 1998) and/or cooler temperatures (Veblen et al. 2000) in the year(s) prior to years of widespread fire. This observed relationship may be caused by anomalously low temperatures and high precipitation that reduce the normal climatic constraints on fine fuel production (Knapp 1995, Swetnam and Betancourt 1998), resulting in higher fine-fuel continuity and increased potential for widespread fire in subsequent years. Years of widespread fire in fire histories are positively correlated with increased antecedent precipitation (Swetnam and Betancourt 1998).

Climate–fire relationships during the mid to late 20th century parallel those in the fire history record. From 1980 forward, WFAB on federal lands (USDA Forest Service [USFS], U.S. Department of Interior Bureau of Land Management [BLM], National Park Service [NPS], and Bureau of Indian Affairs [BIA]) was related to monthly Palmer drought severity index (PDSI), and the sign and magnitude of the relationships were consistent with reconstructed fire histories (Westerling et al. 2003). The additional temporal precision allowed by monthly observed climate and WFAB records also suggested region-specific seasonal mechanisms stemming from latitudinal and altitudinal differences in ecosystem structure and the onset of the fire season (Westerling et al. 2003). These relationships were strong enough to produce PDSI-based forecasts of WFAB (Westerling et al. 2002, 2003, 2006). These relationships were then hindcast to 1701 (Westerling and Swetnam 2003) using reconstructed PDSI and validated against fire scar reconstructions of annual fire extent in the Southwest (Westerling and Swetnam 2003). However, the lack of complete high-resolution area-burned data for all agencies prior to 1980 has hindered climate- and ecosystem-specific analyses of wildfire in the early and mid 20th century.

The WFAB data from a variety of sources have been aggregated annually since 1916 at the state level, first from USDA Forest Service and Department of Interior annual fire statistics reports (e.g., USDA 1937–1967, USDA 1968–1990, USDA 1998) and later from archived information at the National Interagency Fire Management Integrated Database (e.g., USDA 1993). These records span much of the 20th century and have allowed analyses of longer-term WFAB–climate relationships. McKenzie et al. (2004) constructed linear regression models of the state-level WFAB as a function of summer (June, July, August) temperature and precipitation in 11 western states: Arizona (AZ), California (CA), Colorado (CO), Idaho (ID), Montana (MT), New Mexico (NM), Nevada (NV), Oregon (OR), Utah (UT), Washington (WA), and Wyoming (WY). Collins et al. (2006) used a similar data set to attribute regional area burned to major modes of coupled ocean–atmosphere variation. These analyses of the state-level data point to the need for an in-depth analysis of seasonal climate relationships with area burned, but the lack of ecological specificity in fire data aggregated by states limits application to regional or continental scales.

Previous research has frequently focused on the relatively short-term timescale of atmospheric events related to area burned by fires (e.g., Gedalof et al. 2005). Synoptic climatology during the fire season is the main driver of fire weather and along with topography, landscape structure, fuels, number of ignitions, and fire suppression resources and strategy, affects the area burned by a given fire event. The role of atmospheric

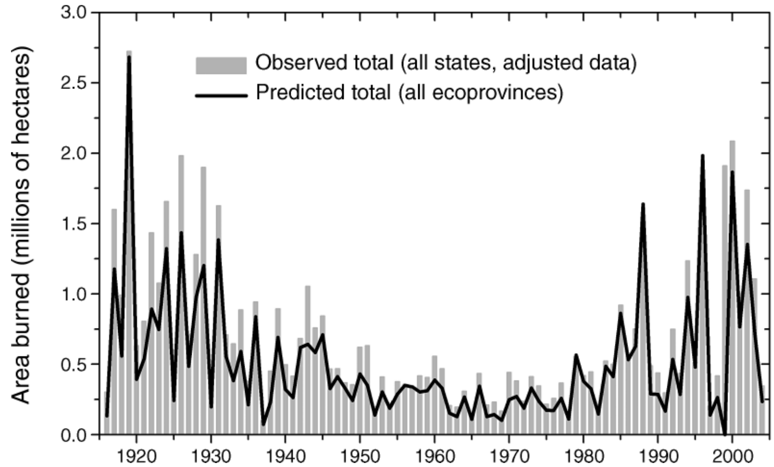

FIG. 1. Observed and reconstructed area-burned comparison. Time series of observed total wildfire area burned (WFAB) for 11 western U.S. states (bars, adjusted for area reporting bias) and reconstructed total WFAB for 16 ecoprovinces (line) for the period 1916–2004.

and sea surface temperature patterns in large fires has been well described in both Canada (Flannigan and Harrington 1988, Johnson and Wowchuck 1993, Skinner et al. 1999, 2002, 2006, Gillett et al. 2004) and the United States (Schaefer 1957, Schroeder 1969, Gedalof et al. 2005, Liu 2006, Trouet et al. 2006). The role of seasonal to interannual climate variation has received less attention, but the importance of extreme fire weather and ignitions is often contingent on climatic factors operating at longer time scales that influence fuel moisture and continuity.

The mid-20th-century decline and subsequent increase in annual West-wide WFAB fit a hypothesis of increasingly effective fire suppression and fuel accumulation (Fig. 1; Agee 1993, Pyne 1997), but evidence from paleo and modern fire histories indicates the combined influence of climate, vegetation, land use, and land management is likely a strong contributor to total variation in WFAB, with regional and local differences in the relative influence of these factors producing the aggregated response (Stephens 2005). A common working ecological hypothesis is that the relationship between climate and fire is mediated by vegetation structure and composition and sensitivity to moisture at the broad scales of ecoprovinces (e.g., Westerling et al. 2002, McKenzie et al. 2004). More specifically, the area burned by fire in any given year is indirectly related to climate through climatic influence on fuels (e.g., Carcaillet et al. 2001) via the production and drying of vegetation. Evidence of this would be different ecoprovince WFAB sensitivities to climate consistent with the dominant vegetation composition in an ecoprovince. Although ecoprovinces are large, classify vegetation only coarsely, and have inherent within-province diversity, consistent repetition of similar climate–fire patterns across similar ecoprovinces would indicate an important relationship between climate and fuels in the ecoprovince fire regime. Testing this hypothesis would lead to an ecosystem-specific set of climate–fire–vegetation relationships useful to land managers faced with mitigating the vulnerability of ecosystem services such as water resources, forest products, habitat for species of concern, and recreation.

In this paper we focus on large-scale, interannual to seasonal climate (precipitation, temperature, and drought) that may precondition different ecosystems to increases in area burned. Specifically, we reconstruct the area burned in each of 16 Bailey's ecoprovinces (Bailey 1995) that together cover most of the western United States and relate variation in these WFAB time series to climatic influences for the period 1916–2003. By stratifying the fire and climate data using ecoprovinces (Bailey 1995), our approach considers how the seasonality, ecosystem vegetation type, and coarse physiography affect the relationship between climate and fire. This approach extends previous work by examining the relative role of precipitation, temperature, and drought, as well as extending the time period of the climate–fire analysis to most of the 20th century.

METHODS

Study area

We focused on the ecoprovinces in 11 western U.S. states (AZ, CA, CO, ID, MT, OR, NM, NV, UT, WA, WY), because data sets of fire area burned at both scales of interest (1° latitude $\times$ 1° longitude gridded and state) were available and because they contain much of the federal public land for which ecologically specific climate–fire relationships would be useful. Ecoprovinces (Bailey 1995; Fig. 2) represent coarse aggregations of biophysical constraints on modern ecological assemblages and are subsets of Köppen-Trewartha domains and divisions (Köppen 1931, Trewartha 1968) based on subregional vegetation characteristics with more specific climatic features. Twenty ecoprovinces are contained within the 11 states, and 19 of these are considered in this paper (Table 1). The Black Hills ecoprovince has a very small proportion of its area in WY and is not considered further. Western ecoprovinces are classified within Bailey's humid temperate and dry domains, with representative ecoprovinces in the humid temperate marine and mediterranean divisions and tropical/subtropical steppe, tropical/subtropical desert, temperate steppe, and temperate desert divisions (Bailey 1995).

Mountain ecoprovinces retain the characteristic climate regime of the surrounding lowlands but with important altitudinal zonation in vegetation. Each ecoprovince therefore has distinct climate characteristics and resulting vegetation structure and composition. Mountainous ecoprovinces tend to have heterogeneous vegetation along an altitudinal gradient from lower-elevation grasslands and shrublands and forest ecotones in valleys up through continuous montane and subalpine forest and, in some cases, into alpine tundra. Generally, the more northern and higher-elevation ecoprovinces have higher proportions of forest, and the southern and lower-elevation ecoprovinces have higher proportions of grassland and shrubland. Considering vegetation types at the ecoprovince level should give a more vegetation-specific perspective on the sensitivity of modern fire–vegetation relationships to climate than is possible with state-level data.

Primary fire data and pretreatment

All major data handling and analysis steps are outlined in Fig. 3. We used three separate WFAB data sets for this study. Annual fire data including annual fire statistics reports (USDA Forest Service 1938–1967, 1968–1990, 1993, 1998) were used to build the first data set, which consists of WFAB on federally protected lands in 11 states for the period 1916–2003 (Arno 1996, McKenzie et al. 2004). Interagency fire databases available online only document fires since the 1960s or 1970s, so verification of the earlier state-level annual fire statistics from independent sources was not possible. The area protected by federal agencies, and therefore the area reporting into the database, increases through time, so we adjusted the 1916–2003 state-level WFAB time series by multiplying the reported area burned by the ratio of the total area protected in 2003 to the area protected in a given year. This accounts for systematic bias introduced by changes in reporting (e.g., National Park data was not included until 1926) in the early part of the data set and mitigates the single largest systematic uncertainty in the data set. Other uncertainties remain (such as pre-aerial mapping of fire areas), but probably contributed smaller errors at local (e.g., National Forest) rather than regional or state levels. Second, we used a 1980–2000 gridded data set (Westerling et al. 2003) that includes area burned on all federally managed lands at 1° latitude × 1° longitude spatial resolution. Third, A. L. Westerling (*unpublished data*) developed a similar product, a 1980–2003 large-fire data set derived from a spatially more comprehensive large-fire data set (it includes federal and state agency fire records) pre-aggregated into ecoprovinces (Bailey 1995). The second and third data sets are the same areal coverage, but allowed us to update our analyses to include data for 2001–2003, a period that includes large-fire activity in much of the western United States. The duplication is also necessary because state-level data from CO, ID, MT, and NM were missing from the third data set at the time of this analysis.

Our first goal was to use relationships between the long-term (1916–2003), state-level WFAB data set and the shorter 1980–2000 gridded and 1980–2003 large-fire data sets to reconstruct a full-length (1916–2003) record of WFAB for each ecoprovince in the 11 western states. For the 1980–2000 WFAB data set, we projected the 1° × 1° cells onto a map of ecoprovinces and assigned each grid cell an ecoprovince membership based on simple areal majority. For the 1980–2003 WFAB data set, individual fires from the large-fire database were assigned to each ecoprovince and annually totaled to produce ecoprovince time series. From these, we produced annual WFAB totals in each ecoprovince for the periods 1980–2000 and 1980–2003 (two time series for each province).

Reconstructing ecoprovince area burned: regression methods

The comparatively fine scale of the gridded data is desirable because it can be reliably assigned to ecoprovinces, but it has the disadvantage of very short temporal coverage. The state data cover a longer time period than any similar analysis of climate and fire to date, but states are arbitrary spatial aggregations and ecologically meaningless. We used two types of regression models to reconstruct a time series of WFAB for each ecoprovince based on a combination of the detailed spatial information in the gridded data set and the long time frame of the state data set. The first type assumes that the WFAB ecoprovince and state data are both distributed lognormally and are linearly related; it produces an ordinary regression model that predicts ecoprovince WFAB from multiple state-level WFAB records (log-linear model). The second approach observes the relationship between the mean and variance (the variance is proportional to the mean squared) of the observed data (Fig. 4; see *Results*) and suggests a generalized linear model (GLM; McCullagh and Nelder 1989) of the gamma family (gamma model). This approach assumes the area-burned data are still lognormal, but as the mean increases, the variance increases proportionally to the mean squared. We applied both log-linear and gamma GLMs to estimates of ecoprovince area burned for both the 1980–2000 ("00") grid-based and 1980–2003 ("03") large-fire data sets to produce four candidate models for each ecoprovince. All regressions were performed in the S-Plus environment (version 6.1 for Windows; Insightful

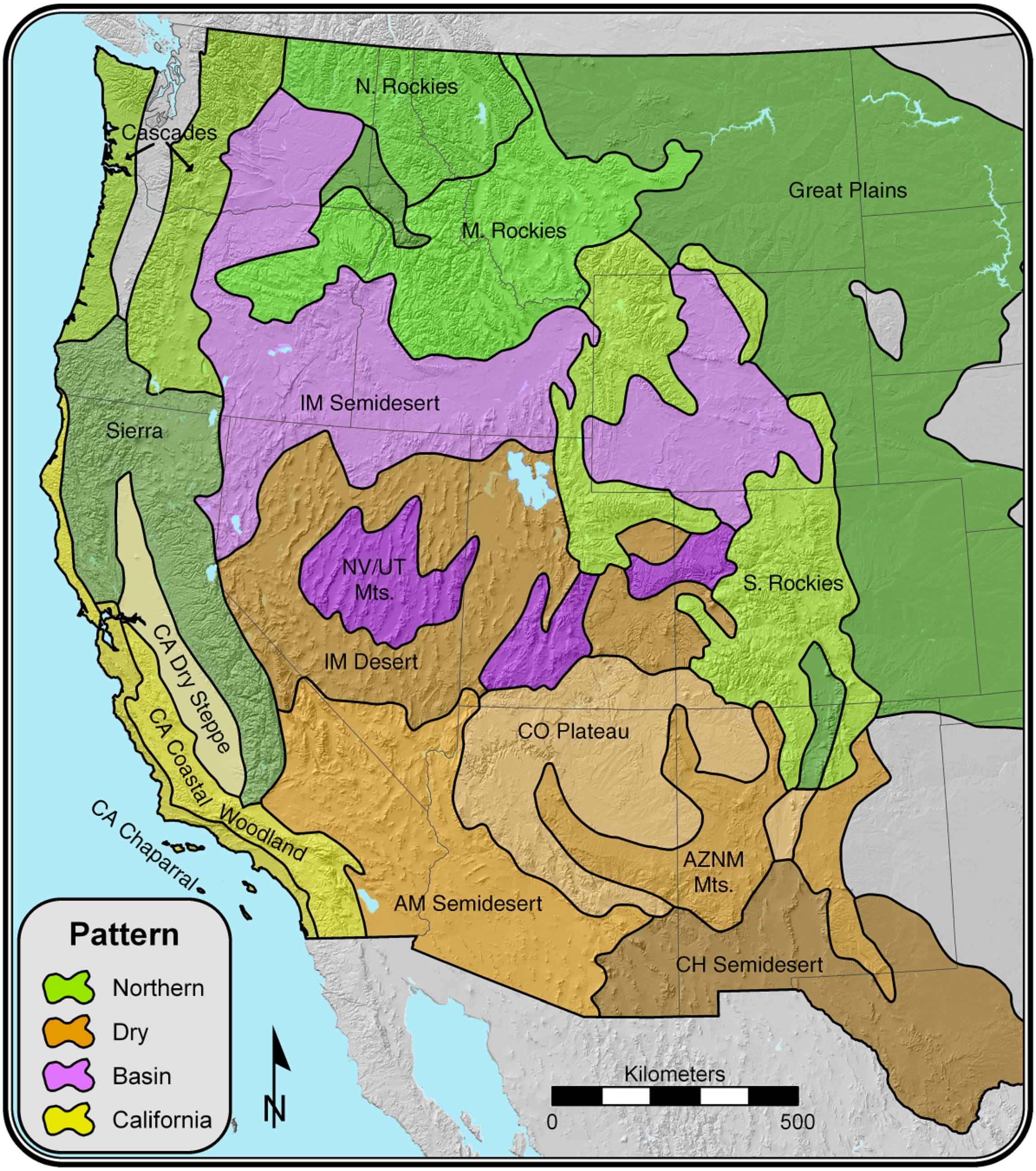

FIG. 2. Ecoprovinces of the western United States and common patterns of climate–fire associations from correlation and diagnostic regression models (see *Results* and *Discussion*). The 16 ecoprovinces for which we provide fire or fire/climate models are labeled. The similar colors group ecoprovinces with similar patterns of climate relationships (northern/mountain ecoprovinces, dry/lower-elevation ecoprovinces, Great Basin and Columbia Basin ecoprovinces, and California ecoprovinces). See Table 1 for an explanation of ecoprovince abbreviations.

Corporation 2002). Predictors were the western states (and their interactions) contained within each ecoprovince. We used forward selection regression for both loglinear and gamma models, and predictors were retained if the *P* value (*t* distribution) for their coefficients was <0.1. We accepted a final model when the Akaike Information Criterion (AIC) could not be minimized further by removing or adding terms. To simultaneously cross-validate and compare the four candidate models for each ecoprovince, we calculated the predicted residual sum of squares (PRESS) root mean square error (RMSE) and accepted the model with the lowest RMSE as the reconstruction model. We then used the best model to estimate the 1916–2003 area burned for each ecoprovince by projecting the observed state WFAB values onto the fitted model.

TABLE 1. Ecoprovince area-burned statistics for the period 1980–2000, calculated from gridded fire data in Westerling et al. (2003).

Ecoprovince	Bailey code	Abbreviation	1980–2000 area burned: Analysis area (ha × 10^7)	1980–2000 area burned: Annual mean (ha × 10^4)	1980–2000 area burned: Peak fire season	Proportion of ecoprovince, annual mean (×10^{-3})
Pacific Lowland Mixed	242	Pacific Lowl.	0.38	0.01	Sep–Oct	0.02
California Coastal Steppe	263	CA C. Steppe	0.12	0.02	Apr; Jul; Oct	0.18
Arizona–New Mexico Mountains Semidesert	M313	AZNM Mts	1.30†	0.93	May–Jul	0.72
American Semidesert and Desert	322	AM Semidesert	2.27	1.74	Apr–Aug	0.77
California Dry Steppe	262	CA Dry Steppe	0.50	0.42	Jul–Sep	0.85
Southwest Plateau/Plains Steppe	315	SW Plateau	0.25†	0.22	Feb–Apr; Jun	0.89
Colorado Plateau Semidesert	313	CO Plateau	1.95	1.76	Apr–Aug	0.90
Great Plains-Palouse Dry Steppe	331	Great Plains	3.52†	3.31	Jun–Sep	0.94
Cascade Mixed Forest	M242	Cascades	1.38	1.95	Jul–Aug	1.41
Northern Rocky Mountain Forest	M333	N. Rockies	0.99	1.39	Jun–Oct	1.41
Chihuahuan Semidesert	321	CH Semidesert	1.37†	2.14	May–Jul	1.57
Southern Rocky Mountains Steppe-Forest	M331	S. Rockies	2.65	5.47	Jun–Sep	2.06
Nevada-Utah Mountains-Semidesert	M341	NV/UT Mts	1.13	2.39	Jun–Aug	2.11
Middle Rocky Mountains Steppe-Forest	M332	M. Rockies	2.12	8.28	Jun–Sep	3.91
California Coast Chaparral Forest/Shrub	261	CA Chaparral	0.27	1.07	Jul; Sep–Nov	4.01
Sierran Steppe-Mixed Forest	M261	Sierra	1.77	7.22	Jun–Oct	4.08
Intermountain Semidesert/Desert	341	IM Desert	2.77	11.46	Jun–Sep	4.13
Intermountain Semidesert	342	IM Semidesert	4.12	21.23	Jun–Oct	5.15
California Coastal Range	M262	CA Woodland	0.64	4.90	Apr–Nov	7.60

Note: Ecoprovinces are arranged by the fraction of the province area burned annually, lowest to highest.
† Partial ecoprovince in analysis; some ecoprovinces exceed borders of 11 western U.S. states from which fire data were taken.

Climate data and pretreatment

We obtained monthly state climate division precipitation (PPT), temperature (T), and Palmer drought severity index (PDSI) data from the National Climatic Data Center (Karl et al. 1986, NCDC 1994). For each ecoprovince, we used climate-division data to develop 15 seasonal climate variables we hypothesized to be likely predictors of fire area burned at the large scales of ecoprovinces: annual (hydrological year, or October–September), winter (October–March), spring (March–May), growing season (May–September), and summer (July–September) total PPT, mean T, and mean PDSI. Annual and winter variables include months (October–December) from the year immediately prior to the fire year in question. Climate division areas vary greatly and climate division boundaries are not consistent with ecoprovince boundaries, so we used an area-weighted principal components analysis (PCA; Preisendorfer 1988) to reduce the constituent divisional climate time series into a single 1910–2003 time series, aggregated at the ecoprovince level, for each of the 15 seasonal climate variables. For example, an area-weighted PCA was run on the covariance matrix of the annual precipitation time series for each of several climate divisions within an ecoprovince. This extracts the common variance without potential biases from mixing smaller and larger climate divisions by simply averaging the time series.

We evaluated the autocorrelation in each ecoprovince climate time series and used an autoregressive model (up to third order) to remove any significant autocorrelation. We used a $\log_{10}$ transformation for the ecoprovince fire time series due to the highly nonlinear nature of the fire data; these time series did not consistently exhibit strong (lag 1, $r < 0.25$) autocorrelation.

Climate and fire area burned

We first focused on the period 1977–2003 to describe the climate–fire relationships for ecoprovinces for three reasons. First, this period is comparable to the same period covered by previous studies of modern fire–climate relationships. Second, this period coincides with decades of increased global mean temperature. Third, 1977 marks a shift in the Pacific Decadal Oscillation (Mantua et al. 1997) and possibly changes in the influence of the Pacific Ocean on western North American climate (Trenberth 1990, Hare and Mantua 2000). We then investigated the feasibility of constructing diagnostic climate models for the full 1916–2003 period, which encompasses more climatic variability and provides comparison to more recent relationships.

To broadly categorize the relationships between climate variables and fire for each ecoprovince, we calculated Pearson correlation coefficients between each ecoprovince seasonal (year of, lag 1, and lag 2) climate time series and the annual WFAB time series for that ecoprovince. Our objective was to interpret common signals in climate–fire patterns, so we approached this analysis without correcting for the probability values

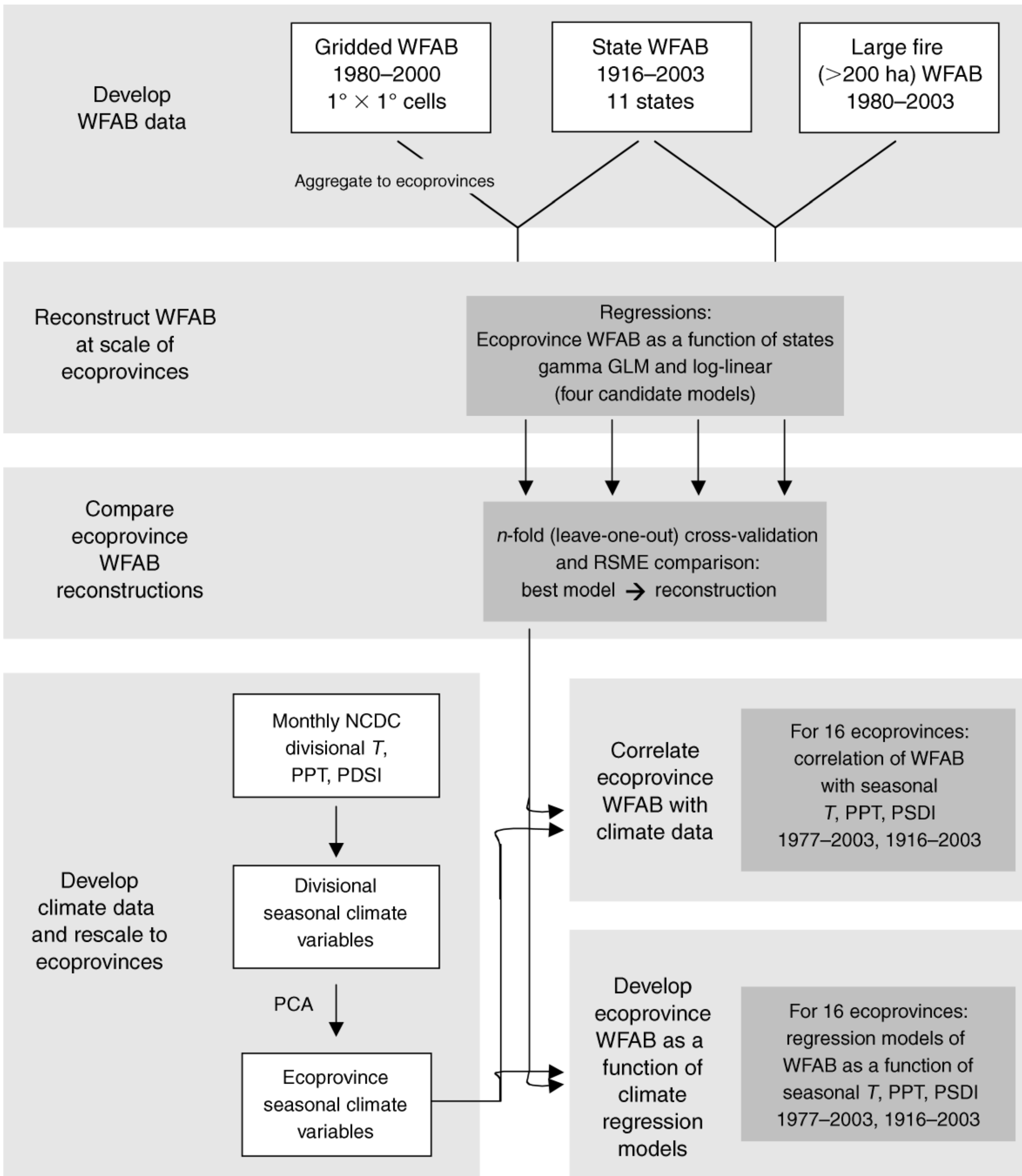

FIG. 3. Data handling and analysis workflow. Abbreviations are: GLM, generalized linear models; NCDC, National Climatic Data Center; PCA, principal components analysis; PDSI, Palmer drought severity index; PPT, precipitation; RMSE, root mean square error; *T*, temperature; WFAB, wildland fire area burned.

associated with conducting many independent correlation analyses. We did this for both the 1977–2003 and 1916–2003 periods.

To evaluate the interaction of different seasonal variables in different ecoprovinces, we constructed linear multiple regression models relating each ecoprovince WFAB time series (response variable) to pre-whitened seasonal PPT, *T*, and PDSI. Except for the inclusion of lagged climate variables, the methods for producing candidate predictive models are the same as the criteria used for the ecoprovince WFAB reconstruction. We included lagged versions (up to two years) of the climate variables as candidate predictors. We assumed that climate in the year of fire was the strongest influence on fuel moisture and built forward selection models of fire using the year-of-fire predictors first, but the sensitivity of vegetation to antecedent climate conditions and the preponderance of lag relationships in fire history data suggested the possibility of also considering lag relationships. Once the year-of-fire predictors had been exhausted, we continued to build forward selection models with the lag 1 climate predictors, but allowed the lag 1 and lag 2 predictors to preempt the year-of-fire predictors. To minimize the influence of collinearity among predictors, we calculated the variance inflation factor (VIF), and for VIF > 5 (Haan 2002), we discarded variables until no variables could be added or removed without increasing the AIC and VIF. The differences in AIC between candidate predictors were sometimes small and resulted in discrimination against one candidate predictor in favor of another when both predictors would have produced significant models. Therefore several diagnostic regression models exist that would be statistically acceptable for a given ecoprovince. The models and diagnostic terms presented are those meeting three criteria: minimum AIC, acceptable VIF for each term, and maximum variance explained. In most cases, the first term in the model is the single best predictor in both a correlation sense (see Appendices A and B) and a minimum AIC sense. When it is not, correlations are usually similar for several candidate predictors. When interpreting the full models, subsequent variables reflect the sensitivity of the model residuals to an additional predictor given that the first predictor is already in the model. The sign of terms entered last into the regression model are therefore sometimes indicative of contingent relationships.

Finally, to cross-validate the models, we calculated the PRESS RMSE for each 1977–2003 and 1916–2003 regression model. We used the ratio of the RMSE to the standard deviation of ecoprovince area burned as a comparative indicator of the cross-ecoprovince leave-one-out prediction error.

Results

Fire area burned

Summary statistics for WFAB in each ecoprovince in 1980–2000 and ecoprovince abbreviations used throughout the text are summarized in Table 1. There are orders of magnitude differences between mean WFAB in the Pacific Lowl. (least) and the IM Semidesert (greatest). When adjusted by ecoprovince area in the analysis, the CA Woodland ecoprovince has the highest mean annual ecoprovince fraction area burned. For the period 1980–2000, the gridded WFAB ecoprovinces have variable seasonality. Fire seasons in ecoprovinces characterized primarily by higher-elevation mountain vegetation types and those farthest north peaked later in the year than in lower-elevation, more southern ecoprovinces (Table 1).

A nonlinear relationship exists between the mean and variance for the gridded, large-fire ecoprovince and state-observed WFAB time series (Fig. 4). The relationship between the variance and mean for all three areal aggregations of fire data (latitude/longitude grid square, state, or ecoprovince) indicates a gamma family relationship in which the variance is proportional to the mean squared. Only the uncorrected state-level data set has an unsatisfactory resemblance to the gamma relationship.

Reconstructing ecoprovince area burned

For 16 of the 19 ecoprovinces, reconstructions of significant area burned were developed from the state and gridded fire data (mean variance explained = 0.66, range = 0.34–0.96; Table 2). In three ecoprovinces (CA C. Steppe, SW Plateau, and Pacific Lowl.), the variability in annual WFAB was not significantly related to the state WFAB time series; we did not pursue these further. These ecoprovinces also had the smallest analysis area and smallest mean annual area burned of the ecoprovinces in the West. The model fit for CA Chaparral (residual deviance = 0.34) and Cascades ecoprovinces ($R^2 = 0.36$), though significant, was poor compared to the rest of the ecoprovinces (Table 2). We limited prediction for CA Chaparral to 1931–2004 because model residuals indicated poor fit prior to 1931.

Overall, gamma GLMs were superior to log-linear models in seven reconstructions: AM Semidesert, AZNM Mts, CA Chaparral, CH Semidesert, CO Plateau, NV/UT Mts, and S. Rockies. Gamma GLMs produced large overprediction errors for the year 2002 in four southwestern ecoprovince models with CO and AZ as predictors; both these states had relatively low annual WFAB values during the training period. These models were still superior in a RMSE sense, so we constrained the 2002 values to the maximum predicted WFAB for the ecoprovince during the rest of the 1916–2003 period to avoid the influence of the extreme outlier year on climate–fire relationships. The PRESS RMSE values (Table 2) underscore the importance of correct predictions of large values for the strength of the regression relationships, but many of the values approximated mean WFAB and reflected reasonably good fit given the short time period of the training data and the high variability in the observed values. Overall, the reconstructions capture the observed adjusted state-level WFAB for the West (Fig. 1), underpredicting on average by $B_0 = -6.1 \times 10^4$ ha ($r^2 = 0.93$, $F = 1052$, df = 1, 87, $P = 0.000$).

Climate data and pretreatment

The first principal component time series of the aggregated ecoprovince climate division time series was in all cases positively correlated with each constituent time series. In some of the larger ecoprovinces the magnitude of correlations between each constituent climate division and the leading PC time series varies more than in smaller ecoprovinces, indicating that the heterogeneity of the climate divisions led to lower proportions of total variance explained. The range of variance explained was 0.48–0.96 for the first PC time series; values were typically highest for temperature variables and lowest for precipitation variables (data not shown).

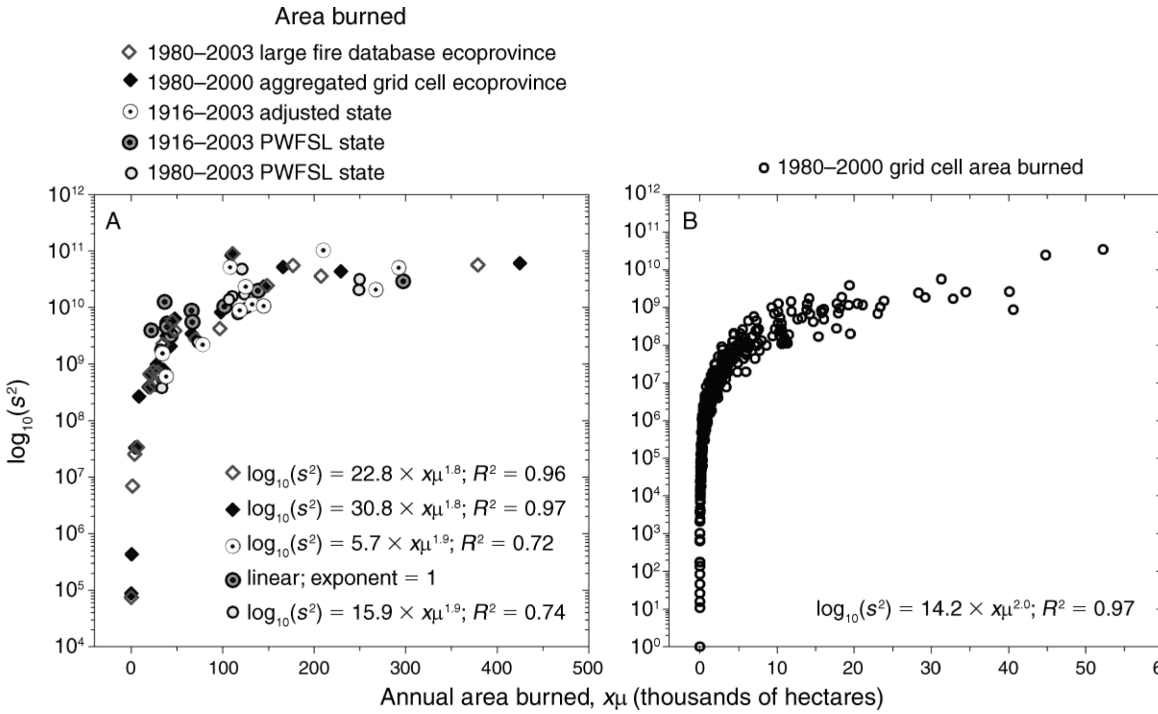

FIG. 4. The relationship between the mean and variance (s^2; measured in hectares) in annual wildfire area burned (WFAB) for (A) states and ecoprovinces and (B) latitude/longitude grid cells in the western United States. The variance is proportional to the mean squared in all WFAB data sets, leading to the choice of the gamma family generalized linear model in WFAB reconstructions.

TABLE 2. Statistical summary for ecoprovince reconstruction models.

Ecoprovince	Model: Type	Model: Predictors†	Fitted mean 1980–2003 (ha)	PRESS RMSE (ha)	R^2 or expl. deviance‡
AM Semidesert	Gamma.00	AZ + NV	19 974	7318	0.69
AZNM Mts	Gamma.00	ID + AZ	12 996	13 771	0.58
CA Chaparral	Gamma.00	CA + NV + CA:NV	12 857	24 309	0.34
CA Woodland	log.03	log(CA) + log(OR)	44 774	52 773	0.48
CA C. Steppe		no model			
CA Dry Steppe	log.00	CA	3220	10 666	0.58
Cascades	log.03	log(OR)	20 413	35 763	0.36
CH Semidesert	Gamma.00	AZ + NM	26 198	24 192	0.57
CO Plateau	Gamma.00	AZ + CO + NM + AZ:NM	22 442	12 559	0.80
Great Plains	log.00	log(MT)	35 107	15 636	0.74
IM Semidesert	log.03	log(OR) + log(ID) + log(NV) + log(WA)	176 510	85 233	0.85
IM Desert	log.03	log(NV) + log(UT) + log(CO) + log(NV):log(UT) + log(NV):log(CO) + log(UT):log(CO) + log(NV):log(UT):log(CO)	98 561	39 906	0.96
M. Rockies	log.00	log(WY) + log(OR) + log(ID)	65 451	86 568	0.77
NV/UT Mts	Gamma.00	NV + UT	22 755	14 768	0.68
N. Rockies	log.00	log(ID) + log(WA)	13 284	17 143	0.79
Pacific Lowl.		no model			
Sierra	log.00	log(CA) + log(OR)	63 862	85 247	0.60
S. Rockies	Gamma.03	log(MT) + log(WY) + log(MT):log(WY)	64 402	37 267	0.76
SW Plateau		no model			

Notes: Model types indicate gamma generalized linear model (GLM) and log-linear models for 1980–2000 or 1980–2003. PRESS RMSE is the predicted residual sum of squares root mean square error. See Table 1 for an explanation of ecoprovince abbreviations and *Introduction* for an explanation of the state abbreviations.

† State-level area burned from the area-reporting-adjusted data set of the Pacific Wildland Fire Sciences Laboratory, Pacific Northwest Research Station, USDA Forest Service.

‡ Deviance explained = (null deviance − residual deviance)/null deviance.

Climate–fire relationships

Correlations for 1977–2003.—Significant ($n = 27$, $r_{sig} \geq 0.32$, $\alpha = 0.05$) ecoprovince climate–fire correlations exhibit three geographic patterns (Appendix A; Fig. 2). First, several northern or mountainous ecoprovinces exhibit strong approximately equal correlations between WFAB and year-of-fire temperature (positive) and precipitation–PDSI variables (negative) with few lag 1 or 2 precipitation relationships. The only significant positive lag 1 relationship is for winter. This pattern is evident in Cascades, N. Rockies, M. Rockies, S. Rockies, and Sierra. Second, several drier ecoprovinces have more and stronger positive lag 1 precipitation–PDSI correlations, especially winter, than year-of-fire climate variables. This pattern is evident in the AM Semidesert, AZNM Mts, IM Semidesert, and CH Semidesert. Third, the Great Basin ecoprovinces IM Desert and NV/UT Mts have no significant year-of-fire climate relationships, but several moderately strong lag 1 positive precipitation and PDSI correlations. The CO Plateau ecoprovince has weaker characteristics of the second and third groups, with no significant year-of-fire temperature relationships and generally weak year-of-fire precipitation and PDSI, but it is also missing the stronger lag 1 precipitation–PDSI relationship. The three California (CA Chaparral, CA Woodland, CA Dry Steppe) ecoprovinces do not fit neatly into any of these categories, but all three have significant, negative associations with both spring and summer (but not growing-season) precipitation. The Great Plains ecoprovince is characterized by strong year-of-fire relationships similar to the mountain ecoprovinces but also with no significant lag 1 or lag 2 correlations.

All significant year-of-fire precipitation and PDSI correlations were negative. In the S. Rockies, Sierra, Great Plains, and CA Dry Steppe, WFAB was best correlated with precipitation for all seasons, while the WFAB for S. Rockies and the CH Semidesert was better correlated with PDSI for all seasons. The AZNM Mts, IM Desert, and the NV/UT Mts ecoprovinces had no significant year-of-fire correlations with precipitation, and CA Dry Steppe, CA Woodland, IM Desert, and the NV/UT Mts had no significant year-of-fire PDSI correlations. Lag 1 precipitation correlations differ among ecoprovinces, but the significant relationships are nearly all positive. The AM Semidesert, AZNM Mts, CH Semidesert, CO Plateau, IM Desert, N. Rockies, and Sierra all have significant, positive correlations with lag 1 winter precipitation. Furthermore, all ecoprovinces except CA Chaparral exhibited positive correlation coefficients (significant or not) with lag 1 winter precipitation. Significant lag 1 PDSI correlations were all positive, and nearly all nonsignificant correlation coefficients for lag 1 PDSI were also positive. Lag 2 precipitation was generally not important in most ecoprovinces. Lag 2 PDSI was correlated in spring, growing season, and summer for CA Chaparral (positive) and M. Rockies (negative), but was otherwise not important.

All significant year-of-fire seasonal temperature variables were positive. Lag 1 seasonal temperatures were rarely significant. Lag 2 seasonal temperature varies in significance and sign with ecoprovince, but most significant relationships were positive; only the CA Chaparral and CA Woodland ecoprovinces had negative lag 2 temperature correlations.

Correlations for 1916–2003.—The geographic patterns observed for the period 1977–2003 also occurred in the significant correlations ($n = 88$, $r_{sig} \geq 0.17$, $\alpha = 0.05$) observed in the extended 1916–2003 period (Fig. 2; Appendix B), but correlations were generally weaker. The northern/mountain group (Cascades, Great Plains, N. Rockies, M. Rockies, S. Rockies, and Sierra) still consisted of the same ecoprovinces, but all significant temperature correlations were positive and all significant precipitation and PDSI correlations were negative; winter precipitation no longer figured significantly in any of these ecoprovinces. The remaining ecoprovinces are characterized by significant positive correlations with lag 1 precipitation and/or PDSI. However, there are two different responses within this generalization. The first group is similar to the mountainous ecoprovinces but with a few significant positive lag 1 or 2 precipitation or PDSI correlations (e.g., CO Plateau). The second group consists of arid and southwestern ecoprovinces with weak year-of-fire relationships and stronger positive correlations with lag 1 precipitation and PDSI.

Temperature relationships for the year of fire were again positive, while precipitation and PDSI relationships for the year of fire were negative. There were more significant temperature correlations (mostly positive) for 1916–2003 than 1977–2003, especially in spring. Significant lag 1 relationships were rare for temperature, always positive for precipitation, and common and always positive for PDSI. Growing-season temperature was significant for five more ecoprovinces than for 1977–2003, while lag 1 winter precipitation and PDSI were still significant for several ecoprovinces.

Diagnostic regression models

Between $R^2 = 0.33$ and $R^2 = 0.87$ (mean $R^2 = 0.64$) of the variability in reconstructed 1977–2003 WFAB could be explained by three to six climate predictors and, in a few cases, their interactions (Fig. 5, Table 3). The RMSE/SD values for these models ranged from 0.56 to 2.08 (Table 3), indicating a moderate level of cross-validated forecasting skill. Precipitation terms (34) were more common than either temperature (21) or PDSI (16). The first term in 11 of 16 models (and the second term in seven models) for the 1977–2003 period was a negative relationship with precipitation or PDSI during some part of the primary fire season (spring, summer, or growing season) in the year of fire (Table 3). Similarly, negative lag 1 or lag 2 precipitation or PDSI predictors

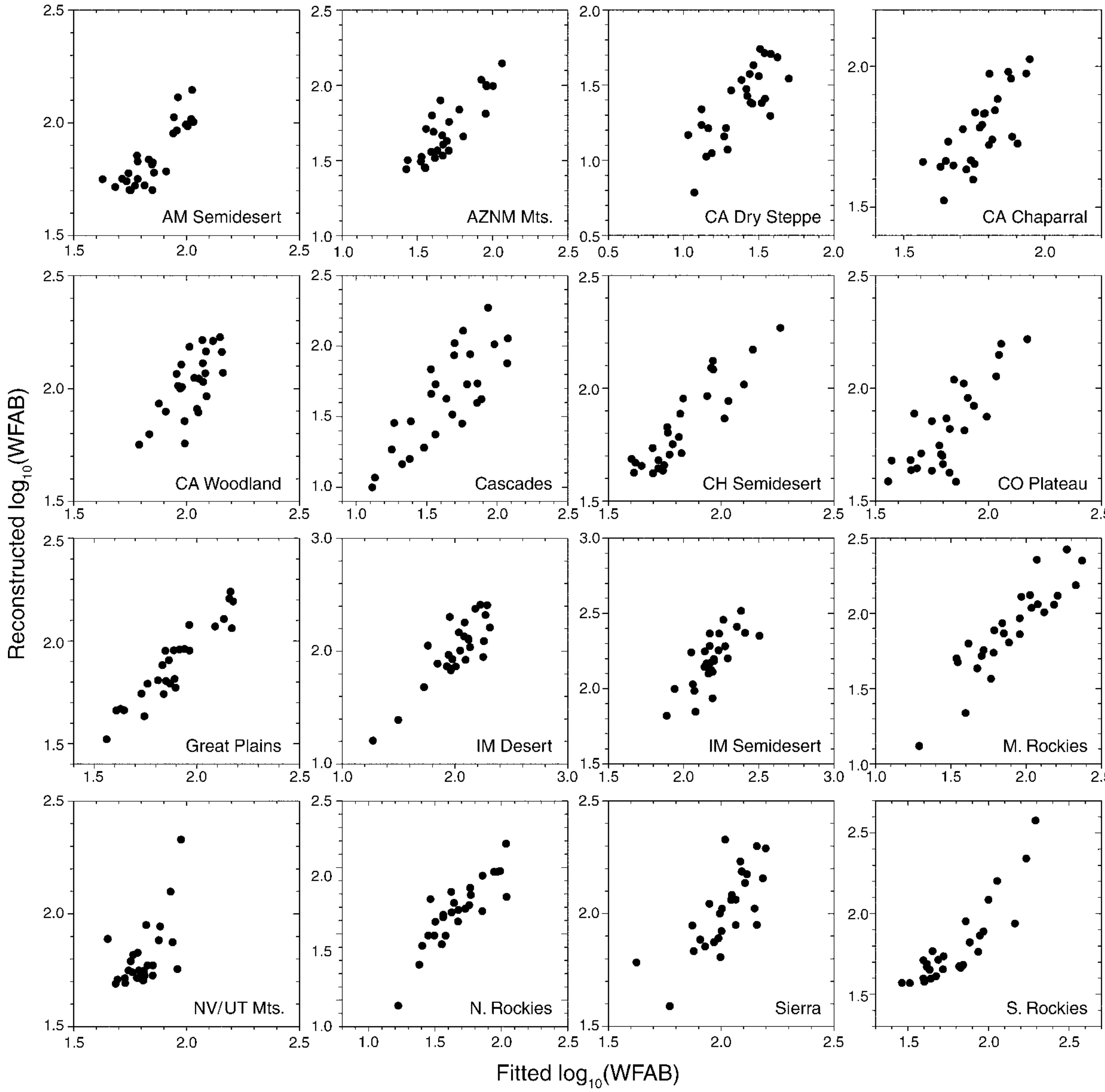

FIG. 5. Reconstructed ecoprovince wildfire area burned (WFAB; originally measured in hectares) vs. fitted values from diagnostic climate–fire prediction models for 1977–2003. Note that scales change with ecoprovince. See Table 1 for an explanation of ecoprovince abbreviations.

were significant for eight models, while positive lag 1 or lag 2 predictors for the same variables were important in seven models (Table 3). Annual PDSI for the year of fire was a better negative predictor for CH Semidesert and AZNM Mts. The NV/UT Mts ecoprovince had no significant year-of-fire predictors; the best predictor was positive annual precipitation the year prior to fire (Table 3). Finally, the IM Desert ecoprovince had a positive relationship with winter precipitation in the winter immediately preceding fire while the CA Chaparral ecoprovince had a negative relationship with winter PDSI for the same winter (Table 3).

The 1916–2003 models did not perform as well as the 1977–2003 models in an R^2 or RMSE (Fig. 6, Table 4) sense. Between 0.25 and 0.57 (mean = 0.39) of the variance could be accounted for by three to nine predictors and in some cases their interactions (Table 4). The RMSE/SD values are often > 3.0 (Table 4), indicating little forecasting skill. Temperature and precipitation had similar numbers of significant model terms (37 and 38, respectively), while PDSI had fewer significant terms (21). The first term in 15 of 16 models was year-of-fire climate: seven models had a negative precipitation term, three models had negative summer PDSI, and five models had positive temperature. The first term in NV/UT Mts was positive lag 1 growing-season PPT.

TABLE 3. Climate-fire diagnostic regression models for 1977–2003.

Ecoprovince	1977–2003 model†	R^2	RMSE/SD
AM Semidesert	−GS.PPT + −Spr.PPT + −Spr.T + −L1.GS.PPT + L1.Wnt.PDSI	0.72	1.42
AZNM Mts	−Ann.PDSI + −Sum.PPT + L1.Wnt.PPT + L1.Spr.T + L2.Sum.T	0.74	1.62
CA Chaparral	−Wnt.PDSI + −Sum.PPT + Wnt.PDSI : Sum.PPT + −L2.Spr.T	0.54	1.81
CA Woodland	−Sum.PPT + L1.Wnt.T + −L1.Spr.T + L1.Sum.PPT	0.47	1.41
CA Dry Steppe	−Sum.PPT + −Spr.PPT + Spr.PDSI + −Wnt.PPT	0.59	0.78
Cascades	−GS.PPT + L1.Wnt.PPT + −L1.Wnt.T + L2.Wnt.PPT + −L2.Sum.PPT	0.65	1.27
CH Semidesert	−Ann.PDSI + Wnt.PPT + L1.Spr.PDSI + Ann.PDSI : Wnt.PPT	0.80	1.07
CO Plateau	−Sum.PPT + −Sum.PDSI + −L1.GS.PPT + L1.Ann.PPT + L2.GS.T	0.63	1.35
Great Plains	−Sum.PPT + −Spr.PPT + −Wnt.PPT + L1.Wnt.T + −L1.Spr.PPT + L1.Sum.PDSI	0.87	0.56
IM Semidesert	−GS.PPT + L1.Spr.PDSI + L2.Wnt.PDSI + L2.Spr.T	0.56	2.08
IM Desert	Wnt.PPT + Wnt.T + L2.Spr.T + L2.Wnt.PDSI + L2.Wnt.T + Wnt.PPT : Wnt.T	0.71	1.64
M. Rockies	−Sum.PDSI + Wnt.PPT + L2.Spr.T + L2.Spr.PDSI + −L2.Sum.PPT + −L2.Ann.T	0.81	0.64
NV/UT Mts	L1.Ann.PPT + L2.Spr.T + L2.GS.PPT	0.33	1.31
N. Rockies	−Sum.PDSI + Wnt.T + −L1.Sum.PPT + −L1.GS.T	0.74	0.79
Sierra	−Sum.PDSI + L1.Wnt.PPT + −L1.GS.PPT + L1.Wnt.PPT : L1.GS.PPT	0.53	1.11
S. Rockies	−Spr.PPT + −Sum.PPT + Wnt.T + −Spr.T + L2.Spr.PDSI + Spr.PPT : Sum.PPT	0.77	0.69

Notes: A + followed by − refers to the additive regression effect of a negative predictor; the absence of a − symbol indicates that the predictor is positive. RMSE stands for root mean square error. Model abbreviations are: Ann, annual (water year), October–September; Sum, summer, June–August; GS, growing season, May–September; Spr, spring, March–May; Wnt, winter, October–March; L1, lag 1, or year prior; L2, lag 2; T, mean temperature; PPT, precipitation; PDSI, Palmer drought severity index. See Table 1 for an explanation of the ecoprovince abbreviations.

† All models are statistically significant; all $P < 0.02$ for $\alpha = 0.05$.

Winter predictors were significant in 14 of the 16 1977–2003 models (Table 3). Eight ecoprovinces (AM Semidesert, AZNM Mts, Cascades, CH Semidesert, IM Semidesert, IM Desert, M. Rockies, Sierra) had one or more significant positive terms for prior (year-of, lag 1, or lag 2) winter precipitation or PDSI. Winter temperature was a significant positive predictor in the N. Rockies, S. Rockies, and IM Desert ecoprovinces. Winter climate variables were also prominent in the 1916–2003 models (Table 4). The CO Plateau, Great Plains, IM Semidesert, CH Semidesert, IM Desert, and N. Rockies ecoprovinces all had significant, positive predictors for year-of-fire winter precipitation or PPT. The AM Semidesert, AZNM Mts, CA Woodland, CO Plateau, Great Plains, IM Semidesert, NV/UT Mts, and N. Rockies ecoprovinces had significant positive lag 1 winter precipitation or PDSI predictors. Only CA Woodland and M. Rockies had negative winter precipitation terms, both in the winter immediately preceding the fire season.

Spring predictors were significant in 12 1977–2003 models (Table 3). Negative associations with year-of-fire spring precipitation were the first or second term in AM Semidesert, Great Plains, and S. Rockies. The same relationship occurs in CA Dry Steppe, but CA Dry Steppe also has a positive relationship with spring PDSI. This apparent inconsistency (negative precipitation and positive PDSI associations in the same season) may indicate either a contingency or non-stationary mechanism for WFAB. Seven models had positive lag 1 or lag 2 spring temperature predictors, and five models had positive lag 1 or lag 2 spring precipitation or PDSI predictors. For 1916–2003, year-of-fire, lag 1, or lag 2 spring temperature was a positive predictor in 12 models, while year-of-fire, lag 1, or lag 2 spring precipitation or PDSI was a positive predictor in eight models. Only CA Chaparral had a negative spring precipitation term.

DISCUSSION

Climate and wildland fire area burned

Strong relationships between climate and fire exist across the western United States, but the nature of those relationships varies with climate and vegetation. Furthermore the strongest relationships are similar when the earlier part of the 20th century is considered, indicating that climate has been an important determinant of area burned for most of the century.

Dry, warm conditions in the seasons leading up to and including the fire season are associated with increased WFAB in most ecoprovinces (Appendices A and B; Table 2), particularly in the northern and mountain ecoprovinces (Fig. 2). The mechanism for the relationship is, presumably, that low precipitation and high evapotranspiration deplete fuel moisture over larger than normal areas (Keetch and Byram 1968, Bessie and Johnson 1995). These conditions increase the probability of ignition (fine, dead fuels) as well as the potential for fire spread (dead fuels of all sizes, usually 1–100 hr fuels such as canopy and shrub foliage or grasses; Van Wagner 1977). Lack of precipitation in the year of fire is more important than drought (PDSI) or temperature in most regressions, although PDSI is a better predictor in some ecoprovinces, especially the northern and middle Rocky Mountain ecoprovinces.

In contrast, in the southwestern and arid ecoprovinces, moist conditions the seasons prior to the fire season are more important than warmer temperatures or drought conditions in the year of fire. Moist conditions produce fine fuels in the understory, which cure in subsequent years to become available fuels, prior to the arrival of monsoon rain in the summer (Swetnam and

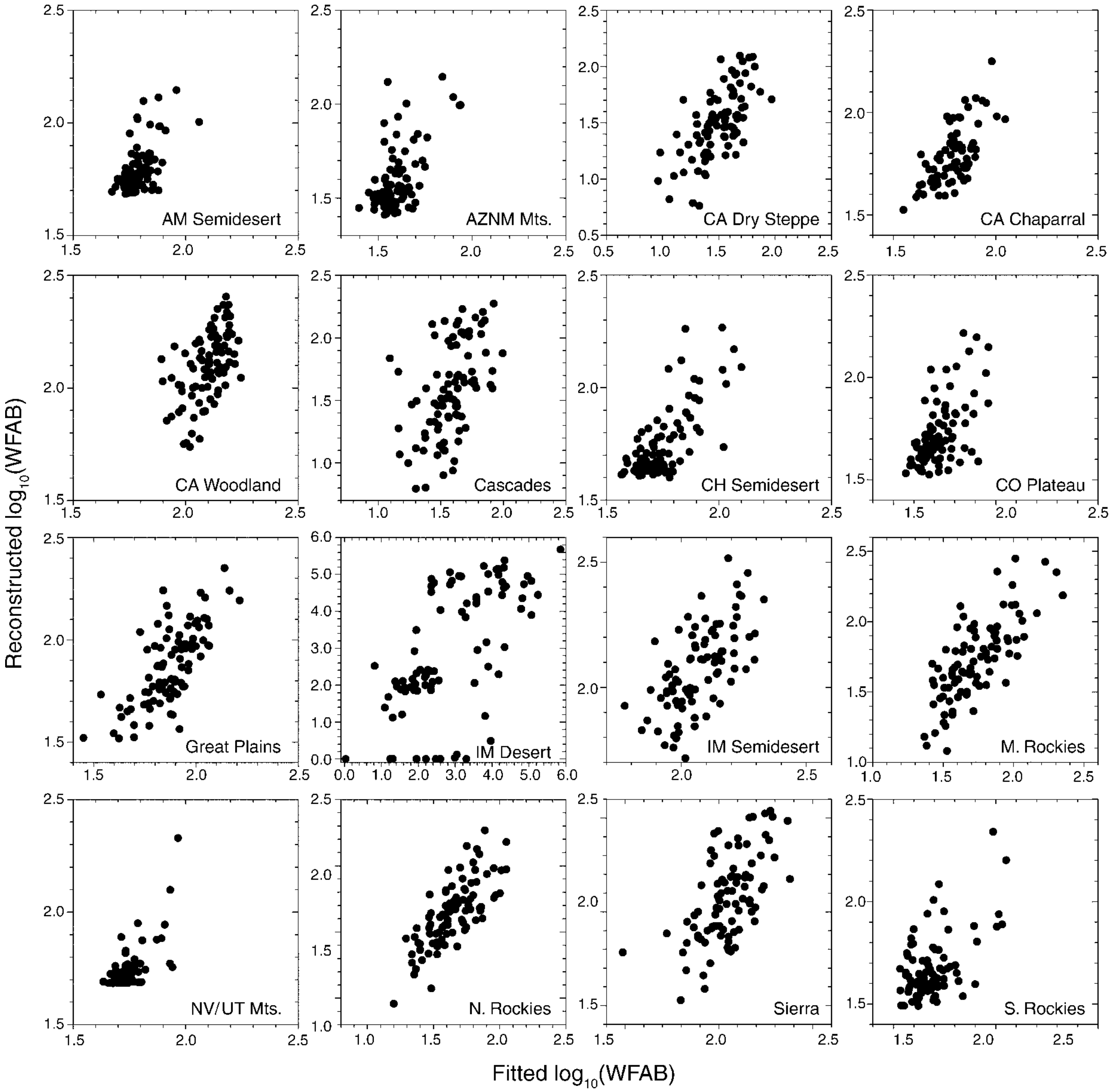

FIG. 6. Reconstructed ecoprovince wildfire area burned (WFAB; originally measured in hectares) vs. fitted values from diagnostic climate–fire prediction models for 1916–2003. Note that scales change with ecoprovince. See Table 1 for an explanation of ecoprovince abbreviations.

Betancourt 1998). It is unclear whether these fuels are sufficient to increase flame lengths sufficiently to generate increased crown fire activity, which is likely in the less fuel-limited systems. In the NV/UT Mts and IM Desert, which together comprise the Great Basin and its basin-and-range mountains, the positive role of year-prior precipitation is even more important. These ecoprovinces have lagged relationships and appear to be fuel limited (sensu Knapp 1995) because the only significant relationships with WFAB are associated with fuel availability: warm, wet conditions in winter and spring lead to larger WFAB a year or more in the future.

We found that ecosystem geography matters and is tied to similar patterns of climate–fire relationships that appear related to fuels. The pattern of correlations between climate and area burned and diagnostic regression models for the Rocky Mountains, Sierra Nevada, and Cascade Range indicates a common mechanism for climate–fuel–fire relationships in primarily forested ecoprovinces. Low precipitation, high temperature, and negative PDSI immediately preceding and during the year of fire are associated with increased WFAB, probably because persistent hot temperatures and low humidity are required to dry out fine fuels in these ecoprovinces even when winters are comparatively mild. For the period 1977–2003, correlations between area burned and seasonal climate suggest the Cascades and Northern Rockies are sensitive primarily to low

TABLE 4. Climate-fire diagnostic regression models for 1916–2003.

Ecoprovince	1916–2003 model†	R^2	RMSE/SD
AM Semidesert	−Sum.PDSI + L1.Wnt.PPT + L1.Spr.T + L1.Spr.T:L1.Wnt.PPT	0.33	>3.0
AZNM Mts	GS.T + Spr.T + L1.Wnt.PPT+ L2.Sum.T + L2.Spr.PPT+ GS.T:Spr.T	0.34	>3.0
CA Chaparral	−Spr.PPT + Sum.PDSI + Spr.T + L1.GS.PDSI + −L1.GS.PPT + −L2.Sum.T + L2.Sum.PDSI + L2.Spr.T + Sum.PDSI:Spr.T +L1.GS.PPT:L1.GS.PDSI	0.46	2.49
CA Woodland	−Wnt.PPT + Spr.PDSI + −Sum.T + L1.Spr.PPT + L1.Wnt.PDSI + L1.Spr.PPT:L1.Wnt.PDSI	0.30	>3.0
CA Dry Steppe	−Ann.PPT + Spr.PDSI + Spr.T + −Sum.PPT + L1.Spr.PPT + L1.Ann.T + L2.Spr.PDSI + −L2.Ann.PPT + L2.Wnt.T + L1.Ann.T:L1.Spr.PPT	0.44	>3.0
Cascades	−Sum.PDSI + −L1.GS.PPT + L2.Spr.T	0.25	>3.0
CH Semidesert	Ann.T + −Ann.PPT + Wnt.PPT + L1.Spr.PDSI + −L1.Sum.PDSI + L2.Spr.PDSI + L2.Ann.T + Ann.T:Ann.PPT + Ann.PPT:Wnt.PPT	0.53	2.81
CO Plateau	−GS.PPT+ Wnt.T + L1.Wnt.PPT + L1.Wnt.T + GS.PPT:Wnt.T + L1.Wnt.PPT:L1.Wnt.T	0.34	>3.0
Great Plains	−GS.PPT + Ann.T + L1.Wnt.T + L1.Wnt.PDSI + L2.Wnt.PDSI + L1.Wnt.PDSI:L2.Wnt.PDSI	0.51	>3.0
IM Semidesert	Spr.T + −Ann.PPT + Spr.PPT + Wnt.PPT + L1.Spr.PPT + L1.Wnt.PPT + L1.Wnt.T + L2.Wnt.PDSI	0.42	2.16
IM Desert	Ann.T + −Ann.PPT + Wnt.PDSI + L1.Ann.T + L1.GS.PDSI + L1.Spr.T + L2.Wnt.PPT + Ann.PPT:Wnt.PDSI	0.38	2.23
M. Rockies	−GS.PPT + −Wnt.PPT + Wnt.T + GS.T + L1.Ann.T + L2.Spr.T + L2.Spr.PPT	0.56	1.59
NV/UT Mts	L1.GS.PPT + L1.Wnt.PPT + L2.Spr.T + L2.GS.PPT + −GS.PPT + Spr.PPT + L1.GS.PPT:L1.Wnt.PPT	0.46	0.64
N. Rockies	−Ann.PPT + Ann.T + −GS.PPT + Wnt.PDSI + L1.Wnt.PPT + L1.Sum.T + L2.Spr.T + L2.Sum.PPT + L2.Sum.T	0.57	>3.0
Sierra	−Sum.PDSI + L1.Spr.PDSI + L1.Spr.T + −L1.GS.PPT + L2.Spr.T + −L2.Sum.PPT + −L2.GS.T	0.39	>3.0
S. Rockies	GS.T + −Sum.PDSI + L1.Spr.T + GS.T:Sum.PDSI	0.33	>3.0

Notes: A + followed by − refers to the additive regression effect of a negative predictor; the absence of a − symbol indicates that the predictor is positive. RMSE stands for root mean square error. See Table 1 for an explanation of the ecoprovince abbreviations and Table 3 for an explanation of model abbreviations.

† All models are statistically significant; all $P < 0.02$ for $\alpha = 0.05$.

precipitation during the fire season (summer and growing season), whereas WFAB in the Sierra Nevada, Southern Rockies, and Middle Rockies is sensitive to low precipitation during a longer window from the winter immediately preceding fire through the fire season. This is consistent with a length-of-fire season limitation on WFAB in northern mountainous ecoprovinces, although the relationships are significant for all seasons during the 1916–2003 period. The regression models for all ecoprovinces in this category implicate precipitation and PDSI more than temperature in large WFAB, and the interactions between year-of-fire temperature and precipitation were usually not significant.

For 1977–2003, negative correlations between year-of-fire winter precipitation and WFAB for the Sierra Nevada and Southern Rockies indicate a limiting influence of above-average snowpack on fires in these ecoprovinces. The other mountainous ecoprovinces share this relationship between 1916 and 2003, suggesting that relationships described in Westerling et al. (2006) hold for more of the 20th century than previously shown. Most ecoprovinces exhibit a negative relationship with winter precipitation, but few are significant. These relationships all support our claim that drying of fuels is the primary mechanism for large WFAB in the higher-elevation and northern mountainous ecoprovinces. Wild fire area burned in these ecoprovinces thus appears to be limited by climate rather than fuel availability, and potentially ignitions, though our analyses cannot address this latter point.

In contrast, much of the southwestern United States appears to require a more complicated mechanism for large WFAB. Models for AM Semidesert, AZNM Mts, CH Semidesert, CO Plateau, and IM Semidesert suggest WFAB is associated primarily with facilitation of vegetation growth the winter(s) prior to fire and only secondarily with drying of fuels the year of fire. These ecoprovinces appear to be intermediate between fire regimes that are exclusively fuel limited and those that are primarily climate limited, with elements of both apparent especially in the 1916–2003 correlations and regression models. These results corroborate prior inferences about climate–fire relationships in the Southwest (Westerling et al. 2002, 2003, Crimmins and Comrie 2004).

The repeated importance of winter climate variables in the correlation and regression analyses reveal the capacity for antecedent climate to precondition large-fire years in the American West, presumably via water stored in snow or soil. Although we did not examine snowpack explicitly, the sensitivity of ecoprovince WFAB to winter precipitation and drought merits further investigation. If the observed late-20th-century trend toward winters with warmer temperature, lower snowpack, and increased proportion of rain in low-to-mid-elevation precipitation in the western United States (Mote et al. 2005, Knowles et al. 2006) continues, increases in the area burned by fire are likely in lower and middle elevations of mountainous ecoprovinces. In the Southwest, the role of winter conditions in future area burned depends upon how much winter precipitation falls as snow and how long it persists. Warming spring and winter conditions will presumably continue to lengthen the fire season in these areas (e.g., Westerling et al. 2006). On one hand, if this leads to less favorable conditions for fine fuel production by eliminating the carryover of soil moisture, WFAB might decrease because vegetation production will decrease. On the other hand, if the combination of warmer and wetter conditions leads to increased vegetation production, the earlier onset of dry fuels with a longer growing season could lead to increased WFAB.

Fire data and reconstructions

We identified a mean–variance relationship in area-burned statistics, characteristic of a gamma distribution, that led to more robust reconstructions for several ecoprovinces. The gamma mean–variance relationship of the WFAB totals (Fig. 4) is independent of the size of the grain (from $1° \times 1°$ grid cells to large states and ecoprovinces) considered and may be useful in modeling the areal component of fire regimes in much the same way that frequency–area power laws for fires (Malamud et al. 2005) may help overcome inherent difficulties in modeling disturbance processes at multiple scales (e.g., McKenzie et al. 1996). The mean–variance relationship illustrates that potential increases in mean annual ecoprovince area burned are likely to be accompanied by very large increases in the interannual variability in area burned, and if it exists at multiple scales, the scale independence of this general relationship is a powerful tool. It also may help assess the impacts of climate change on ecosystem vegetation. If models can reliably forecast changes in the mean area burned, it is possible to also specify the variability about that mean and better quantify the uncertainty in modeling ecosystem response to climate change.

Gamma-family GLMs were generally superior in southwestern ecoprovinces, whereas log-linear models were equal in the cooler mountainous and transitional ecoprovinces (Table 2). At least during the model training period, the assumption that the model errors are lognormally distributed is insufficient for some ecoprovinces, and specifying the gamma link relationship provides better reconstructions. In practice, for ecoprovinces of the Southwest, the variance for a given mean WFAB is consistent, implying a global control. One explanation is that these ecoprovinces are usually dry enough to burn in most fire seasons because the fire season is longer in the Southwest than the mountainous or northern ecoprovinces (Westerling et al. 2003), and interannual variability is high due in part to the alternately facilitating and limiting climate conditions associated with the El Niño-Southern Oscillation (Swetnam and Betancourt 1998). For example, the correlation coefficients and regression model parameters show that the largest fire years are facilitated by antecedent positive moisture anomalies. This mechanism likely produces large, spatially homogeneous areas of continuous fine fuels; a regional but temporary climate shift increases quantity or continuity of fuels via vegetation growth and leads to subsequent nonlinear increases in WFAB. Alternatively, the relative rate of fire spread at fine scales associated with different fuel types (e.g., Fosberg et al. 1993) may cumulatively determine whether gamma or logarithmic models better describe WFAB.

Ecosystem controls on climate–fire relationships

The relationships described here suggest that the relationships between climate and WFAB are complicated by ecosystem vegetation. A clear dichotomy between "fuel-limited"/"moisture-limited" and "climate-limited"/"energy-limited" fire regimes in western U.S. ecosystems does not hold up, at least at the scale of ecoprovinces. For example, the northern/mountain ecosystem pattern (Fig. 2) is characterized by positive temperature and negative precipitation correlations and diagnostic model terms that suggest drying of fuels is the primary mechanism. However, secondary relationships more consistent with fuel production are also evident in the N. Rockies and Sierra, which have weak but significant positive correlations with lagged winter precipitation for 1977–2003 (Appendix A). In the 1916–2003 diagnostic regression models, the N. Rockies also had a positive lagged winter precipitation term. Most ecoprovinces have stronger characteristics of fuel (moisture) or climate (energy) limitation, but the results support the idea that there is a range of vegetation types and seasonal climates that produce fire regimes limited by both fuel and climate.

The ecoprovince concept clarifies climate–fire relationships in terms of dominant vegetation type. Our study confirms that high temperature, low precipitation, and drought affect fire most strongly in forested ecosystems where these factors have strong relationships with WFAB. However, the influence of above-average antecedent precipitation in ecosystems dominated by grass or shrubland is clear. Differences in ecoprovince vegetation and climate–fire relationships also imply that the area burned by fire does not mean the same thing ecologically in all places. Fire severity is probably a much better indicator of the ecological effects of a fire, large or small, on an ecosystem. The relationship between climate and fire severity, measured across different vegetation types, might give better insight into the future effects of climate than area burned alone.

Evidence from historical fire scar records for the antecedent influence of precipitation on fire in dry forest ecosystems (Swetnam and Betancourt 1998) is consistent with the relationships we observed. The positive influence of high antecedent precipitation on fire is more widespread than fire histories from the southern and middle Rocky Mountains alone would imply, although it is difficult to interpret ecologically without knowing exactly how much of the relationship is attributable to fires occurring in lower-elevation montane forests. Knapp (1995) found similar predictive capacity in antecedent climate variables for ecosystems in the Great Basin. Westerling et al. (2002) observed a widespread wet/dry pattern comparable to the one described by Swetnam and Betancourt (1998). We show that the lagged effects are associated with precipitation more than PDSI and temperature and are much more widespread, occurring even in ecoprovinces with a significant fraction of mountain and forested area.

The hypothesized mechanism of fuel limitation followed by fuel production and fuel drying appears reasonable for grass, shrub, and open-forest ecosystems where surface fires are common. But why would antecedent winter precipitation be a positive (though small) influence on WFAB in forested ecosystems where new fine fuels are not likely to be important drivers of fire (e.g., Bessie and Johnson 1995)? It is possibly a poorly understood function of fine-fuel moisture dynamics and live/dead fuels in understory vegetation. Alternatively, there may be a necessary distinction between the cause of fire starts and the factors that influence fire spread (Knapp 1995). Our analyses indicate that year-of-fire climate is the strongest influence on area burned in forested ecosystems, but fire size may be limited secondarily by fuel continuity between or within forest stands (Rollins et al. 2002). For example, continuity may be less limiting for fire regimes in which crown fires are the dominant mechanism than in lower-elevation forests characterized by surface fires, but our analysis does not have the detailed vegetation data required to address this.

Climate variables were sufficient to explain variations in WFAB in many ecoprovinces for the period 1977–2003. Especially successful predictions in the southwestern and western mountain ecoprovinces demonstrate the potential to use climate variables for predicting WFAB in most of the ecoprovinces in the West. A few climate variables account for much of the WFAB, and patterns of climate–fire associations make sense given ecoprovince vegetation structure. Therefore, the effects of climate change on fire in the western United States must be considered in the context of dominant vegetation and its response to climate. The strong relationships observed in the mountainous ecoprovinces also suggest that fire disturbance is likely to be a more dominant driver of ecosystem change than climate-mediated changes in species assemblages. Although on average less than a few percent of the area of ecoprovinces burn in a given year (Table 1), the ecological effects of these fires are locally important and, over time, might contribute to relatively rapid ecosystem changes. Those ecosystems in which WFAB is sensitive to temperature (especially the facilitating role of fire season temperatures in depleting soil moisture through evapotranspiration) are especially vulnerable in the short term. Lack of skill in predicting future patterns of precipitation (both spatial and seasonal) represents a large source of uncertainty for ecoprovinces that are largely sensitive to precipitation and drought (McKenzie et al. 2004).

Limitations

Estimates of area burned on public lands are subject to uncertainty for two main reasons. First, methods for documenting area burned have changed over time, and protocols have presumably varied through time and across agencies. Second, the total area protected, its distribution among agencies, and the coordination of reporting area burned between agencies has also changed over time. The results presented here are based on a fire area database that has no verification early in the 20th century. The observations are summarized in agency reports and must therefore be considered estimates. We controlled for the most important source of systematic uncertainty (the area reporting into the databases we used), but a comprehensive, West-wide effort to use fire atlases, past aerial photography, and local archives would be required to control for other sources of uncertainty. However, the value of properly verified fire-area-burned data, especially early in the century, cannot be overestimated for efforts to understand the past range of variability in fire regimes, the consequences of human activities for changes in fire regimes and fuel conditions in the West, or the relationship between climate and fire. A West-wide, comprehensive retrospective analysis that verifies the accuracy of early-20th-century estimates of area burned would provide more certainty to the results of future analyses.

The cross-validation of the climate–fire models indicates that the diagnostic models are not yet developed to the point at which prediction of annual area burned from a few climate variables can estimate the precise value. Explained variance for the full 1916–2003 reconstructions may be lower than for 1977–2003 because the linear relationships are not stationary or the reconstructions do not adequately estimate WFAB earlier in the century. The latter explanation appears to be unfounded, because the reconstructions explained most of the variance observed for most ecoprovinces (Table 2), produced PRESS RMSE values generally consistent with mean WFAB (Table 2), and described the total area burned (Fig. 1). The former explanation, though not treated explicitly here, is possible given the influence of decadal climate variability on fuel moisture and production, the influence of shifts in fire policy and resource management on land use, or the role of different climate–vegetation interactions within ecoprovinces over time.

The residual variance in the regression models could come from a number of sources. The highly nonlinear nature of the WFAB data is one possibility. However, though forecasting is clearly beyond the scope of this exercise, the diagnostic relationships (Tables 3 and 4) and correlations (Appendix A) are strong enough to indicate geographical patterns in the nature of the fire–climate relationships (Fig. 2). These patterns are consistent and have simple relationships that can be explored in greater detail at finer scales. The nature of vegetation distribution may also contribute to unexplained variance. Ecoprovinces of the western United States are heterogeneous in their vegetation composition, especially in mountainous areas (e.g., S. Rockies, which stretches from open woodland to alpine meadows). The mixture of sensitivities observed in some ecoprovince regression models probably represents a mixture of vegetation types. There is potentially a scale mismatch introduced by using ecoprovinces; ecoprovinces can sometimes contain several different vegetation types with different fire regimes and different sensitivities to climate. Statistically, variance could also be explained by tailoring the scale of climate and fire relationships to more specific ecological divisions, although improved quantitative analyses will not be possible unless the area and precise locations of all large fires in the 20th century are known. A third source of residual variance could be that the change in protected area influenced the results despite our attempt to control for it. For example, changing fire regimes due to climatic influences could be statistically inseparable from changes in the proportion of forested vs. non-forested lands reporting into the state WFAB fire database.

Another important factor that this analysis does not consider is the distinction between extreme weather and climate. For example, in southern California, Santa Ana winds in late autumn and early winter can produce very large area burned. The 1977–2003 climate–fire models for California coastal ecoprovinces confirmed some of the relationships Keeley (2004) described for the central and south California coast. Keeley found that area burned in the central Californian coast was negatively correlated with summer precipitation, which we observed in CA Woodland and CA Chaparral. Winter PDSI and temperature were also important relationships in Keeley's analysis, and we observed comparable results. Lagged spring temperature was also common between the two studies. These relationships are also consistent with increased potential for ignition and fire spread via prolonged drying of dead fuels, but the extreme event nature of the actual fires, if considered in our analyses, might explain more of the variability in area burned.

Implications for ecosystem management

The climate–fire relationships presented identify ecosystem-specific mechanisms relating climate to WFAB. Ecoprovinces proved a useful compromise between ecologically imprecise state-level aggregations of fire data and highly localized gridded fire data, and the differences in climate–fire relationships among the ecoprovinces underscore the necessity of considering ecological context (vegetation, fuels, and seasonal climate) to identify specific climate drivers of fire area burned. Future research should relate WFAB to the seasonality of proximate climate mechanisms such as water balance deficit, soil moisture, and fuel moisture. The impacts of fire suppression, changes in land use, and public land management could then be assessed in the context of known climate–fire relationships. Ecosystem management strategies that incorporate fire might also be refined. Other applications include fire-area-burned forecasting (e.g., Westerling et al. 2002) and the capacity to develop future climate–fire models based on a much larger range of climate conditions than late-20th-century observations. Climate change can potentially lead to larger and more frequent fires and to cascading effects on vegetation and carbon balance (e.g., Kasischke et al. 1995) and other ecosystem services, but the climatic mechanisms and the implications of climate change vary with ecosystem vegetation.

Climate controls on the area burned by wildfire in the western United States are strong, even during the dominant period of fire suppression and exclusion in the last two-thirds of the 20th century. Roughly 39% (1916–2003) to 64% (1977–2003) of the fire area burned can be related directly to climate. The variance explained by climate implies that fuel treatments, for example, might be tailored to specific ecosystems and climate–fire relationships. Recognizing that most ecoprovinces have significant ecological variability, climate-limited ecoprovinces may be less influenced by fuel treatment than fuel-limited ecoprovinces (at least for area burned, if not fire severity). This argument also implies that management options for responding to climate change might be more or less limited, depending on the nature of fire–climate relationships. In fuel-limited ecosystems, fuel treatments can probably mitigate fire vulnerability and increase resilience more readily than in climate-limited ecosystems in which adaptation to climate change is a more realistic approach.

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APPENDIX A

Fire–climate correlations for the period 1977–2003 (*Ecological Archives* A019-040-A1).

APPENDIX B

Fire–climate correlations for the period 1916–2003 (*Ecological Archives* A019-040-A2).