CLIMATE AND WILDFIRE AREA BURNED IN WESTERN U.S. ECOPROVINCES, 1916-2003

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We demonstrate that wildfire area burned (WFAB) in the American West was significantly controlled by climate (combinations of precipitation, temperature, and/or drought) during most of the 20th century (1916-2003). Persistent, ecosystem-specific correlations between climate variables and area burned are grouped by vegetation type for 16 ecoprovinces across the West. Most mountainous ecoprovinces exhibit strong year-of-fire relationships with anomalously low precipitation, low Palmer Drought Severity Index (PDSI), and high temperature. Many grass/shrub dominated ecoprovinces have stronger positive relationships with antecedent precipitation/PDSI. Some ecoprovinces appear sensitive to different climate variables between 1977-2003 than 1916-2003, potentially reflecting changes in the reporting areas included in wildfire statistics. For 1977-2003, a few climate variables explain a substantial fraction of the area burned (from 33 to 87 percent, mean 64 percent), indicating strong linkages between climate and area burned. For 1916-2003, the relationships are weaker, but between 25 percent and 57 percent (mean 39 percent) of the total variability could be accounted for with climate. At ecoprovince scales, seasonal climate is sufficient to explain a significant fraction of the variance in WFAB, although the specific climate mechanisms vary with ecosystem vegetation in the ecoprovinces. The relationship between the mean and the variance for WFAB repeatedly exhibits a gamma distribution for independent data sets and spatial scales of fire data. We hypothesize that the variance is commonly proportional to the mean squared for WFAB, and that the mechanism leading to the gamma distribution is connected to the climate-vegetation interactions that lead to fuel drying and production. 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. Despite the possible influence of fire suppression, exclusion, and fuel treatment, WFAB is still substantially controlled by climate. The implications for future planning and management in natural resource and ecosystem management are that future WFAB will likely depend on ecosystem-specific, seasonal variation in climate. The impacts of climate change on fire regimes will vary with the relative energy or water limitations of ecosystems.

**KEYWORDS:** Fire, climate, climate change, drought, ecoprovinces, forest, fuels, ecosystem management, gamma distribution
INTRODUCTION

The area burned annually by wildfire in the western United States (U.S.) influences policy decisions and future land-use agendas of public land management agencies. The nation-wide area burned on federal agency lands gradually increased since the mid 1970s (Agee 1997), capped by a string of years with large areas burned between 2000 and 2004 (National Interagency Fire Center 2005). Suppression costs incurred by all agencies have approached or exceeded one billion dollars (U.S.) 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, fires and fire regimes 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). It is possible, for example, that other factors, not just suppression, led to the recently observed area burned. From an ecological standpoint, the annual area burned by fire across the western U.S. 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.

The importance of attributing causal mechanisms to the increase in fire area burned during the 20th century is underscored by the size of recent fires, the cost associated with suppressing them, and the ecological effects that land managers face in responding to climate
change, future fires, and their impacts on natural resources. If the predominant factor driving area burned is fire hazard associated with fuel structure, the role of climate must be understood in order to weigh the importance of mitigation (e.g., fuels) and adaptation (e.g., to the less tractable impacts of climate).

Considerable research has focused on mechanisms forcing interannual variability in wildland fire area burned (WFAB) in the conterminous Western states. While the decline and subsequent increase in annual West-wide WFAB fits timelines of more effective fire suppression and ubiquitous fuel accumulation (Figure 1) (Agee 1993, Pyne 1997), 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). It is also likely that not all ecosystems with increasing WFAB trends have increased 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 prior to Euro-American settlement, fire suppression and fire exclusion were strongly controlled by climate (Swetnam 1990, Larsen 1996, Barrett et al. 1997, Swetnam and Betancourt 1998, Veblen et al. 2000, Brown and Sheppard 2001, Heyerdahl et al. 2002, Taylor and Skinner 2003, Weisberg and Swanson 2003, Brown et al. 2005, Hessl et al. 2004). These pre-settlement 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 foliar moisture and/or low moisture in fine, dead surface fuels and ultimately, the potential for widespread fire.
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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. It has been suggested that the observed relationship is caused by anomalously low temperatures and high precipitation that mitigate the climatic constraints on fine fuel production (Knapp 1995, Swetnam and Betancourt 1998), resulting in higher fine-fuel continuity that leads to an increased potential for widespread fire if subsequent years are dry. Years of widespread fire in fire histories appear positively related to increased antecedent precipitation (Swetnam and Betancourt 1998) but it is often difficult, especially in ecosystems that are not likely to be fuel limited, to determine if this is a real climate forcing on fire activity, an artifact of low sample size, the autocorrelated nature of climate reconstructions, or a combination of several factors.

During the late 20th century, WFAB on federal lands (U.S. Department of Agriculture 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 quite consistent with those in the reconstructed paleo 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 2004) using reconstructed PDSI, and validated against fire scar reconstructions of annual fire extent in the Southwest (Westerling and Swetnam 2004, 2006). However, the lack of complete, high-resolution, digitized data for all agencies prior to 1980 has hindered climate- and ecosystem-specific analyses of wildfire in the early and mid 20th century.

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 and later from archived information at the National Interagency Fire Management Integrated Database. 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 (JJA) 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). While limited in their consideration of seasonal climate and non-climatic sources of error (such as the heterogeneity within states), these relationships were strong enough to develop hypotheses about the future area burned for each state given future climate scenarios. Collins et al. (2006) used a similar dataset to attribute regional area burned to major modes of coupled ocean-atmosphere variation.

Synoptic climatology during the fire season is the proximate driver of fire weather and along with topography, fuels, general ecological structure, number of ignitions and fire suppression resources and strategy, affects the area burned by a given fire event. The role of atmospheric patterns in large fires has been well described in both Canada (Flannigan and Harrington 1988, Johnson and Wowchuck 1993, Skinner et al. 1999, Skinner et al. 2002) and the
U.S. (Schroeder 1957, Schaefer 1969, Gedalof et al. 2005). The role of seasonal to interannual climate variation has received less attention, but the importance of extreme fire weather and ignitions associated with brief events is often contingent on climatic factors operating at longer time scales that influence fuel moisture and availability.

Previous research has frequently focused on the relatively short-term operational time scale of fires (Gedalof et al. 2005). In this paper we focus on large scale, inter-annual to seasonal climate (precipitation, temperature, drought) that may precondition different ecosystems for large area burned. We use a novel reconstruction technique to relate the WFAB databases described above – one from Westerling et al. (2003) and one from McKenzie et al. (2004) – to reconstruct the area burned in each of 16 Bailey’s ecoprovinces (Bailey 1995) that together comprise most of the western U.S. for the period 1916-2003. We also relate variation in these WFAB time series to climatic influences. Our approach considers the capacity of seasonality, ecosystem vegetation type, and coarse physiography to produce different results in the relationship between climate and fire by using ecoprovinces (Bailey 1995) to partition the fire response to seasonal climate (Westerling et al. 2002). 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.

A common working ecological hypothesis is that the relationship between climate and fire is mediated by vegetation structure and sensitivity to moisture at the broad scales of ecoprovinces (e.g., Westerling et al. 2002); the area burned by fire in any given year is indirectly related to climate by climatic influence on fuels (e.g., Carcaillet et al. 2001). Evidence of this would be different ecoprovince WFAB sensitivities to climate consistent with the dominant
vegetation structure in an ecoprovence. While 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 a climate/fuels signal in an aggregate 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.

**METHODS**

**Study Area**

We focused on the ecoprovinces in 11 Western states (AZ, CA, CO, ID, MT, OR, NM, NV, UT, WA, WY), because datasets at both scales of interest (1° lat. x 1° lon. gridded and state) were available and because they contain much of the public land for which ecologically specific climate-fire relationships would be useful. Ecoprovinces (Bailey 1995, Figure 2) represent coarse aggregations of biophysical constraints on modern ecological assemblages, and are subsets of Köppen-Trewartha domains and divisions 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-shrublands / 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. These north/south and elevation differences represent subregional mechanisms that affect fire-regime sensitivity to climate. Such mechanisms derive from vegetation characteristics limiting fire at seasonal and longer time scales (fuel moisture, fuel continuity) and that differ for different vegetation physiognomies (e.g., grasslands, shrublands, and forests). Despite the limitations with respect to describing climatic controls on fine-scale fire regimes, aggregating 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 Pre-treatment**

All major data handling and analysis steps are outlined in Figure 6. We used three separate WFAB datasets for this study. First, we obtained annual area burned data for combined federal, state, and private lands (Smokey Bear reports 1916-1982, combined Department of Interior (DOI)/ United States Forest Service (USFS) reports 1983-1989 from Don Long and Dennis Simmerman, USFS Rocky Mountain Research Station-Missoula; 1990-1997 USFS fire
statistics from Janice Peterson, Mount Baker-Snoqualmie National Forest; and 1998-2003 USFS fire statistics from Marian Villasenor, USFS Fire and Aviation Management, Planning and Budget). We used an adjusted 1916-2003 state-level time series, corrected for the area-reporting observation bias associated with the changes in public lands administered by the USFS and DOI over the period of the 20th century (Westerling and Littell, in prep). Second, we used a 1980-2000 gridded dataset (Westerling et al. 2003) that includes area burned on all federally managed lands at 1° latitude x 1° longitude spatial resolution. Third, Westerling (unpublished data) developed a similar product, a 1980-2003 large-fire dataset derived from a spatially more comprehensive large-fire dataset (it includes federal and state lands agency fire records) pre-aggregated into ecoprovinces (Bailey 1995). The second and third datasets 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 U.S. The duplication is also necessary because state-level data from CO, ID, MT, and NM were missing from the third dataset at the time of this analysis.

Our goal was to use relationships between the long-term (1916-2003), state-level WFAB dataset and the shorter 1980-2000 gridded and 1980-2003 large-fire datasets to reconstruct a full-length (1916-2003) record of WFAB for each ecoprovince in the 11 Western states. For the 1980-2000 WFAB dataset, we projected the 1° x 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 dataset, fire events from the large fire database (Westerling, in prep.) 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

We compared two regression approaches to relate the 1980-2000/2003 ecoprovince-level
WFAB to the state WFAB for the same time period. The first approach assumes that the WFAB
ecoprovince and state data are both distributed log-normally and are linearly related; it produces
a classical least-squares linear model that predicts ecoprovince WFAB from multiple constituent
state-level WFAB records for the training period (log-log model). The second approach extends
the log-linear assumption by specifying the relationship between the mean and variance (gamma
model) of the observed data (Figure 3) in the link function of a generalized linear model
(McCullagh and Nelder 1989). This approach assumes the area burned data are still Gaussian,
but as the mean increases, the variance increases proportionally to the mean squared. We applied
both log-log and gamma modeling approaches to estimates of ecoprovince area burned for both
the 1980-2000 (“00”) grid-based and 1980-2003(“03”) large fire datasets to produce four
candidate models for each ecoprovince.

All regressions were performed in the S+ environment (version 6.1 for Windows,
Insightful Corp. 2000). For the log-log and gamma ecoprovince models, all states (and
their interactions) with area contributing to the ecoprovince targeted for reconstruction were
considered possible predictors (Figure 2). Both log-log and gamma strategies relied on iteratively
entering and removing candidate state predictors and their interactions into the regression model.
Predictors were considered for retention if the p-value associated with $t$ was less than 0.1. We
considered all possible interaction terms (full model), and non-significant state predictors were
retained if they contributed to significant interaction terms. 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 (P.R.E.S.S.) root mean square
error (RMSE) and accepted the model with the lowest P.R.E.S.S. RMSE as the reconstruction
model. The P.R.E.S.S. approach to cross-validation calculates the average prediction error by
iteratively leaving out each observation and re-assessing the model fit. 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.

Climate Data and Pre-treatment

We obtained monthly state climate-division precipitation (PPT), temperature (T), and
Palmer Drought Severity Index (PDSI) data from the National Climatic Data Center (NCDC,
online, accessed 02-Jun-04, Karl et al. 1986). For each ecoprovince, we used the raw 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 Oct.-Sept.),
Winter (ONDJFM), Spring (MAM), Growing Season (MJIAS), and Summer (JAS) PPT, T, and
PDSI. Annual and winter variables include months (OND) 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) to produce a 1910-2003 time series, aggregated at the ecoprovince level, for each
of the 15 climate variables. Each time series is the leading principal component derived from a
PCA on the covariance matrix produced by square-root area-weighting each climate division
time series contributing to the ecoprovince (Preisendorfer 1988). This allows the desired
emphasis on the common variance without potential biases from mixing smaller and larger
climate divisions by simply averaging the time series.

Relating Climate and Fire

We evaluated the autocorrelation in each ecoprovince climate time series and used an AIC
minimization criterion to determine the best order autoregressive model (up to third order) for
pre-whitening the seasonal climate time series. We used a log_{10} transformation for the
ecoprovince fire time series due to the highly non-linear nature of the fire data; these time series
did not consistently exhibit strong (lag 1, r < 0.25) autocorrelation. We first focused on the period
1977-2003 to describe the climate/fire relationships for ecoprovinces during the same period
covered by previous studies. This period is also indicated by a continent-wide increase in mean
temperature and the post-1977 changes in the influence of the Pacific Ocean on western North
American climate (Trenberth 1990, Hare and Mantua 2000). The 1977 regime shift represents a
significant restructuring of ocean-atmosphere relationships in the Pacific Ocean and the
transition from a cool phase of the Pacific Decadal Oscillation to a warm phase (Mantua et al.
1997). We then investigated the feasibility of constructing diagnostic climate models for the full
1916-2003 period, which encompasses more climatic variability and provides a good basis for
evaluating more recent relationships.
To broadly categorize the correlation patterns between climate and fire for each ecoprovince as well as the set of ecoprovinces comprising the western U.S., we used simple Pearson correlation analyses 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 associated with conducting many independent correlation analyses. We did this for both the 1977-2003 and 1916-2003 periods.

To evaluate the potentially complex interaction of different seasonal variables given ecoprovince vegetation type, we also sought diagnostic linear least-squares multiple regression models relating each ecoprovince WFAB time series (response) to pre-whitened, seasonal PPT, T, and PDSI. Except for the inclusion of lagged climate variables, the methods for producing candidate predictive models mirror the criteria used for the ecoprovince WFAB reconstruction. We included lagged versions (up to two years) of the climate variables in our search for candidate predictors. This is potentially an undesirably large ratio of predictors to observations, especially for the 1977-2003 models. We assumed that climate in the year-of-fire was the most proximate influence on fuel moisture and built forward-selection models of fire using the year-of-fire predictors first. However, the sensitivity of vegetation to antecedent climate conditions and the preponderance of lag relationships in fire history data suggest the possibility of considering lag relationships equally.

Once the year-of-fire predictors had been exhausted, we continued to build forward-selection models with the lag 1 climate predictors, but limited the minimum candidate model to a single variable and allowed the lag 1 predictors to preempt the year-of-fire predictors if the AIC
of the candidate model was lower. We then evaluated the lag 2 climate predictors in the same way. We calculated the variance inflation factor (VIF) for each predictor in the candidate model to evaluate the influence of colinearity. For predictors with VIF > 5 (Haan 2002), we iteratively discarded and re-entered collinear variables until a balance between acceptable VIF and minimized AIC was achieved. The final candidate model was accepted when all variables or interactions in the model were \( p(t) \leq 0.15 \), VIF < 5.5, and no variables could be added or removed without increasing the AIC while maintaining the first two criteria. Finally, as a means of cross-validation, we calculated the P.R.E.S.S. RMSE for each 1977-2003 and 1916-2003 fire–climate regression model. We used the ratio of the RMSE to the standard deviation as a comparative indicator of the cross-ecoprovince leave-one-out prediction error.

**RESULTS**

**Fire Area Burned Data Characteristics**

Summary statistics for WFAB in each ecoprovince in 1980-2000 and ecoprovinces 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 tended to peak later in the year compared to 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 (Figure 3). Each could be characterized as log-normal, but the relationship between the variance and mean for all three areal aggregations of fire data (lat/long grid square, state, or ecoprovince) indicates a gamma distribution where the variance is proportional to the mean squared. Only the uncorrected state-level dataset has an unsatisfactory resemblance to the gamma relationship.

**Reconstructing Ecoprovince Area Burned**

We produced reasonable reconstructions of ecoprovince area burned for 16 of the 19 ecoprovinces for the 11 Western states (Table 2). The CA C. Steppe, SW Plateau, and Pacific Lowl. ecoprovinces had the smallest analysis area and smallest mean annual area burned of the ecoprovinces in the West. The variability in annual WFAB for these provinces was not significantly related to the state WFAB time series; we did not pursue these further. The model fit for CA Chaparral and Cascades ecoprovinces, 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. Proportion of variance explained for the log-log models varied from 0.36 to 0.96, and the proportion of deviance explained for the gamma models ranged from 0.34 to 0.80.

Overall, gamma models were superior to logarithmic models in seven reconstructions: AM Semidesert, AZNM Mts, CA Chaparral, CH Semidesert, CO Plateau, NV/UT Mts, and S. Rockies. Gamma models produced large errors for the year 2002 in four southwestern ecoprovince models with Colorado and Arizona as predictors, both states that had relatively low
annual WFAB values during the training period. These models were still superior in an 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 P.R.E.S.S. 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 (Figure 1), underpredicting on average by $B_0 = -6.1 \times 10^4$ hectares ($r^2 = 0.93$, $F = 1052$ on 1 and 87 d.f., $p = 0.000$).

**Climate Data and Pre-treatment**

The first PCA 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 to 0.96 for the PC 1 time series, values were typically highest for temperature variables and lowest for precipitation variables (data not shown), and the season of maximum or minimum variance explained varied by ecoprovince. The PC 2 time series usually represented a weak contrast between two constituent groups of climate divisions.
Several general patterns of seasonal correlation between climate variables and ecoprovince WFAB (Figure 2, Appendix 1A) were evident. For the period 1977-2003, all significant (n = 27, $r_{sig} = 0.3218$, $p = 0.05$) year-of-fire seasonal temperature variables are positive. Growing season temperature was the most frequently important, with significant responses in mountainous ecoprovinces and the Great Plains ecoprovince. 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.

We observed only negative significant relationships between area burned and year-of-fire precipitation or PDSI. In the S. Rockies, Sierra, Great Plains, and CA Dry Steppe, precipitation was correlated with annual WFAB for all seasons, while the WFAB for S. Rockies and the CH Semidesert were correlated with PDSI for all seasons. AZNM Mts, IM Desert, and the NV/UT Mts 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 non-significant 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.

Significant ecoprovince climate-fire correlations exhibit three qualitative patterns (Figure 2). First, several 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, IM Desert and NV/UT Mts have no significant year-of-fire climate relationships, but several moderately strong lag 1 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. Great Plains is characterized by strong year-of-fire relationships similar to the mountain ecoprovinces but also with no significant lag 1 or lag 2 correlations.

1916-2003 Correlations
Correlations were generally weaker for the 1916-2003 period, but some patterns emerge (Appendix 1B). All significant \( n = 88, r_{\text{sig}} = 0.169, p = 0.05 \) temperature (precipitation and PDSI) relationships the year-of-fire were again positive (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.

The qualitative patterns observed for the period 1977-2003 also occurred in the extended 1916-2003 period (Figure 2, Appendix 1B). The mountainous 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 ecoprovinces with weak year-of-fire relationships and stronger positive correlations with lag 1 precipitation and PDSI.
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 (Figure 4, 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 (20) 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) the year-of-fire (Table 3). Similarly, negative lag 1 or lag 2 precipitation or PDSI predictors 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 the year-of-fire was a better negative predictor for CH Semidesert and AZNM Mts. The NV/UT Mts had no significant year-of-fire predictors; the best predictor was positive annual precipitation the year prior to fire (Table 3). Finally, IM Desert had a positive relationship with winter precipitation in the winter immediately preceding fire while the CA Chaparral 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 (Figure 5, 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.

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 N. Rockies, S. Rockies, and IM Desert. Winter climate variables were also prominent in the 1916-2003 models (Table 4). CO Plateau, Great Plains, and IM Semidesert CH Semidesert, IM Desert, and N. Rockies all had significant, positive predictors for year-of-fire winter P or PPT. AM Semidesert, AZNM Mts, CA Woodland, CO Plateau, Great Plains, IM Semidesert, NV/UT Mts, N. Rockies 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 in eight models. Only CA Chaparral had a negative spring precipitation term. The AIC procedure for building diagnostic linear models of WFAB as a function of seasonal climate variables (Figure 6) produced significant models for each of the 16 ecoprovince reconstructions. The AIC procedure sometimes discriminated 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 Appendix 1A and 1B) 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.

**DISCUSSION**

**Fire Data and Reconstructions**

This is the first published description of a gamma distribution describing the relationship between area burned mean and variance. Malamud et al. (2005) demonstrated that frequency-area power laws described the observed distribution of area burned very well and have promise
for describing fire regimes across scales and solving inherent difficulties in modeling disturbance processes (e.g., McKenzie et al. 1996). The gamma relationship described by the mean/variance structure of the WFAB totals (Figure 3) is independent of the size of the grain (from 1° x 1° grid cells to large states and ecoprovinces) considered. Modeling the areal component of fire regimes is therefore a tractable problem. The gamma distribution 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. For example, such a relationship allows a realistic specification, over any time frame or spatial scale, of the parameters for fire area burned in dynamic vegetation models. 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 regression models were generally superior in the southwestern ecoprovinces, whereas logarithmic models were equal or superior in the cooler mountainous and transitional ecoprovinces (Table 2). At least during the model training period, the assumption that the model errors are log-normally 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 non-linear 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.

Climate Relationships with Wildland Fire Area Burned

Dry warm conditions in the seasons leading up to and including the fire season are associated with increased WFAB in most ecoprovinces (Appendix 1A and B, Table 2), particularly in the northern and mountain ecoprovinces (Figure 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) (Van Wagner 1977). Precipitation in the year of fire is more important than PDSI or temperature in most regressions, although PDSI is a better predictor in some ecoprovinces, especially the northern and middle Rocky Mountain ecoprovinces. Drought conditions the year of fire are less important than moist conditions the seasons prior to the fire season in most of the southwestern ecoprovinces. The mechanism behind this relationships is
probably that such conditions are associated with the production of fine fuels in the understory
that then cure in subsequent years and represent available fuels prior to the arrival of monsoon
rain in the summer (Swetnam and 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. NV/UT Mts and IM Desert, which together comprise the
Great Basin and its basin-and-range mountains, are exceptions, and the positive role of year-prior
precipitation is 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.

The pattern of climate-area burned correlations 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 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. Most ecoprovinces exhibit a negative relationship with
winter precipitation, but few are significant. These relationships all suggest that drying of fuels is
the primary mechanism for large WFAB in the higher elevation and northern mountainous
ecoprovinces. WFAB in these ecoprovinces thus appears to be limited by climate and/or
ignitions.

In contrast, much of the southwestern U.S. appears to require a more complicated
mechanism for large WFAB. AM Semidesert, AZNM Mts, CH Semidesert, CO Plateau, and IM
Semidesert are all best correlated with climate variables consistent with facilitation of vegetation
growth the winter(s) prior to fire and 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). It is also possible that the combination of changing fire regime (due to climate) and
changes in the proportion of forested vs. non-forested lands reporting into the state WFAB fire
database could lead to such results. At the scale of ecoprovinces, it is difficult to determine
whether the change in climate drivers or the change in reporting resulted in the mixed models.
More mechanistic studies at finer scales would be required to fully understand these results.

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.

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 U.S. (Mote et al. 2005, Knowles et al. 2006) continues, increases in
the area burned by fire are likely in lower elevations of mountainous ecoprovinces. In the
Southwest, the role of winter conditions in future area burned depends on 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.

The cross-validation of the climate – fire models indicates that the diagnostic models are
not yet developed to the point where prediction of annual area burned from a few climate
variables can estimate the precise value. However, given the highly non-linear nature of the
WFAB data, this is not surprising. Forecasting is clearly beyond the scope of this exercise, but
the diagnostic relationships (Tables 5 and 6) and correlations (Appendix 1) are strong enough to
indicate geographical patterns in the nature of the fire climate relationships (Figure 2). These
patterns are consistent and have simple relationships that can be explored in greater detail at finer
scales.

A concise interpretation of climate-vegetation-fire mechanisms for each ecoprovince is
challenging. Ecoprovinces of the western U.S. 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, but it is also possible that
the change in protected area influenced the results despite our attempt to control for it.

**Ecosystem Controls on Climate-Fire Relationships**
The relationships described above suggest that a clear dichotomy between “fuel limited”/“moisture limited” and “climate limited”/“energy limited” fire regimes in Western ecosystems does not hold up, at least at the scale of ecoprovinces. For example, the northern/mountain ecosystem pattern (Figure 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 1A). 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 is 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. 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 P.R.E.S.S. RMSE values generally consistent with mean WFAB (Table 2), and described the total area burned (Figure 1). The former explanation, while 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. A few climate variables account for much of the WFAB, and patterns of climate-fire associations make sense given ecoprovence vegetation structure. Therefore, the effects of climate change on fire in the western U.S. 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).

**Implications for Ecosystem Management**

The climate-fire relationships presented identify ecosystem-specific mechanisms relating
cclimate 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. Similarly, multi-
scale predictive models that link hemispheric climate variability to sub-regional climate and
vegetation production and drying could significantly improve prediction of WFAB. 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 derived from such models. 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
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 U.S. 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 unexplained variability could be due to a number of factors, including fire suppression, land use, or climate variables we did not consider. 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. 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 limitation. In fuel-limited ecosystems, fuel-treatments can probably mitigate fire vulnerability and increase resilience more readily than in climate-limited ecosystems where adaptation to climate change is a more realistic approach.
We would like to acknowledge Steve McKay and Janice Peterson (USDA Forest Service PNW Research Station) for compiling the original 1916-2003 state-level area burned data. Tom Swetnam provided advice in the early stages of analysis, and Nate Mantua, Jim Agee, Linda Brubaker, and Crystal Raymond provided helpful comments on an earlier draft of this manuscript. A. Westerling was supported by NOAA OGP during the work. This publication was supported by the Western Mountain Initiative and partially funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. NA17RJ1232, Contribution no. 1400.
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TABLE 1. Ecoprovince area burned statistics 1980-2000, calculated from gridded fire data in Westerling et al. (2003). Ecoprosions are arranged by the fraction of the province area burned annually, lowest to highest.

<table>
<thead>
<tr>
<th>Ecoprosion</th>
<th>Bailey Code</th>
<th>Abbreviation</th>
<th>Analysis area (ha x 10^7)</th>
<th>Annual mean (ha x 10^4)</th>
<th>Peak fire season</th>
<th>Annual mean (x 10^-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacific Lowland Mixed</td>
<td>242</td>
<td>Pacific Lowl.</td>
<td>0.38</td>
<td>0.01</td>
<td>Sep.-Oct.</td>
<td>0.02</td>
</tr>
<tr>
<td>Cal. Coastal Steppe</td>
<td>263</td>
<td>CA C. Steppe</td>
<td>0.12</td>
<td>0.02</td>
<td>Apr; Jul; Oct.</td>
<td>0.18</td>
</tr>
<tr>
<td>Ariz.-New Mex. Mts. Semi-Desert</td>
<td>M313</td>
<td>AZNM Mts</td>
<td>1.30*</td>
<td>0.93</td>
<td>May – Jul.</td>
<td>0.72</td>
</tr>
<tr>
<td>American Semi-Desert and Desert</td>
<td>322</td>
<td>AM Semidesert</td>
<td>2.27</td>
<td>1.74</td>
<td>Apr.-Aug.</td>
<td>0.77</td>
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<tr>
<td>Cal. Dry Steppe</td>
<td>262</td>
<td>CA Dry Steppe</td>
<td>0.50</td>
<td>0.42</td>
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<td>0.85</td>
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<td>Southwest Plateau / Plains Steppe</td>
<td>315</td>
<td>SW Plateau</td>
<td>0.25*</td>
<td>0.22</td>
<td>Feb-Apr.; Jun.</td>
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<tr>
<td>Ecoprovince</td>
<td>Code</td>
<td>State/Region</td>
<td>Fire Area Burned (Mean)</td>
<td>Season</td>
<td>Notes</td>
<td></td>
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<tr>
<td>-------------------------------------</td>
<td>------</td>
<td>-------------------</td>
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<td>Colo. Plateau Semi-Desert</td>
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<td>CO Plateau</td>
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<td>Apr.-Aug.</td>
<td>0.90</td>
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<tr>
<td>Great Plains-Palouse Dry Steppe</td>
<td>331</td>
<td>Great Plains</td>
<td>3.52*</td>
<td>Jun.-Sep.</td>
<td>0.94</td>
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</tr>
<tr>
<td>Cascade Mixed Forest</td>
<td>M242</td>
<td>Cascades</td>
<td>1.38</td>
<td>Jul.-Aug.</td>
<td>1.41</td>
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<tr>
<td>Northern Rocky Mt. Forest</td>
<td>M333</td>
<td>N. Rockies</td>
<td>0.99</td>
<td>Jun. – Oct.</td>
<td>1.41</td>
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<tr>
<td>Chihuahuan Semi-Desert</td>
<td>321</td>
<td>CH Semidesert</td>
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<td>May. – Jul.</td>
<td>1.57</td>
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<td>South. Rocky Mt. Steppe- Forest</td>
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<td>S. Rockies</td>
<td>2.65</td>
<td>Jun. – Sep.</td>
<td>2.06</td>
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<tr>
<td>Nev.-Utah Mountains-Semi-Desert</td>
<td>M341</td>
<td>NV/UT Mts</td>
<td>1.13</td>
<td>Jun. – Aug.</td>
<td>2.11</td>
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<td>Middle Rocky Mt. Steppe- Forest</td>
<td>M332</td>
<td>M. Rockies</td>
<td>2.12</td>
<td>Jun. - Sep.</td>
<td>3.91</td>
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<td>Cal. Coast. Chaparral Forest/Shrub</td>
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<td>CA Chaparral</td>
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<td>Jul.; Sep. – Nov.</td>
<td>4.01</td>
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<tr>
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<td>Sierra</td>
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<td>Jun. – Oct.</td>
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<tr>
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<td>IM Desert</td>
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<td>Jun. – Sep.</td>
<td>4.13</td>
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<tr>
<td>Intermountain Semi-Desert</td>
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<td>IM Semidesert</td>
<td>4.12</td>
<td>Jun. – Oct.</td>
<td>5.15</td>
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<td>CA Woodland</td>
<td>0.64</td>
<td>Apr. – Nov.</td>
<td>7.60</td>
<td></td>
</tr>
</tbody>
</table>

*Partial ecoprovince in analysis; some ecoprovinces exceed borders of 11 Western states from which fire data was taken.
TABLE 2. Statistical summary for ecoprovince reconstruction models.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Model type</th>
<th>Model predictors*</th>
<th>Fitted mean 1980-2003 (ha)</th>
<th>P.R.E.S.S. RMSE (ha)</th>
<th>$R^2$ or expl. deviance**</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Semidesert</td>
<td>Gamma.00</td>
<td>AZ + NV</td>
<td>19974</td>
<td>7318</td>
<td>0.69</td>
</tr>
<tr>
<td>AZNM Mts</td>
<td>Gamma.00</td>
<td>ID + AZ</td>
<td>12996</td>
<td>13771</td>
<td>0.58</td>
</tr>
<tr>
<td>CA Chaparral</td>
<td>Gamma.00</td>
<td>CA + NV + CA:NV</td>
<td>12857</td>
<td>24309</td>
<td>0.34</td>
</tr>
<tr>
<td>CA Woodland</td>
<td>log.03</td>
<td>log(CA) + log(OR)</td>
<td>44774</td>
<td>52773</td>
<td>0.48</td>
</tr>
<tr>
<td>CA C. Steppe</td>
<td>NO MODEL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA Dry Steppe</td>
<td>log.00</td>
<td>CA</td>
<td>3220</td>
<td>10666</td>
<td>0.58</td>
</tr>
<tr>
<td>Cascades</td>
<td>log.03</td>
<td>log(OR)</td>
<td>20413</td>
<td>35763</td>
<td>0.36</td>
</tr>
<tr>
<td>CH Semidesert</td>
<td>Gamma.00</td>
<td>AZ + NM</td>
<td>26198</td>
<td>24192</td>
<td>0.57</td>
</tr>
<tr>
<td>Region</td>
<td>Polytype</td>
<td>Equation</td>
<td>Residual Deviance</td>
<td>Null Deviance</td>
<td>Deviance Explained</td>
</tr>
<tr>
<td>---------------</td>
<td>----------</td>
<td>--------------------------------------------------------</td>
<td>-------------------</td>
<td>---------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>CO Plateau</td>
<td>Gamma.00</td>
<td>AZ + CO + NM + AZ:NM</td>
<td>22442</td>
<td>12559</td>
<td>0.80</td>
</tr>
<tr>
<td>Great Plains</td>
<td>log.00</td>
<td>log(MT)</td>
<td>35107</td>
<td>15636</td>
<td>0.74</td>
</tr>
<tr>
<td>IM Semidesert</td>
<td>log.03</td>
<td>log(OR) + log(ID) + log(NV) + log(WA)</td>
<td>176510</td>
<td>85233</td>
<td>0.85</td>
</tr>
<tr>
<td>IM Desert</td>
<td>log.03</td>
<td>log(NV):log(CO) + log(UT):log(CO) + log(NV) + log(UT):log(CO)</td>
<td>98561</td>
<td>39906</td>
<td>0.96</td>
</tr>
<tr>
<td>M. Rockies</td>
<td>log.00</td>
<td>log(WY) + log(OR) + log(ID)</td>
<td>65451</td>
<td>86568</td>
<td>0.77</td>
</tr>
<tr>
<td>NV/UT Mts</td>
<td>Gamma.00</td>
<td>NV + UT</td>
<td>22755</td>
<td>14768</td>
<td>0.68</td>
</tr>
<tr>
<td>N. Rockies</td>
<td>log.00</td>
<td>log(ID) + log(WA)</td>
<td>13284</td>
<td>17143</td>
<td>0.79</td>
</tr>
<tr>
<td>Pacific Lowl.</td>
<td>NO MODEL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sierra</td>
<td>log.00</td>
<td>log(CA) + log(OR)</td>
<td>63862</td>
<td>85247</td>
<td>0.60</td>
</tr>
<tr>
<td>S. Rockies</td>
<td>Gamma.03</td>
<td>log(MT) + log(WY) + log(MT):log(WY)</td>
<td>64402</td>
<td>37267</td>
<td>0.76</td>
</tr>
</tbody>
</table>

*State-level area burned from the area reporting-adjusted PWFSL dataset.
**Deviance explained = (Null Deviance – Residual Deviance)/Null Deviance
### Table 3. Climate-fire diagnostic regression models for 1977-2003.

<table>
<thead>
<tr>
<th>Ecoprovince</th>
<th>1977-2003 Model*</th>
<th>$R^2$</th>
<th>RMSE / SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Semidesert</td>
<td>$-\text{GS.P} + -\text{Spr.P} + -\text{Spr.T} + -\text{L1.GS.P} + \text{L1.Wnt.PDSI}**$</td>
<td>0.72</td>
<td>1.42</td>
</tr>
<tr>
<td>AZNM Mts</td>
<td>$-\text{ANN.PDSI} + -\text{Sum.P} + \text{L1.WNT.P} + \text{L1.SPR.T} + \text{L2.Sum.T}$</td>
<td>0.74</td>
<td>1.62</td>
</tr>
<tr>
<td>CA Chaparral</td>
<td>$-\text{Wnt.PDSI} + -\text{Sum.P} + \text{Wnt.PDSI} : \text{Sum.P} + -\text{L2.Spr.T}$</td>
<td>0.54</td>
<td>1.81</td>
</tr>
<tr>
<td>CA Woodland</td>
<td>$-\text{Sum.P} + \text{L1.Wnt.T} + -\text{L1.Spr.T} + \text{L1.Sum.P}$</td>
<td>0.47</td>
<td>1.41</td>
</tr>
<tr>
<td>CA Dry Steppe</td>
<td>$-\text{Sum.P} + -\text{Spr.P} + \text{Spr.PDSI} + -\text{Wnt.P}$</td>
<td>0.59</td>
<td>0.78</td>
</tr>
<tr>
<td>Cascades</td>
<td>$-\text{GS.P} + \text{L1.Wnt.P} + -\text{L1.Wnt.T} + \text{L2.Wnt.P} + -\text{L2.Sum.P}$</td>
<td>0.65</td>
<td>1.27</td>
</tr>
<tr>
<td>CH Semidesert</td>
<td>$-\text{Ann.PDSI} + \text{Wnt.P} + \text{L1.Spr.PDSI} + \text{Ann.PDSI} : \text{Wnt.P}$</td>
<td>0.80</td>
<td>1.07</td>
</tr>
<tr>
<td>CO Plateau</td>
<td>$-\text{Sum.P} + -\text{Sum.PDSI} + -\text{L1.GS.P} + \text{L1.Ann.P} + \text{L2.GS.T}$</td>
<td>0.63</td>
<td>1.35</td>
</tr>
<tr>
<td>Great Plains</td>
<td>$-\text{Sum.P} + -\text{Spr.P} + -\text{Wnt.P} + \text{L1.Wnt.T} + -\text{L1.Spr.P} + \text{L1.Sum.PDSI}$</td>
<td>0.87</td>
<td>0.56</td>
</tr>
<tr>
<td>IM Semidesert</td>
<td>$-\text{GS.P} + \text{L1.Spr.PDSI} + \text{L2.Wnt.PDSI} + \text{L2.Spr.T}$</td>
<td>0.56</td>
<td>2.08</td>
</tr>
<tr>
<td>IM Desert</td>
<td>$\text{Wnt.P} + \text{Wnt.T} + \text{L2.Spr.T} + \text{L2.Wnt.PDSI} + \text{L2.Wnt.T} + \text{Wnt.P} : \text{Wnt.T}$</td>
<td>0.71</td>
<td>1.64</td>
</tr>
<tr>
<td>M. Rockies</td>
<td>$-\text{Sum.PDSI} + \text{Wnt.P} + \text{L2.Spr.T} + \text{L2.Spr.PDSI} + -\text{L2.Sum.P} + -\text{L2.Ann.T}$</td>
<td>0.81</td>
<td>0.64</td>
</tr>
<tr>
<td>NV/UT Mts</td>
<td>$\text{L1.Ann.P} + \text{L2.Spr.T} + \text{L2.GS.P}$</td>
<td>0.33</td>
<td>1.31</td>
</tr>
<tr>
<td>Region</td>
<td>Model Equation</td>
<td>R²</td>
<td>p</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------------------------------</td>
<td>-----</td>
<td>----</td>
</tr>
<tr>
<td>N. Rockies</td>
<td>- Sum.PDSI + Wnt.T + L1.Sum.P - L1.GS.T</td>
<td>0.74</td>
<td>0.79</td>
</tr>
<tr>
<td>Sierra</td>
<td>- Sum.PDSI + L1.Wnt.P + L1.GS.P + L1.Wnt.P :L1.GS.P</td>
<td>0.53</td>
<td>1.11</td>
</tr>
<tr>
<td>S. Rockies</td>
<td>- Spr.P + -Sum.P + Wnt.T + Spr.T + L2.Spr.PDSI + Spr.P :Sum.P</td>
<td>0.77</td>
<td>0.69</td>
</tr>
</tbody>
</table>

* All models are statistically significant; all p < 0.02.

** Notation: + followed by – refers to the additive regression effect of a negative predictor; the absence of a – symbol indicates the predictor is positive.
<table>
<thead>
<tr>
<th>Ecoprovince</th>
<th>1916-2003 Model**</th>
<th>$R^2$</th>
<th>RMSE / SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZNM Mts</td>
<td>GS.T + SPR.T + L1.WNT.P + L2.Sum.T + L2.SPR.P + GS.T :SPR.T</td>
<td>0.34</td>
<td>&gt; 3.0</td>
</tr>
<tr>
<td>CA Chaparral</td>
<td>-Spr.P + Sum.PDSI + Spr.T + L1.GS.PDSI + - L1.GS.P + - L2.Sum.T + L2.Sum.PDSI</td>
<td>0.46</td>
<td>2.49</td>
</tr>
<tr>
<td>Cascades</td>
<td>-Sum.PDSI + - L1.GS.P + L2.Spr.T</td>
<td>0.25</td>
<td>&gt; 3.0</td>
</tr>
</tbody>
</table>
Littell et al. Climate and Ecoprovince Fire Area Burned

Great Plains
: L2.Wnt.PDSI

0.51 > 3.0

IM Semidesert


0.42 2.16

IM Desert
Ann.P : Wnt.PDSI

0.38 2.23

M. Rockies


0.56 1.59

NV/UT Mts
L1.GS.P : L1.Wnt.P

0.46 0.64

N. Rockies


0.57 > 3.0

Sierra

L2.GS.T

0.39 > 3.0

S. Rockies
GS.T + - Sum.PDSI + L1.Spr.T + GS.T : Sum.PDSI

0.33 > 3.0

** Notation: + followed by – refers to the additive regression effect of a negative predictor; the absence of a – symbol indicates the predictor is positive.
FIGURE LEGENDS

FIGURE 1. Observed and reconstructed area burned comparison. 1916-2004 time series of observed total WFAB for 11 Western states (bars, adjusted for area-reporting bias) and reconstructed total WFAB for 16 ecoprovinces (line).

FIGURE 2. Ecoprovinces of the Western United States and common patterns of climate / fire associations from correlation and diagnostic regression models (see results and discussion).

FIGURE 3. The relationship between the mean and variance in annual WFAB. For states and ecoprovinces (left) and lat/long gridcells (right) in the western U.S., the variance is proportional to the mean squared in all WFAB datasets, leading to the choice of the “gamma model” in WFAB reconstructions. Note linear-log axes.


FIGURE 6. Data handling and analysis workflow.
Figure 2.
**Figure 3.**

![Graphs showing the relationship between log10(s^2) and mean annual area burned, x_\mu (ha \times 10^5).](image)

- $\log_{10}(s^2) = 22.8 \cdot x_\mu^{1.8}; R^2 = 0.96$
- $\log_{10}(s^2) = 30.8 \cdot x_\mu^{1.8}; R^2 = 0.97$
- $\log_{10}(s^2) = 5.7 \cdot x_\mu^{1.9}; R^2 = 0.72$
- $\log_{10}(s^2) = 15.9 \cdot x_\mu^{1.9}; R^2 = 0.74$

- **1980 - 2000 Aggregated Grid Cell Ecoprovince Area Burned**
- **1916 - 2003 PWFSL State Area Burned**
- **1980 - 2003 Large Fire Database Ecoprovince Area Burned**
- **1980 - 2003 PWFSL State Area Burned**
- **1916 - 2003 Adjusted State Area Burned**

- $\log_{10}(s^2) = 14.2 \cdot x_\mu^{2.0}; R^2 = 0.97$
Figure 4.
Fire Area Burned Data

Dataset:
- Gridded fire DB
  - 1980 - 2000
  - 331 1°x1° Cells
- Large fire DB
  - 1980 - 2003
  - Fires > 200 ha

Step 1:
Downscaling states to ecoprovinces to create WFAB time series
- Aggregate grid
  - 1980 - 2000
  - 19 Ecoprovinces
- Large fire DB
  - 1980 - 2003
  - 19 Ecoprovinces

Adjusted States (independent)
- log_{10} Gamma

AIC Criterion

Step 2:
Ecoprovince model comparison
- Model back-cast 1977-2003 and 1916-2003 WFAB for each ecoprovince


Step 3:
Ecoprovence WFAB reconstruction

Step 4:
Climate data
- Seasonal PW.T (5)
- Seasonal PW.P (5)
- Seasonal PW.PDSI (5)

Prewhitening (AIC order): 1916-2003

Step 5:
Ecoprovence WFAB correlations
- Seasonal PW.T (5)
- Seasonal PW.P (5)
- Seasonal PW.PDSI (5)

Step 6:
Ecoprovence WFAB-climate multi. regression models

PWFL. WFAB
1916 - 2003
11 Western states

Area Reporting Adjustment

<< P.R.E.S.S. RMSE

MODEL

Step 4:
Climate data

1910 - 2003 Monthly NCDC Divisional Temp (T) Precip. (P) (PDSI)

Seasonal aggregation
- Winter: ONDJFM
- Spring: MAM
- Graw. Seas.: MJJAS
- Summer: JAS

PCA: division climate to ecoprovence climate

1916-2003
1977-2003

1916-2003 WFAB
1977-2003 WFAB
(dependent, AIC selection)
(independent)