The University of Arizona

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Fire and Climate Synthesis (FACS) Project, JFSP 09-2-01-10

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ABSTRACT

Understanding the role of climate variation in governing fire regimes remains one of the central needs in contemporary fire science and management. Ideally, this understanding should encompass both historical and current fire-climatology, and inform both basic science and ecosystem management. In this project, Fire and Climate Synthesis (FACS) we undertook a detailed synthesis of both paleofire and modern fire based on compilations of existing data sets. We also analyzed three major thematic pathways by which climate has impacted fire policy, including direct and indirect climate effects on fire policy.

Paleofire. We assembled the largest and most comprehensive data set of cross-dated, georeferenced fire-scar paleofire records ever compiled for western North America. Data were provided by over 60 researchers in the field, in the form of data files, published reports, and individual study records. We also accessed the most recent holdings of the International Multiproxy Paleofire Database (IMPD) for inclusion in our compilation. These efforts resulted in the compilation of 1,248 fire history studies from 64 contributors meeting our quality criteria. Study locations extend from southern Canada to north-central Mexico, and cover the 3,248-yr period 1248 BCE to 2011 CE, with sample size > 600 sites covering the period 1700-1990. Seven major forest types are represented, including piñon-juniper, pine-oak woodland, ponderosa pine woodland, dry and mesic mixed conifer, fir, and subalpine forests. Mean annual precipitation ranges from < 30 cm to > 200 cm, while mean annual temperature ranges from 5.0 to 25.3 °C. We identified numerous west-wide fire years in the paleofire record indicating the strong top-down influence of synoptic climate conditions and regulation by major climate oscillatory modes. Our work included the development of new software tools to facilitate future analyses of paleofire data sets (see *Decision Support Tools*, below).

Modern fire. For our synthesis of modern fire-climatology, we focused on analyzing trends and drivers in area burned in western forests, particularly the influence of snowpack duration and climate variables to annual area burned. We compiled annual area burned (AAB) for the western US based on data provide by Dr. AH Westerling, University of California – Merced, for the period 1972-2006. 12,596 fires met data quality standards and were included in analysis. Similar data were obtained from the Canadian Large Fire Database. Spatiotemporal climate layers (monthly mean, minimum, and maximum temperature and precipitation) were obtained from the National Climate Data Center for the same time period. We obtained snowpack data estimating the presence or absence of snowpack from satellite reflectance data aggregated to 25 km2 pixels. Snowpack data were converted to a continuous variable, LDPS (Last Date of Permanent Snowpack). We evaluated all time series for trend over the period of analysis at the scale of each 1° grid cell. For AAB we analyzed the period 1972-1999, and climate variables and snowpack for the period 1972-2006. To separate the influence of multiple drivers, we employed path analysis to identify the relative contributions of seasonalized temperature, precipitation, and snowpack duration to AAB. AAB increased significantly over most of the study area during the period 1972-1999. Seasonalized temperatures increased, and winter precipitation and snow cover duration decreased, over most of the study area significantly over the period of analysis (1972-2006). Winter temperature and precipitation had the strongest effect on snowpack duration. In turn, snowpack duration affected AAB, but results were spatially heterogeneous. Overall, the strongest effects on AAB were the direct effects of winter and temperature, followed by direct effects of spring precipitation. Most indirect effects, i.e.

mediated by climate effects on snowpack, were a relatively small component of variability. Effects of snowpack on AAB were spatially variable in strength and sign. These results suggest that snowpack duration may be an indicator of the factors that control AAB, rather than a mechanism of control. We also compiled the first complete set of "pyroclimographs" for the western US, visualizations that integrate monthly mean temperature, precipitation, and area burned from both lightning- and human-caused fires.

Influence of climate change on fire policy. The objectives of this component of the synthesis were to reconstruct and synthesize the pathways by which past climate-fire events have shaped policy and decision-support systems for national wildland fire management, and to determine ways to proactively use climate change and fire/climate relationship knowledge to inform to policy and guide decision-support systems. We collated information from a wide range of published sources, Incident Reports, current and recent wildland fire policy documentation, peer-reviewed manuscripts, technical reports and other gray literature, and essays and articles on fire management history in the US, including previous syntheses of fire policy history. We also held informal discussions with five national level fire program managers who shared a combined experience of over 150 years in fire management across four of the five primary federal land management agencies. We also reviewed curricula for 15 different courses taught at the National Advanced Fire and Resource Institute (NAFRI). From our literature review and our discussions, we identified two types of climate impacts on fire policy: direct (top-down) and indirect (bottom-up). For each impact type, we identified events, trends, and resulting policy or changes in management. Deliverables from this section of the project include an analysis of climate impacts on US national wildfire policy and practice in the form of webinars and published journal papers.

Decision Support Tools. The technology transfer tools developed from this project include workshops, webinars, publications, analytical tools, presentations, and fact sheets. We also developed several new software applications that facilitate fire history analysis, including Java-based tools for superposed epoch analysis, fire history file combination, and for generating binary output files used for fire history statistical analyses.

BACKGROUND AND PURPOSE

A recent wave of scientific publications and interest in fire climatology derives in part from two new paradigms in climatology: (1) the discovery and understanding of broad-scale ocean-atmosphere oscillations (e.g., El Nino-Southern Oscillation, Pacific Decadal Oscillation, and others) and their teleconnections to regional and continental temperature, precipitation and fire regimes, and (2) the mounting evidence of secular warming trends occurring at local to global scales that are largely driven by increasing greenhouse gases in the atmosphere, and concurrent increases in areas burned and the length of fire seasons. In addition to these developments, fire and climate history datasets have greatly expanded and improved in the past decade. The increased availability of these datasets has facilitated a substantial increase in the literature of fire climatology encompassing both "paleo" (i.e., pre 1900) and modern time periods, especially for the western United States and Canada. Although many new insights have been gained, until recently there has been no synthetic review of western U.S. fire climatology to date. Nor is there a clear and comprehensive regionalization (from the literature and data) of fire-climate patterns, teleconnections, lagging relationships, etc., or evaluation of unknowns and limitations of fire climatology. Furthermore, we are in the early developmental stages of facilitating access to and use of fire history and fire climatology information by managers and policy makers (e.g., "Predictive Services" products). We also have much to learn from past fire-climate events and management/policy responses.

We designed and carried out the Fire and Climate Synthesis (FACS) project for western North America fulfilling the needs of syntheses, improved data access and communication, and learning from past management experiences and policy evolution. In particular, we proposed to: (1) Conduct a quantitative synthesis of paleo and modern fire and climate history time series to define a "geography of fire climatology" of the western U.S.; (2) incorporate the fire-climate synthesis results into a set of existing management decision support tools, to inform managers and decision makers about relationships between climate and fire under past, present, and potential future climate regimes; and (3) conduct a series of workshops and interviews with fire managers to define and explore the applications of fire climatology in fire management (especially resource allocation, appropriate management response, and fuels treatments), and to learn from past management responses to fire-climate events, and the resulting policy changes.

STUDY DESCRIPTION AND LOCATION

The spatial scope of the FACS project is the western United States. Additional information has been incorporated from southwestern and central Canada and northern Mexico.

KEY FINDINGS

Our findings are grouped according to the four main components of the FACS projects: paleofire, modern fire, fire policy, and decision support.

1. Pyrogeography of historical fire regimes in western North America

Understanding the large scale patterns and drivers of historical fire regimes in western North America has been a central focus of our JFSP-supported synthesis effort. Our main FACS objective was to synthesize existing data about historical fire regimes in western North America. As summarized below and in the *Deliverables* associated with this report, we have met and exceeded this objective. Here we summarize our accomplishments in three primary areas of effort: data compilation and synthesis, visualization, and analysis of spatiotemporal synchrony.

Data compilation and synthesis.

Methods. We conducted an exhaustive data search for fire history information from the study area. Our search included published reports (both peer reviewed and in other venues such as GTRs and agency reports) as well as accessing the holdings of the International Multiproxy Paleofire Database (IMPD) for inclusion in our compilation. We also contacted more than 30 active fire researchers with active or past fire history research programs to obtain unpublished data. We limited our search to studies that were (a) georeferenced with adequate precision to permit accurate mapping, either using coordinates obtained from GPS in the field, or by determining coordinates from topographic maps included in publications or field archives; and (b) crossdated using currently accepted standards for determining absolute chronological age of scars or other features, as verified by the contributor. We accepted data in a variety of data formats, including FHX2 files (Grissino-Mayer 2001), electronic spreadsheets, and tabular lists or fire years by site.

For each study, we recorded (a) site name, (b) site acronym if used, (c) electronic filename if provided, (d) georeference, generally either as longitude/latitude or UTM coordinate and zone, (e) state or province and country of origin, (f) name of contributor(s), presence or absence in the IMPD data holdings. Additional attributes were recorded if provided in the site file metadata, including (g) elevation, (h) area sampled, (i) number of trees sampled, (j) ecological community type, and (k) publications associated with the site collection. For site files with incomplete records in any of these categories, we assigned file names or site acronyms, and calculated location georeferenced using topographic maps, DEMs, or communications with the contributor; elevations were calculated by DEM using the georeference provided or calculated. Attributions were confirmed with the contributor where possible.

Ecological community types were, not surprisingly, inconsistent among studies, which were conducted over several decades by multiple investigators and for a wide range of purposes. To provide a consistent basis for ecological assignments, we derived a forest cover type for each georeferenced sample point from the National Atlas (http://nationalatlas.gov/index.html), using the Forest Cover Type layer for the nearest 30m pixel. The climate space occupied by the data sites was calculated using data for from the NCEP/NCAR Reanalysis Project of NOAA (http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis.html); for our preliminary synthesis we used mean annual temperature and precipitation.

Results. These efforts resulted in the compilation of 1,248 fire history studies from 64 contributors meeting our quality criteria. Only one researcher contacted declined to contribute data to the project. Many researchers contributed new, unpublished data that enriched the overall scope of the data set. Study locations extend from southern Canada to north-central Mexico (Figure 1.1). These data cover the 3,248-yr period 1248 BCE to 2011 CE, with sample size > 600 sites covering the period 1700-1990 (Figure 1.2). The FACS fire history dataset is thus the most extensive in both space and time ever compiled.

Across western North America, certain years stand out for the extraordinary amount of fire recorded, with evidence of fire recorded at more than 200 sites three times (1748, 1829, 1851) (Figure 1.3). When corrected for sample size, fire was recorded at ≥ 20 % of sites in 13 years, including 6 times in the 18th century (on average, ~ every 16 yr) and 5 times in the 19th (on average, every 20 yr) (Figure 1.4, Table 1.1).

The FACS fire history network is derived from sites in forested ecosystems representing a broad range of climate conditions (Figure 1.5). Seven major forest types are represented, including piñon-juniper, pine-oak woodland, ponderosa pine woodland, dry and mesic mixed conifer, fir, and subalpine forests. Mean annual precipitation ranges from < 30 cm to > 200 cm, while mean annual temperature ranges from 5.0 to 25.3 °C.

Visualization. Spatiotemporal data such as the FACS data set lend themselves naturally to a variety of visualization approaches. Led by Dr Matthew Hall (University of Arizona), the FACS team has explored novel ways to visualize fire history data. These efforts have included animation of fire-year and climate maps. As an example, FACS prepared an animated series of fire-year maps, using as a base layer a spatial interpolation of the Cook et al. (2004) gridded reconstruction of the Palmer Drought Severity Index (PDSI) for the period 1700-1999 (Figure 1.6).

Analysis of spatiotemporal synchrony. A final element in our synthesis of paleofire in western North America has been the search for patterns and drivers of synchronous fire occurrence. At large spatial scales (e.g., > 10^5 km^2), synchronous fire occurrence reflects primarily top-down entrainment by climatic variation, beyond the spatial scale of fire spread (Williams et al. 2010; McKenzie et al. 2011; Falk et al. 2011). The multicentury FACS network provides an unusually rich opportunity to explore these patterns in the paleo record. Our approach to date has focused on the search for recurrent similarity in fire occurrence among sites, at varying spatial scales. To approach this problem we developed several software applications (described under *Deliverables*) including JAVA applications JOINT and MATRIX (E. Velasquez. Programmer). JOINT facilitates combination of multiple FX2 files, which is essential for multiscale analysis of fire history data. MATRIX takes FHX2 files as input and outputs a series of matrices, including a master binary *year* × *site* matrix, and component matrices used to calculate pairwise similarity/distance indices. MATRIX outputs these similarity matrices for every pair of FACS sites, forming the basis for cluster analysis and, ultimately, regionalization of the fire history network (Figure 1.7). This work will continue beyond the current project.

Personnel: The paleofire component of FACS has been led by Drs Falk and Swetnam, with assistance from Erica Bigio (University of Arizona, Graduate Research Associate) and Dr Thomas Kitzberger (Universidad del Comahue, Bariloche, Argentina). Programming assistance has been provided by Dr Elena Velasquez. Visualizations have been developed by Dr Matthew Hall (UA). We gratefully acknowledge the voluntary contributions of data from contributors to the FACS paleofire data set.

Table 1.1. Years in which fire was recorded at ≥ 20% of active sites in western North America, 1300-2010.

Year	Percent of sites recording fire
1684	21.3
1685	24.1
1729	24.0
1748	31.6
1752	22.2
1763	21.4
1785	24.6
1794	20.5
1822	20.6
1829	24.2
1851	27.2
1870	21.0
1879	23.2

Figure 1.1. Geographic distribution of fire history sites compiled for the western North American Fire and Climate Synthesis (FACS) network.

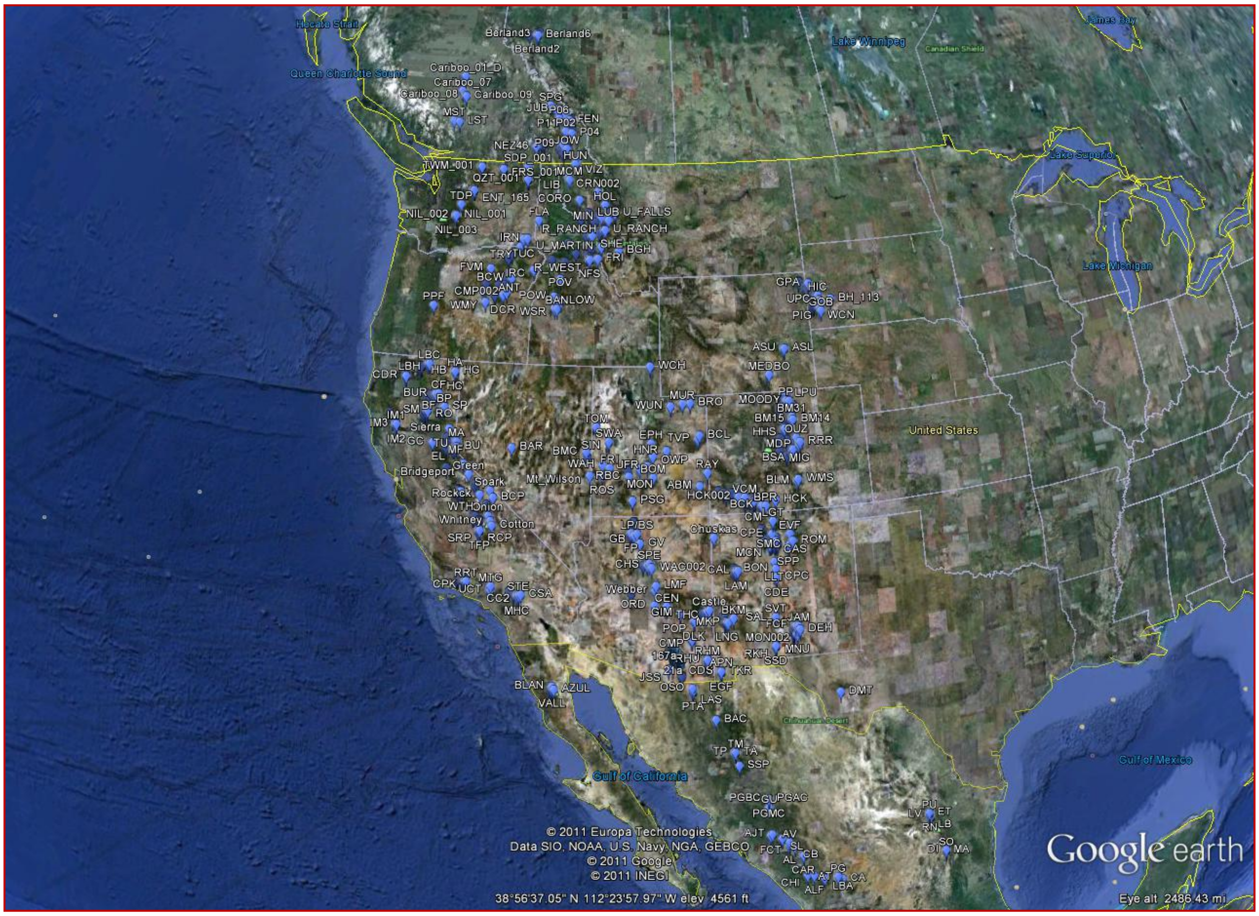


Figure 1.2. Sample size (active fire history sites, by year) across western North America, 1300-2010.

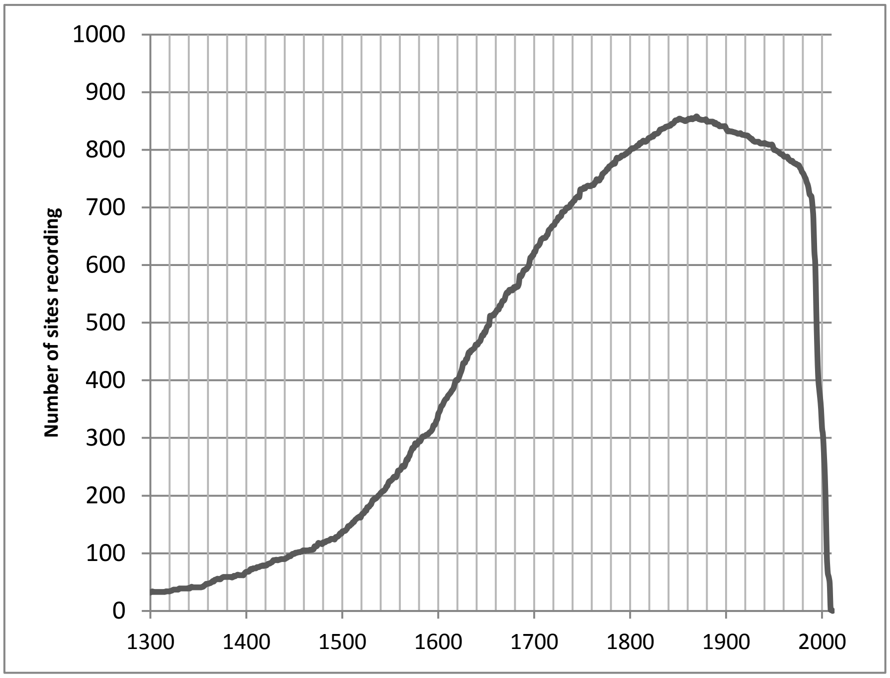


Figure 1.3. Number of sites in western North America with fire, by year 1300-2010.

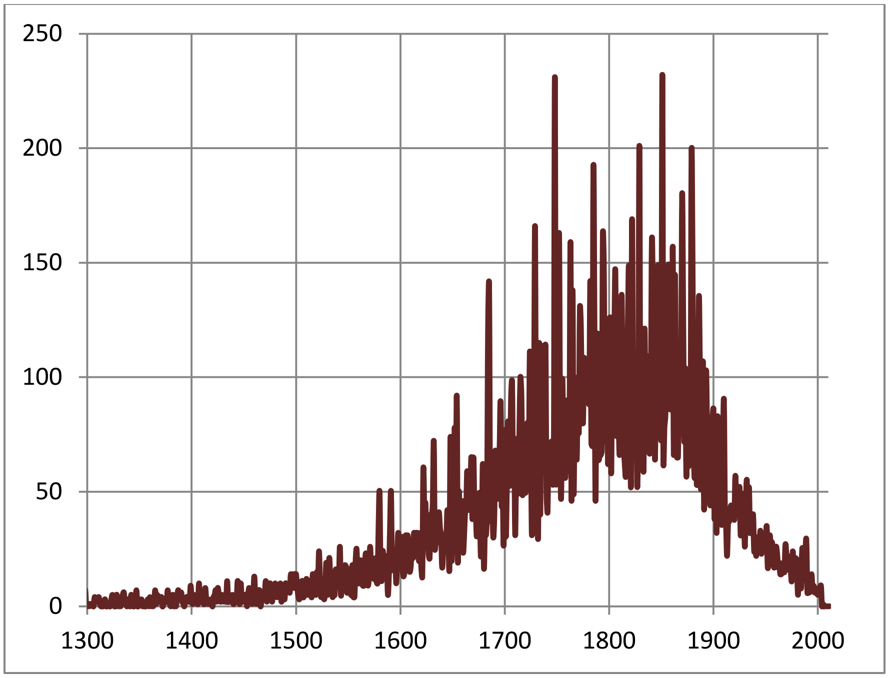


Figure 1.4. Percent of active sites in western North America recording fire, by year 1300-2010.

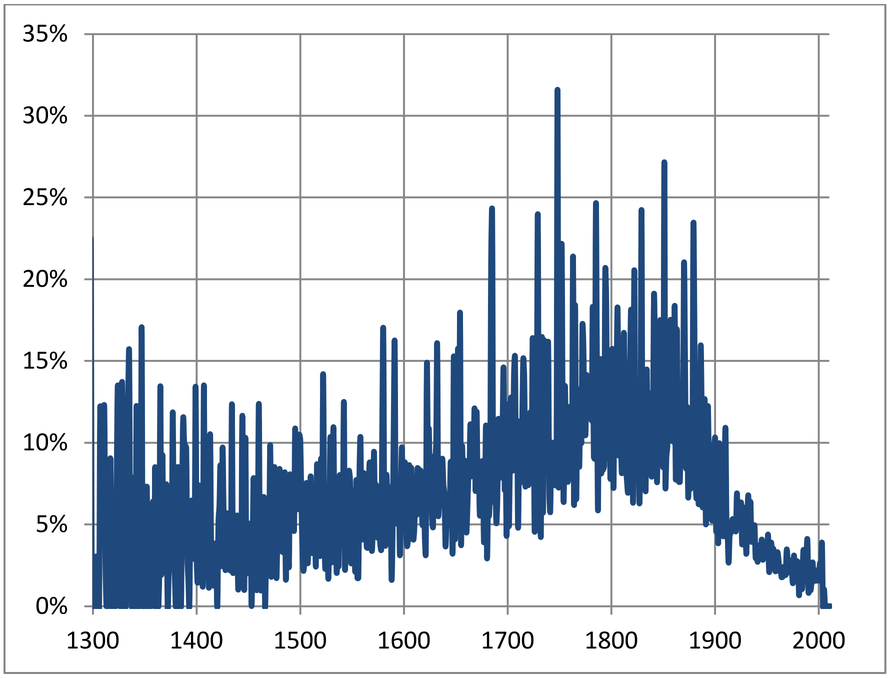


Figure 1.5. FACS sites in climate space (mean annual temperature × mean annual precipitation for year 1970-2000). Climate data derived from the NCEP/NCAR Reanalysis Project, NOAA.

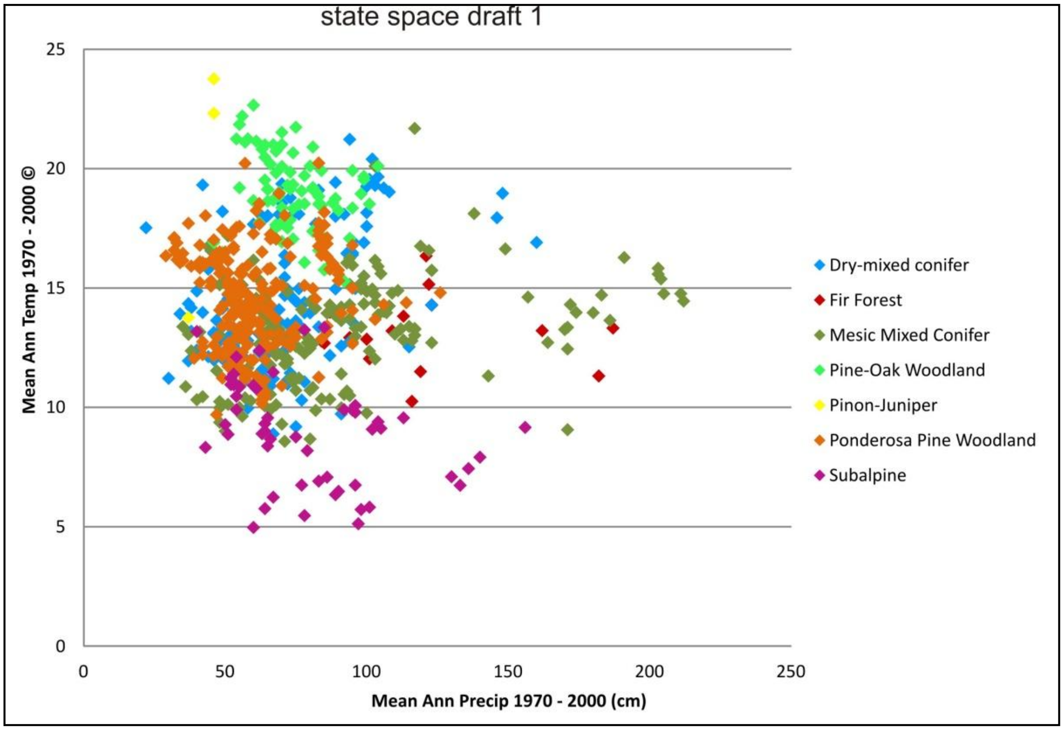


Figure 1.6. Composite image of animation panels depicting fire occurrence in western North America. Background layer is interpolated from the Cook et al. (2004) gridded reconstructed Palmer Drought Severity Index. Figure prepared by M. Hall.

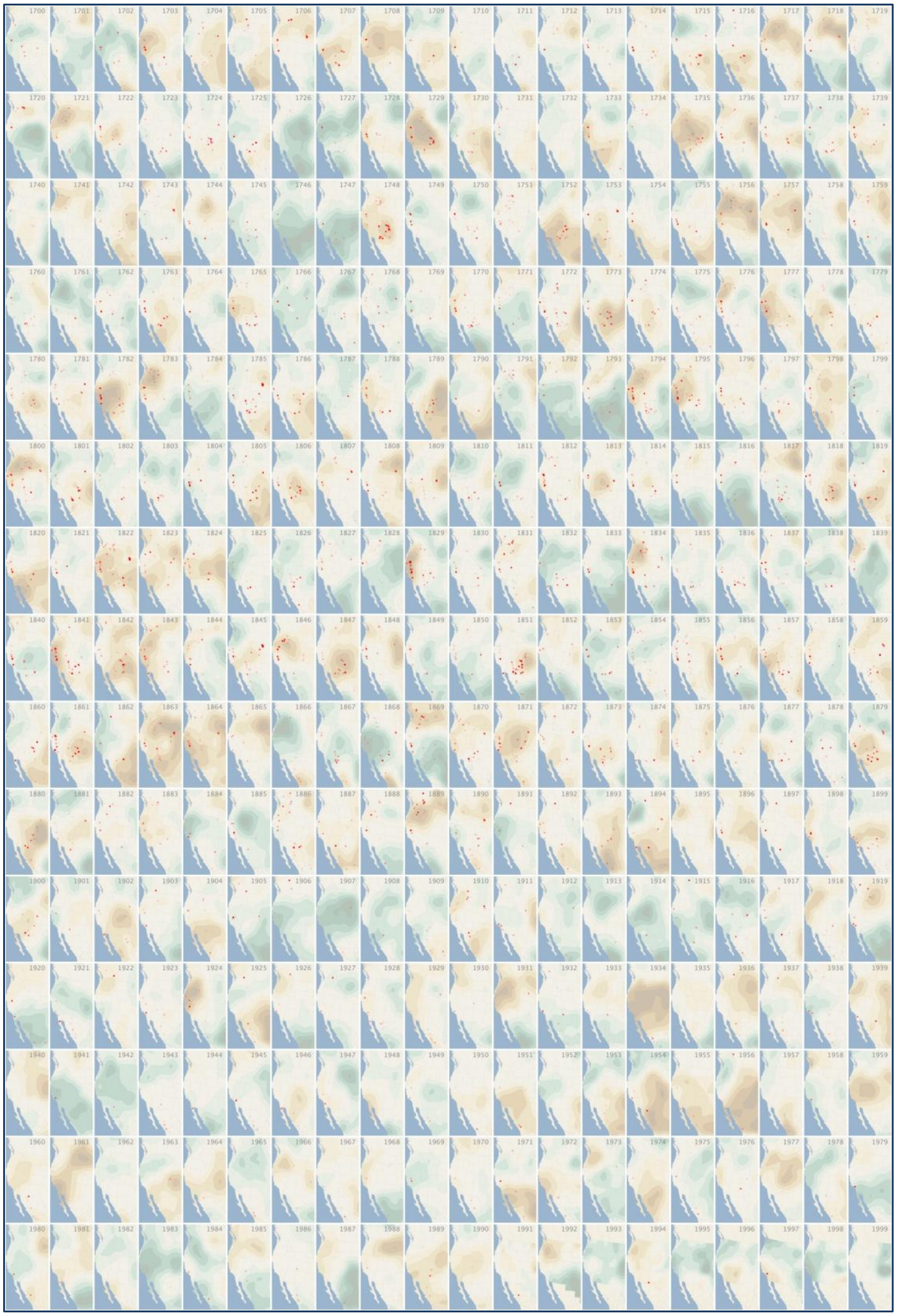
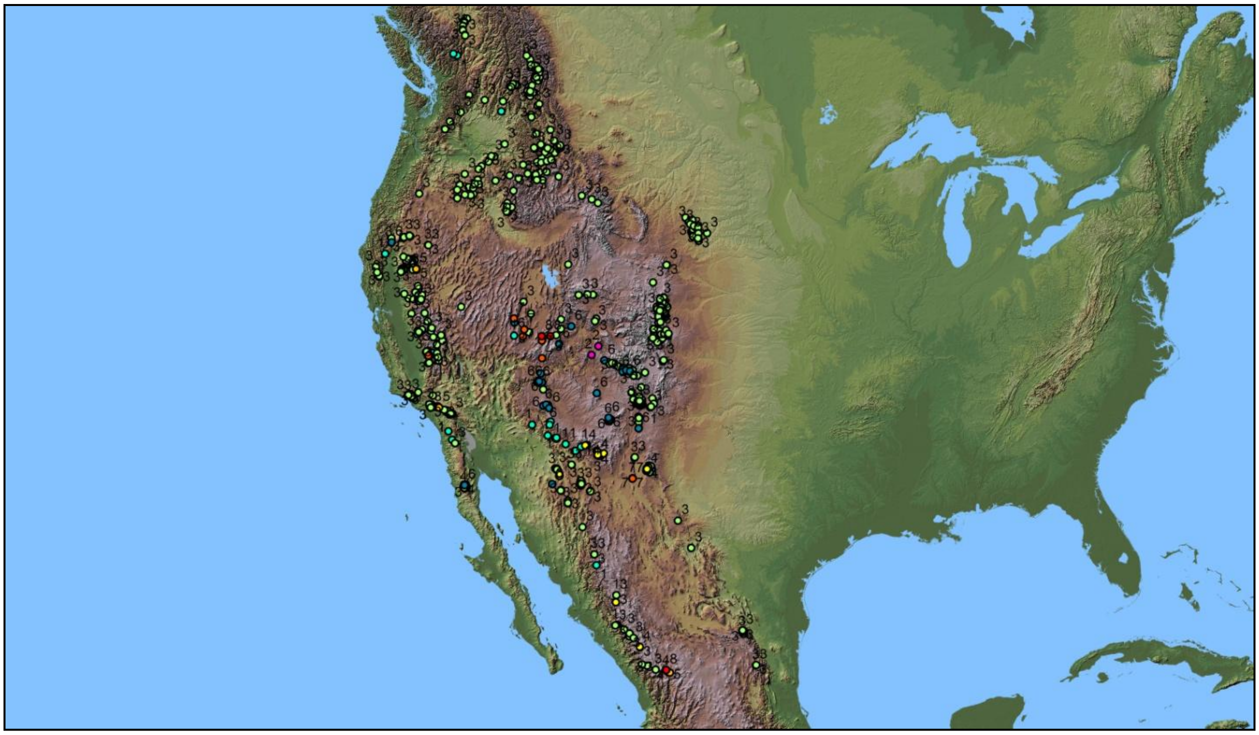


Figure 1.7. Preliminary cluster analysis of fire history sites in western North America.



2. Trends and drivers of annual area burned in western North America under current and future climate

Fire regimes across western North America continue to manifest significant changes since accurate measurements began in the mid-20th century. Fire behavior, effects, sizes, and annual area burned all appear to be in a period of rapid change. Understanding these trends in fire regimes and the factors that are driving these changes is thus critical to fire science and management.

Recent large-scale fire events create an urgent need to identify geographic trends in fire activity, and to understand their underlying causes and consequences on carbon emission budgets. Warming temperatures have been identified as triggering factors for increased fire activity over certain regions of North America but a more complete geographic and physical assessment of climate-modern fire influences is needed in order to make more informed predictions of future fire activity under climate change scenarios.

The timing of snowpack melt has been linked to increased fire activity, but it is not clear whether the duration of snowpack persistence is a direct influence on fire activity (*e.g.*, by regulating the provision of water to soils or plants), or if earlier snowpack melt is a manifestation of warmer spring weather and earlier springs, which desiccate fuels irrespective of the snowpack

Current analyses of the relationships between snowmelt timing, temperature and fire activity are correlational, and high degrees of co-linearity between the predictors make it difficult to adequately decouple these influences. Independent, spatially explicit climate and snow cover duration records are needed to assess the complex interrelationships between climate, snowpack, and fire occurrence over continental scales.

For this synthesis project, we focused on trends and drivers in area burned in western forests. We compiled a comprehensive data set, evaluated evidence of secular trend in key indicators, and tested the strength and interactions of potential driving forces behind these changes. We conclude our synthesis by presenting preliminary projections of burned area under a variety of future GHG emissions and climate scenarios.

We also present the first comprehensive "pyroclimographs" for the western US, based on monthly weather and area burned data. Climographs are a well-known and commonly used form of graphical representation of monthly precipitation totals and average monthly temperature, or other "mean" climate variables over the annual cycle for specific geographic locales. They are useful for grasping the seasonality of climate variations in different places quickly, particularly the months and seasons of maxima and minima conditions as well as overall month-to-month variability. Fire managers and ecologists know that "fire seasons" are also highly variable from one region to another. The first representation of "fire climate regions" in the context of climographs (to our knowledge) was in the classic "Fire Weather" monograph by Schroeder and Buck (1970). Their map of North America sub-divided the entire continent into sub-regions, and ordinary climographs were shown for each sub-region. It appears that Shroeder and Buck developed their map based on expert knowledge of the different seasonal timings of fire occurrence patterns in different sub-regions (their text does not explain their method in detail).

Fire occurrence variables are also highly seasonal and dependent on prevailing climate and geographic patterns. Monthly totals of areas burned and numbers of fires ignited (by cause) tend to show parallel patterns with climographs from those sub-regions. Keeley et al. (2009) showed examples of seasonal "pyrographs" for a set of the LANDFIRE and Canadian ecoprovinces. Pyrographs are particularly useful for identifying maxima and minima of fire ignitions and areas burned, and for distinguishing the relative importance of human-caused versus lightning-caused fires, and how they vary relative to each other by month.

Methods.

Data compilation and mapping**.** We compiled annual area burned (AAB) for the western US based on data provide by Dr. AH Westerling, University of California – Merced, for fires > 200 ha (~500 ac) for the period 1972-2004 (Brown et al. 2002; Malamud et al. 2005; Westerling et al. 2002). 12,596 fires met data standards and were included in analysis. Similar data were obtained from the Canadian Large Fire Database. Spatiotemporal climate layers (monthly mean, minimum, and maximum temperature and precipitation) were obtained from the National Climate Data Center for the same time period. AAB and climate data were gridded using IDRISI Taiga GIS to 1° cells to facilitate analysis. We obtained snowpack data estimating the presence or absence of snowpack from satellite reflectance data aggregated to 25 km^2 pixels. Snowpack data were converted to a continuous variable, LDPS (Last Date of Permanent Snowpack), where LDPS is the last Julian Day of snowpack detected in the pixel. LDPS was poorly estimated for the southern Southwestern US (southern portions of CA, AZ, and NM), probably due to the relatively short duration of snow cover as well as the smaller proportion of upper montane areas within 1° grid cells.

Trends in AAB, climate, and snowpack**.** We evaluated all time series for trend over the period of analysis at the scale of each 1° grid cell. For AAB we analyzed the period 1972-1999, and climate variables and snowpack for the period 1972-2006 (the difference in period of analysis was due to shorter temporal extent of Canadian AAB data with appropriate resolution and quality control). Each variable was divided into seasonal partitions, winter (JFM), spring (AMJ), and summer (JAS) before analysis. We analyzed whether observed trends were statistically significant using two tests suitable for non-normally distributed time series data. The Mann-Kendall test compares each sequential pair of data points and tests for increasing, decreasing, or no-difference increments in each successive pair; the sum of these values is the Mann-Kendall statistic. The Theil-Sen test is a form of linear regression that computes the median slope among all pairs of data. We calculated Mann-Kendall and Theil-Sen statistics using the *z*-values of each variable to allow comparison among variables with different magnitudes. For the purposes of this report, only Mann-Kendall statistics are reported here.

Path analysis of drivers of AAB**.** We applied path analysis to separate the relative contributions of seasonalized temperature, precipitation, and snowpack duration to AAB (Figure 2.1). Path analysis is an extension of multiple factor regression in which relationships among variables are tested explicitly; path coefficients are equivalent to regression coefficients in a multi-variable analysis. Each seasonalized climate driver and LDPS was tested for its contribution to variation in AAB (direct effects) by calculating the path coefficient for each variable (magnitude and sign on the interval -1…+1). Climate variables were also tested for their influence on snowpack and consequent effect on AAB (indirect effects). The total effect of each variable on AAB is the sum of direct and indirect coefficients.

Future projections of snowpack and AAB**.** To evaluate the potential effect of future climate on AAB, climate drivers, and snowpack duration, we applied the results of path analysis to gridded climate projections under the IPCC A1B emissions scenario. We then tested for differences between mean observed values for the period of analysis and calculated values in 2020. These results will be reported separately.

Pyroclimographs. We used the Bailey ecoprovince map of western North America as an example of a geographical sub-division with an ecophysiological basis. This classification does not necessarily represent the direct spatio-temporal patterns of climate variables that drive fire activity, but because the Bailey system corresponds to major biomes and vegetation types, it reflects macro-properties of ecosystems that govern fire regimes (fuel models, fuel moisture regimes) or indirectly (growing season moisture availability and water deficit, seasonal temperature and precipitation). We constructed monthly "pyroclimographs" (*i.e.*, combined "pyro" and "climo" graphs), for eight of the 22 Bailey ecoprovinces in the western US. We used the same annual area burned data (Westerling et al. 2002, updated to 2006) as for the other AAB analyses in this report.

Results.

***Trends in AAB, climate, and snowpack*.** AAB increased significantly over most of the study area during the period 1972-1999 (Figure 2.2). Regional exceptions were stable or slightly decreasing AAB in British Columbia, southern Manitoba, portions of the Northwest Territories, western Alaska, and North and South Dakota.

Seasonalized temperatures increased significantly over the period of analysis (1972-2006). Winter temperatures (JFM) increased most significantly across nearly the entire study area (Figure 2.3, upper panel). The most significant increases were observed in the southwestern US, northern Saskatchewan, and northern Yukon and Northwest Territories. Spring temperatures (AMJ) increased significantly across westernmost North America, but not in the interior states and provinces (Figure 2.4, upper panel). Summer temperatures increased significantly in the western United States, Texas, North Dakota, and most of Canada east of ~125 ° W (Figure 2.5, upper panel).

Winter precipitation decreased over most of the study area (Figure 2.3, lower panel), except for increases in Texas, eastern Nunavut, and northern Manitoba, Yukon, and Northwest Territories. Spring precipitation was more regionally variable, with increases in the northwestern US and southern British Columbia, most of California, southern Yukon and Northwest Territories, and far western Alaska (Figure 2.4, lower panel).

Snow cover duration (LDPS) for 1972-2006 decreased highly significantly over the entire study area, with the exception of the eastern portion of Northwest Territories, northern Manitoba and the US northern great plains states (Figure 2.6).

Path analysis of drivers of AAB.

1. **Effects of climate on snow cover duration.** Winter temperature has an important negative effect on snow cover duration (*i.e.*, higher temperatures are associated with reduced snow cover duration) at mid latitudes and lower elevations, including most of the interior western US except for the high Rocky Mountains, as well as most of Alberta and southern Saskatchewan and Manitoba (Figure 2.7). Spring temperature has a similar negative effect on snow cover duration at high latitudes and higher elevations, including nearly all of Canada and Alaska, and the high Rocky Mountains in the US (Figure 2.8). Not surprisingly, winter precipitation was positively correlated with snowpack duration throughout much of the interior of western North America

and most of Alaska (Figure 2.9).Spring precipitation effects on snow cover duration were relatively weak and spatially incoherent in most areas; most correlations were neutral to negative, suggesting melting effects of spring rains in conjunction with higher temperatures.

2. **Effects of snow cover duration on AAB.** Snow cover effects on AAB were spatially variable (Figure 2.10). Across much of North America the relationship is negative, suggesting the role of greater snowpack in delaying the onset of fire season. Neutral to weakly positive correlations between LDPS and AAB were observed in British Columbia, central Saskatchewan, southern Manitoba, Washington and northern California, and scattered areas in the Southwest and southern Rocky Mountains.
3. **Direct and indirect (via snowpack) effects of climate variables on AAB.** Winter temperatures had moderate positive effects on AAB across much of western North America, but effects were negative in Alaska, Yukon, and Northwest Territories (Figure 2.11, upper panel). Direct effects were the primary contributor to the total effect (Figure 2.11, middle panel); indirect effects (mediated by snowpack) were relatively weak (Figure 2.11, lower panel).Spring temperatures had a stronger and more coherent positive relationship to AAB across most of western North America (Figure 2.12, upper panel), with regional exceptions (neutral to weak relationship) in far northern Canada, western Washington and southwestern British Columbia, and eastern Montana and South Dakota. Nearly all of this total effect derived from direct effects of temperature on AAB (Figure 2.12, middle and lower panels).

   Precipitation effects on AAB were generally more spatially variable than those on temperature. In the US, wetter winters were weakly associated with increased AAB in the Great Basin, Southwest, and eastern Colorado and Montana, areas that are more predominantly fuel limited; a similar relationship was observed across northern Canada. In most of the rest of the study area, drier winters were associated with increased AAB, suggesting a possible effect on early soil desiccation. Nearly all of this effect on AAB was direct; little was mediated via snowpack (Figure 2.13, upper panel). Spring precipitation was more consistently and negatively related to AAB across most of Canada, nearly all of which was derived from direct effects on AAB (Figure 2.13, middle and lower panels) and not via snowpack.

   Overall, the strongest effects on AAB were the direct effects of winter and temperature, followed by direct effects of spring precipitation. Most indirect effects, i.e. mediated by climate effects on snowpack, were a relatively small component of variability. Effects of snowpack on AAB were spatially variable in strength and sign. These results suggest that snowpack duration may be an indicator of the factors that control AAB, rather than a mechanism of control.

Pyroclimographs for the western US. Pyroclimographs for the eight Bailey ecoprovinces selected are shown in Figure 2.14. We found a significant shift of fire seasons to late summer in northern versus southern ecoprovinces, and the different scales of area burned and numbers of ignitions among the sub-regions.

Figure 2.14 illustrates a possible presentation for pyroclimographs at regional scales. We plan to generate pyroclimographs for other western US ecoprovinces, as well as for several other base maps for the western United States, including the LANDFIRE sub-regions, and our own classification of fire-climate sub-regions, based upon our fire climate statistical analyses.

Samples of these graphics in sub-directories on the FACS DVD, and hyperlinked to the various base maps on an interactive page that will be browse-able (clickable with mouse).

One of the important patterns illustrated in the set of examples of pyroclimographs in Figure 2.14 is the important role of human-caused fires in large fire occurrence in the past several decades. We found striking differences in relative importance of human *vs.* lightning set fires in the different regions; despite the predominance of lightning set fires – in terms of numbers of ignitions of fires of all sizes – human-set fires have burned far more area during most months during this period, and most of the fires larger than 100,000 acres in the Southwestern United (since 2000) were set accidentally or intentionally by people.

Keeley, J.E., G.H. Aplet, N.L. Christensen, S.G. Conard, E.A. Johnson, P.N. Omi, D.L. Peterson, and T.W. Swetnam. 2009. *Ecological foundations for fire management in North American forest and shrubland ecosystems*. USDA Forest Service, General Technical Report PNW-GTR-779. 92 pgs.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. *Ecological Applications* 19:1003–1021.

Schroeder, M.J., CC. Buck. 1970. *Fire weather*. Washington, DC: US Department of Agriculture, Forest Service. 229 p.

Personnel. Analyses were led by Dr Thomas Kitzberger, Universidad del Comahue, Bariloche, Argentina, with assistance from Drs Donald Falk and Thomas Swetnam, University of Arizona. Annual area burned data were generously provided by our collaborator Dr Anthony Westerling, University of California – Merced. Dr Matthew Hall (University of Arizona) provided additional data visualizations.

Figure 2.1. Path analysis model used for discriminating direct and indirect effects of climate variables on snowpack and area burned.

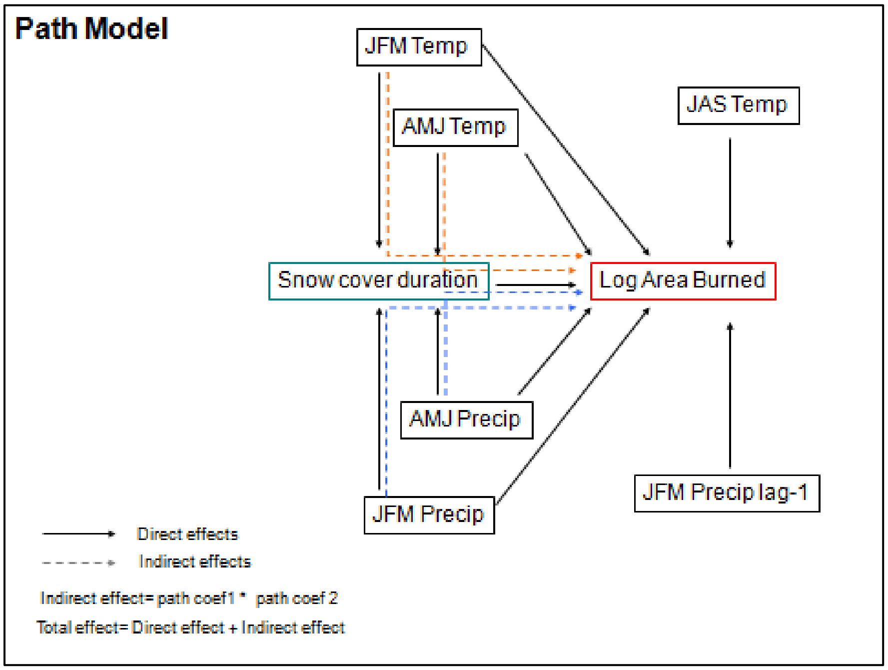


Figure 2.2. Trend in annual area burned in 1° grid cells 1972-1999. Colors indicate significance of trend in standard deviation units (Mann-Kendall results shown).

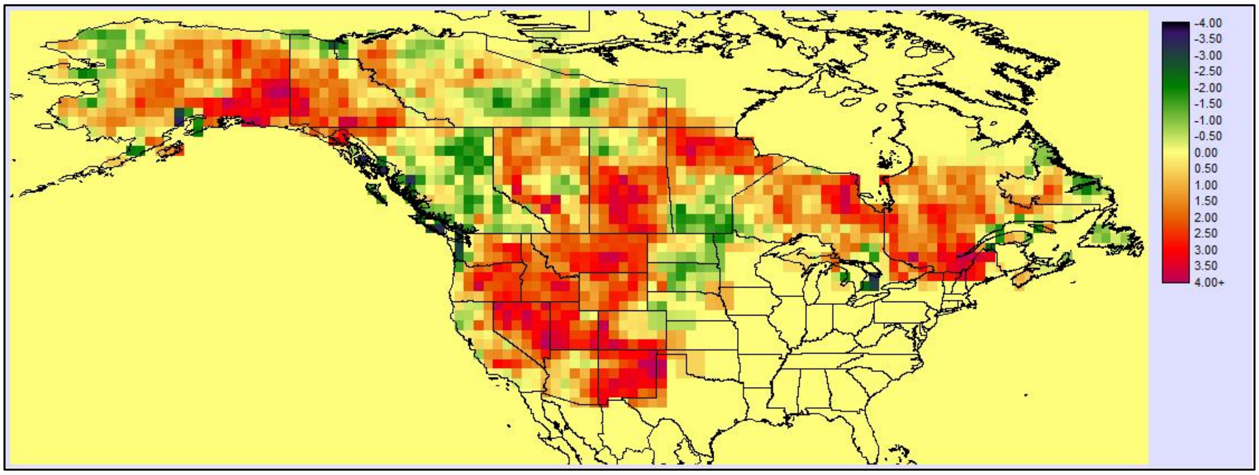


Figure 2.3. Trend in winter (JFM) temperature (upper panel) and precipitation (lower panel) in 1° grid cells, 1972-2006. Lower panel: Units are standard deviations.

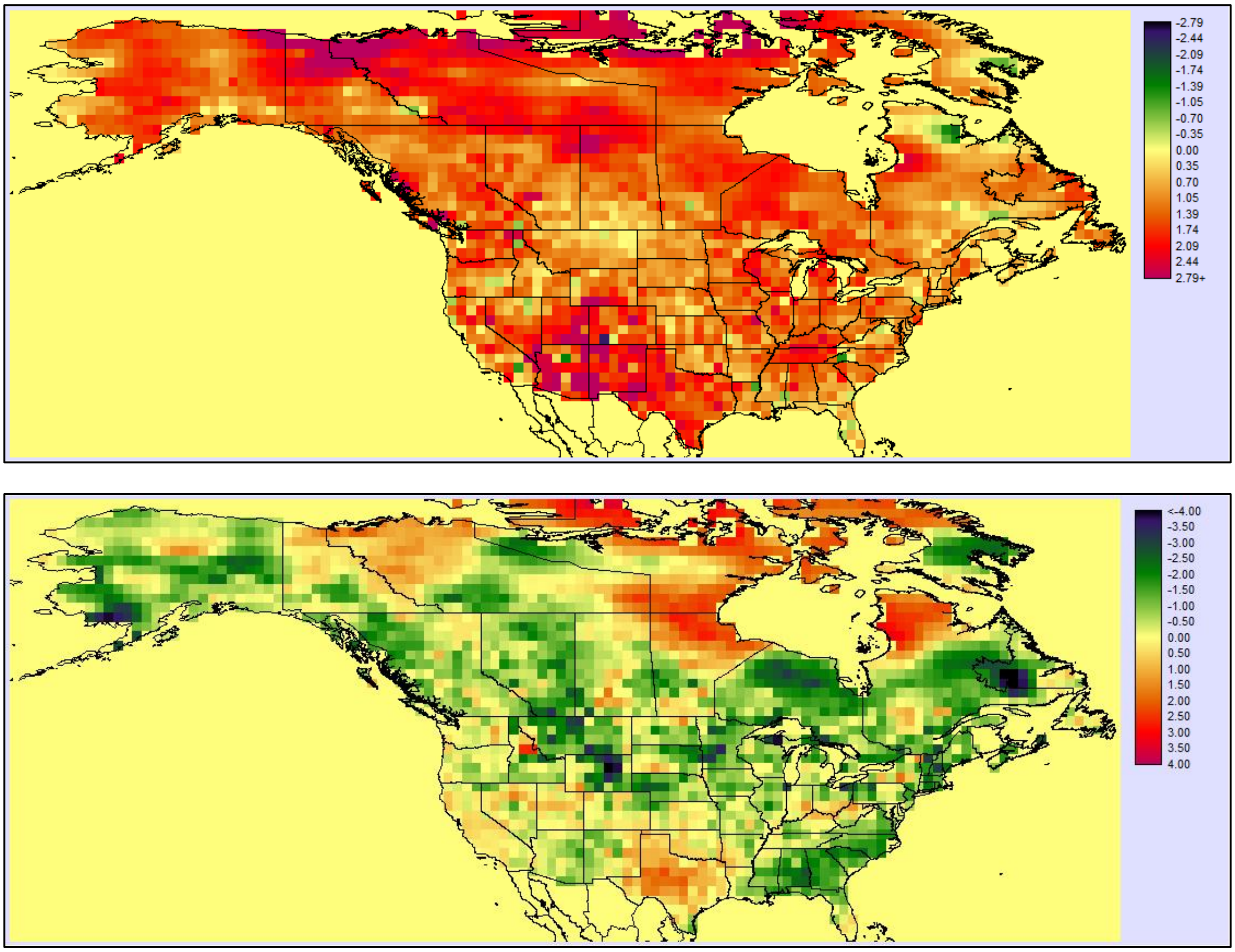


Figure 2.4. Trends in spring (AMJ) temperature (upper panel) and precipitation (lower panel) in 1° grid cells 1972-2006. Units are standard deviations.

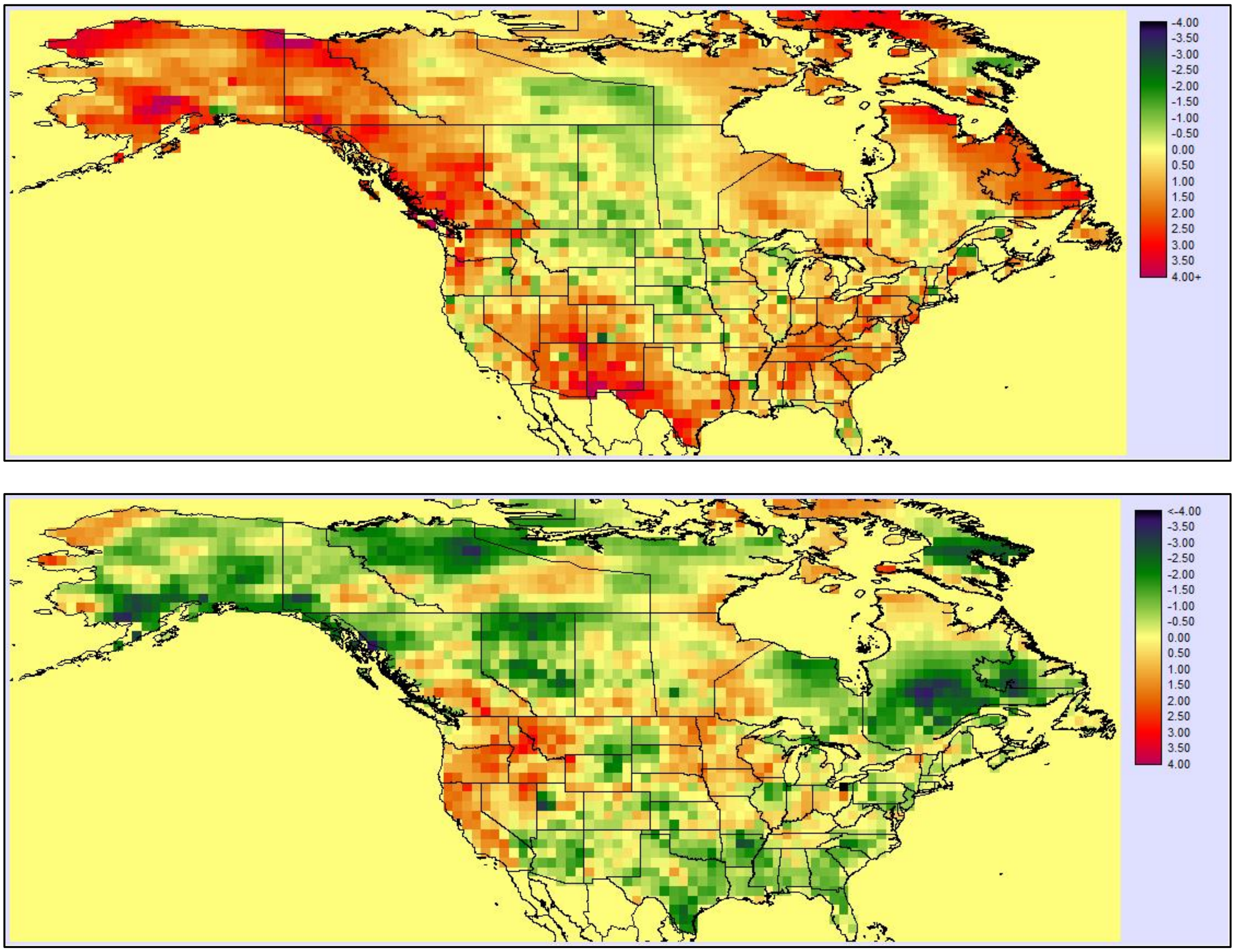


Figure 2.5. Trends in summer (JAS) temperature in 1° grid cells 1972-2006. Units are standard deviations.

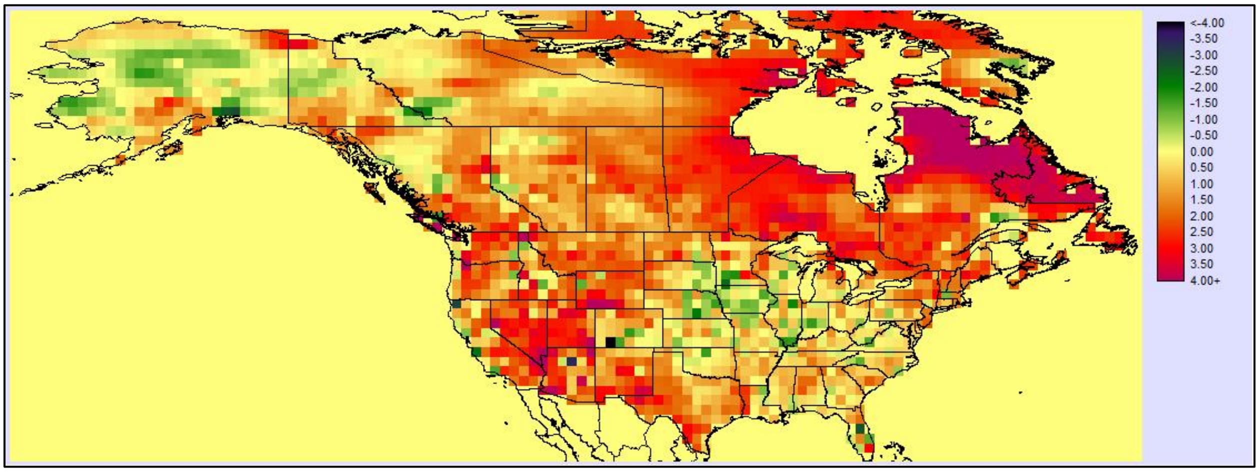


Figure 2.6. Trend in average snowpack duration (Julian last date of permanent snowpack) 1°grid cells, 1972-2006. Units are standard deviations.

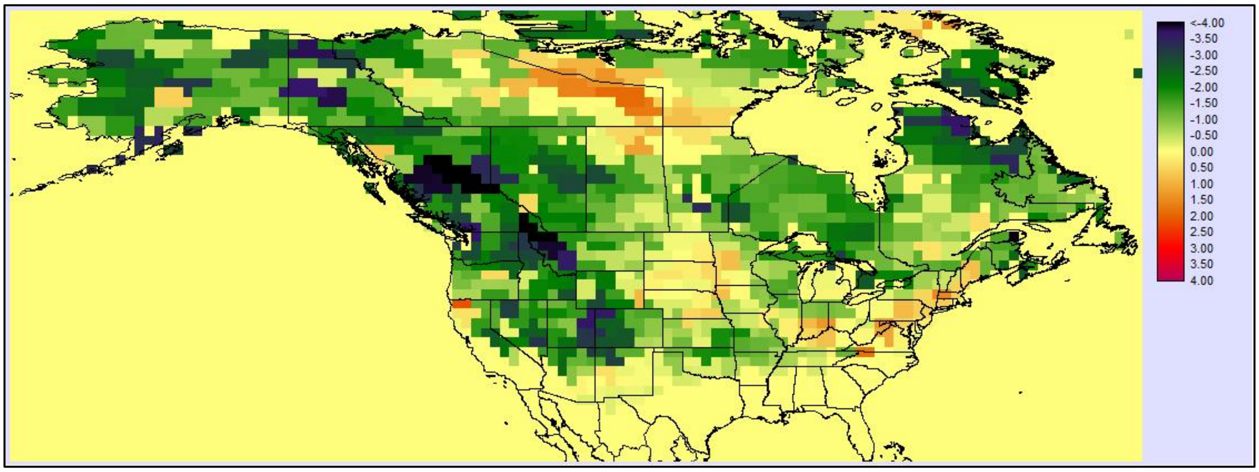


Figure 2.7. Correlation of winter (JFM) temperatures with snow cover duration, 1972-2006. Purple line outlines the approximate area within which Pearson's $\rho > 0.25$.

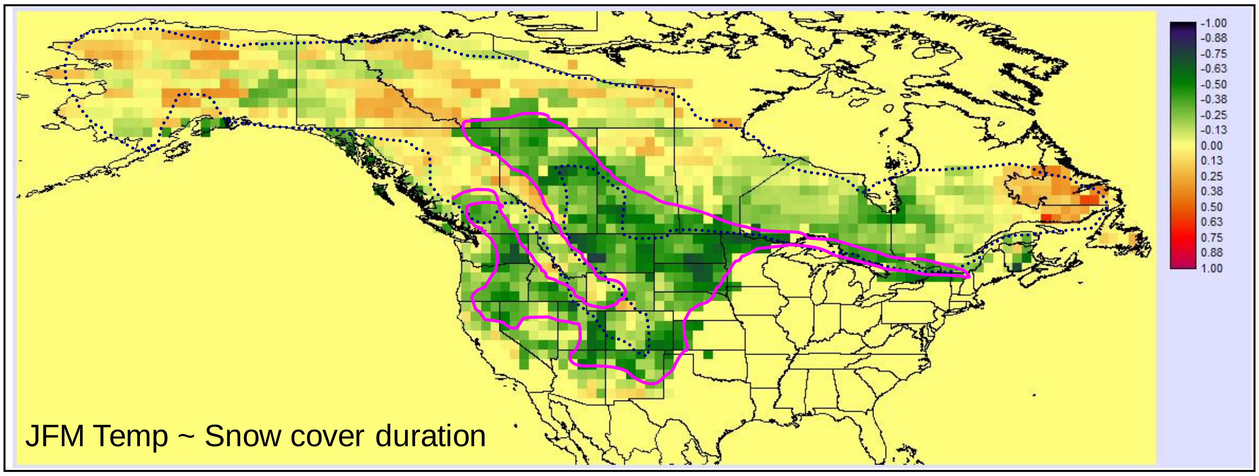


Figure 2.8. Correlation of spring (AMJ) temperatures with snow cover duration, 1972-2006. Blue line outlines the approximate area within which Pearson's $\rho > 0.25$.

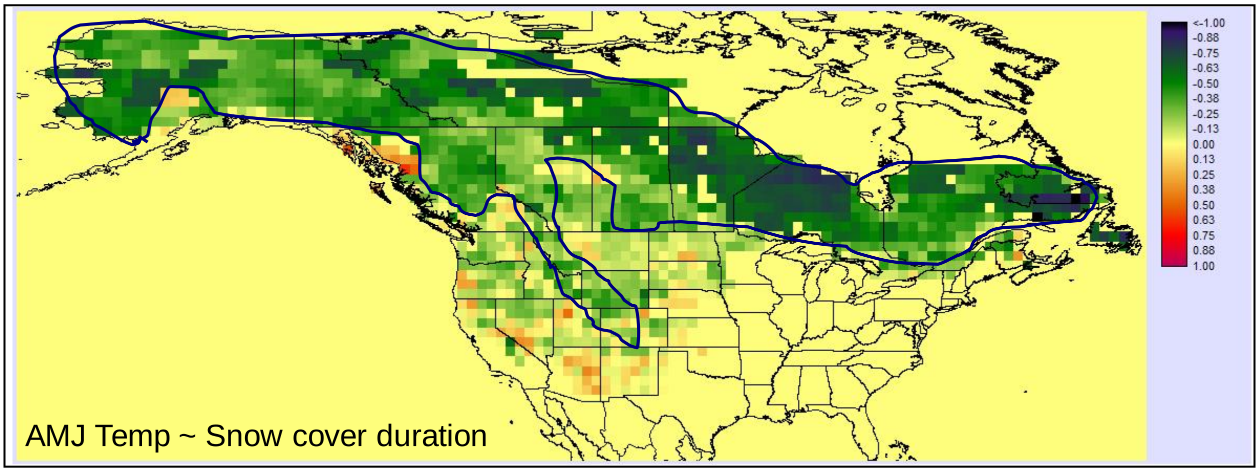


Figure 2.9. Correlation of winter (JFM) precipitation with snow cover duration, 1972-2006. Blue line outlines the approximate area within which Pearson's $\rho > 0.25$.

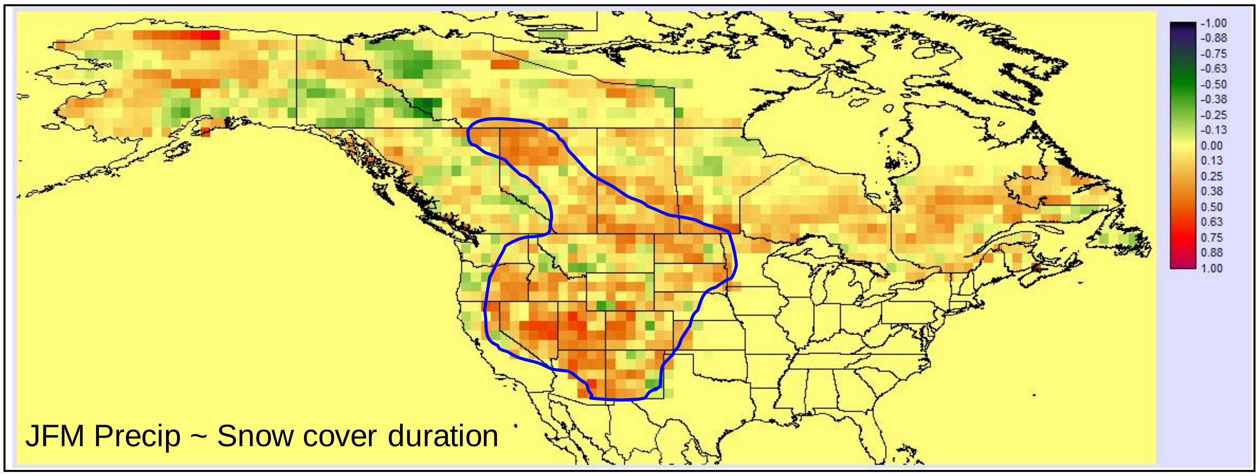


Figure 2.10. Correlation of snow cover duration (LDPS) with log AAB, 1972-2006.

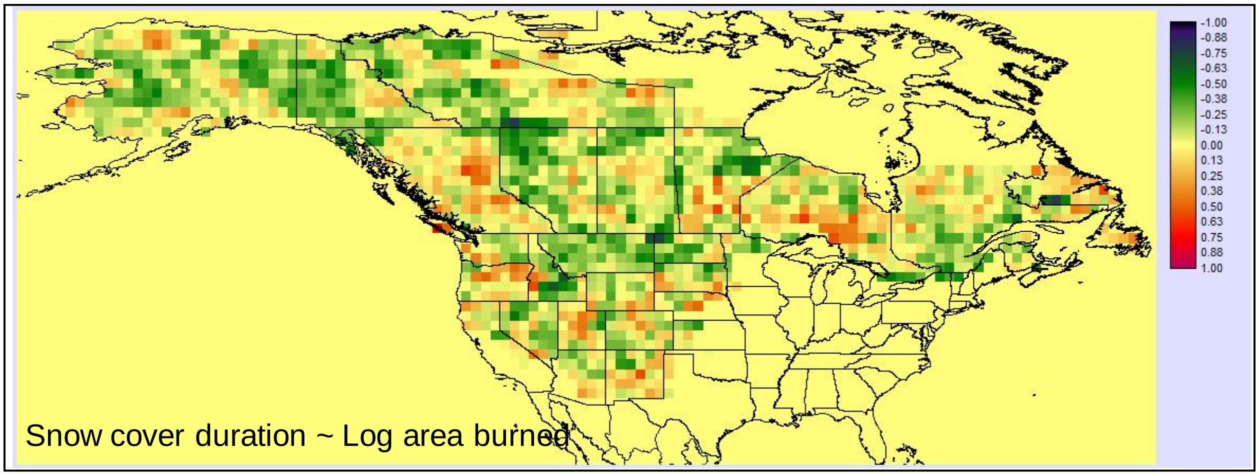


Figure 2.11. Total, (upper panel), direct (middle panel), and indirect (lower panel) effects of winter (JFM) temperature on log area burned. Indirect effects are mediated through snowpack (Figure 2.1).

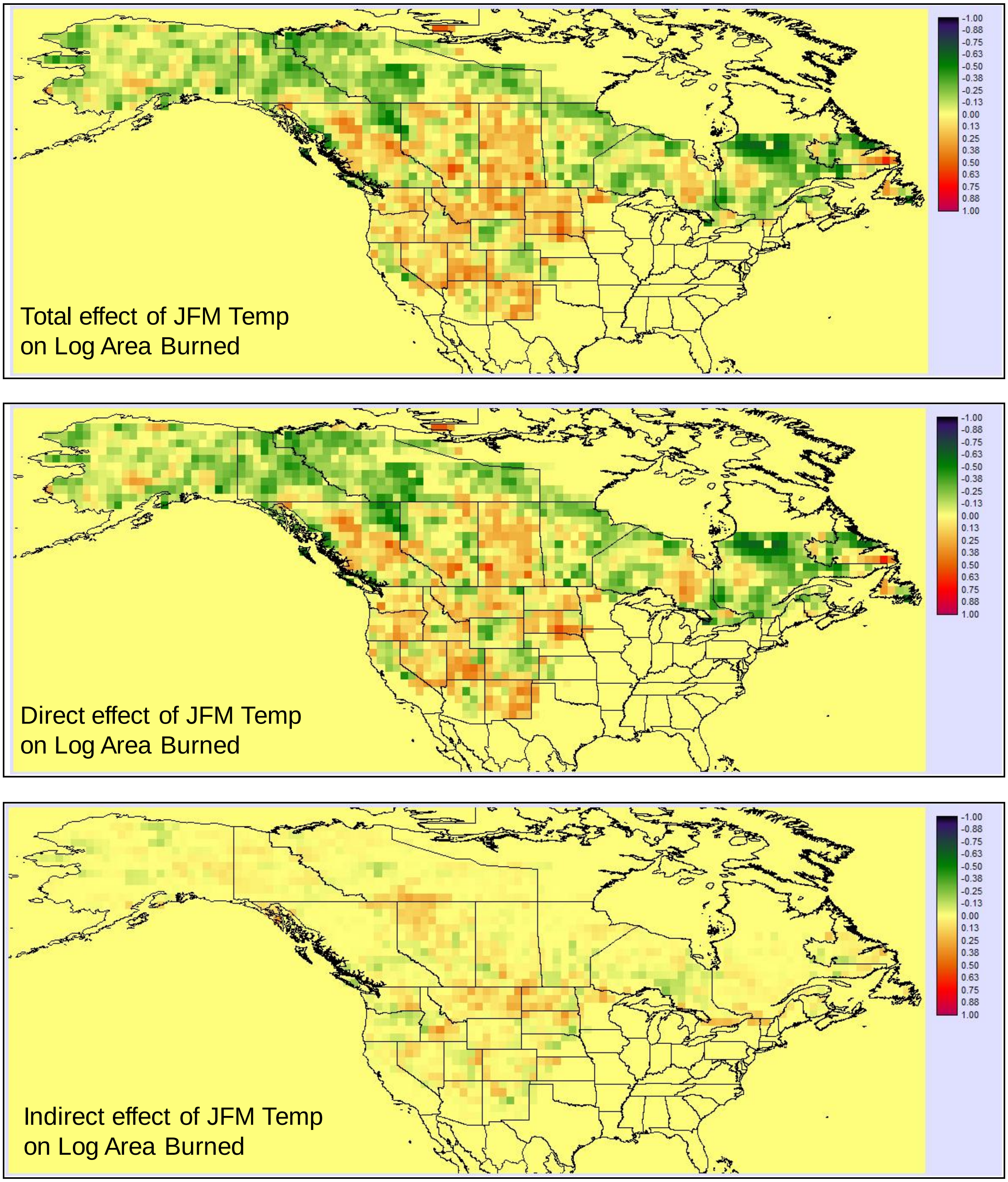


Figure 2.12. Total, (upper panel), direct (middle panel), and indirect (lower panel) effects of spring (AMJ) temperature on log area burned. Indirect effects are mediated through snowpack (Figure 2.1).

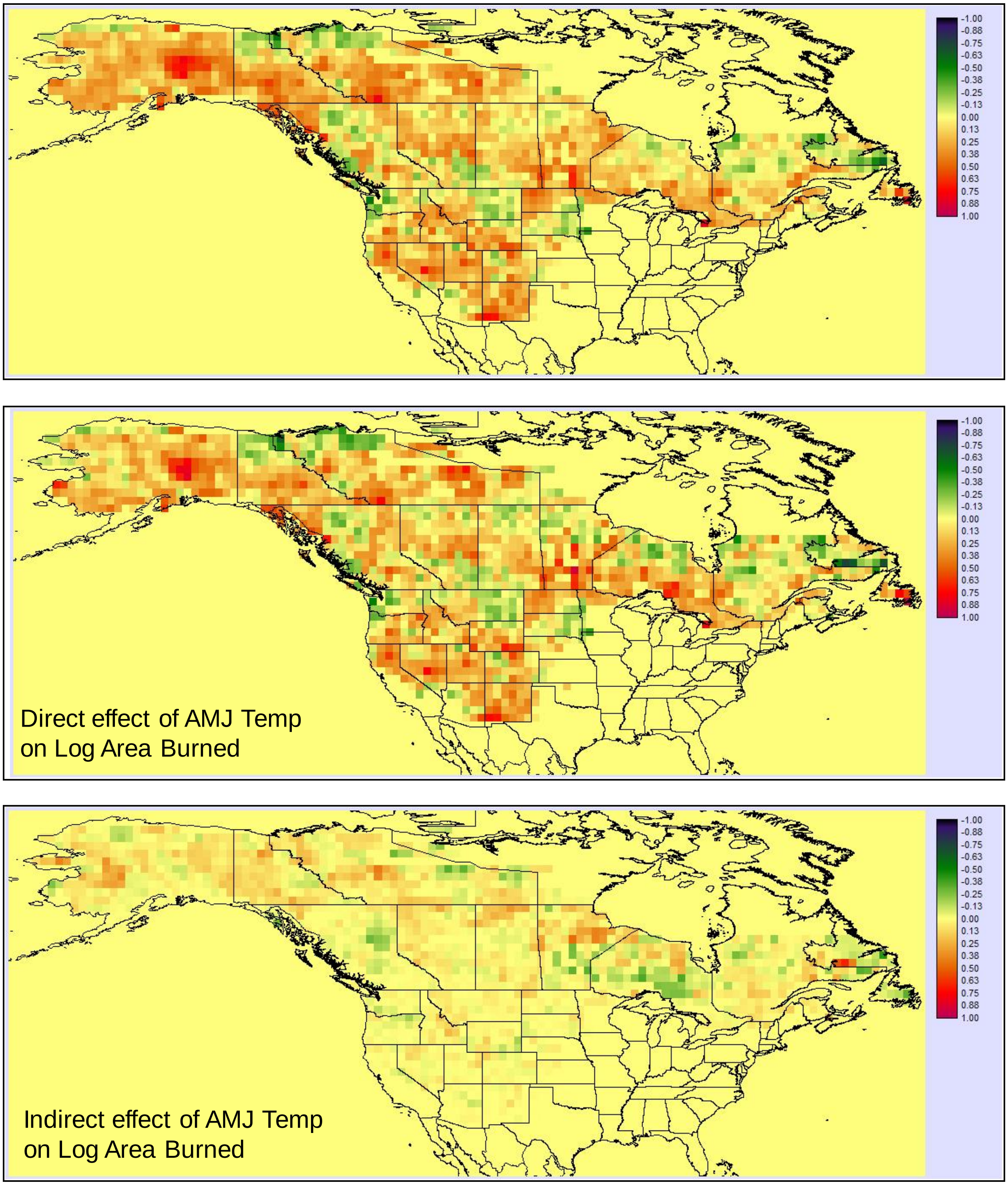


Figure 2.13. Total, (upper panel), direct (middle panel), and indirect (lower panel) effects of winter (JFM) precipitation on log area burned. Indirect effects are mediated through snowpack (Figure 2.1).

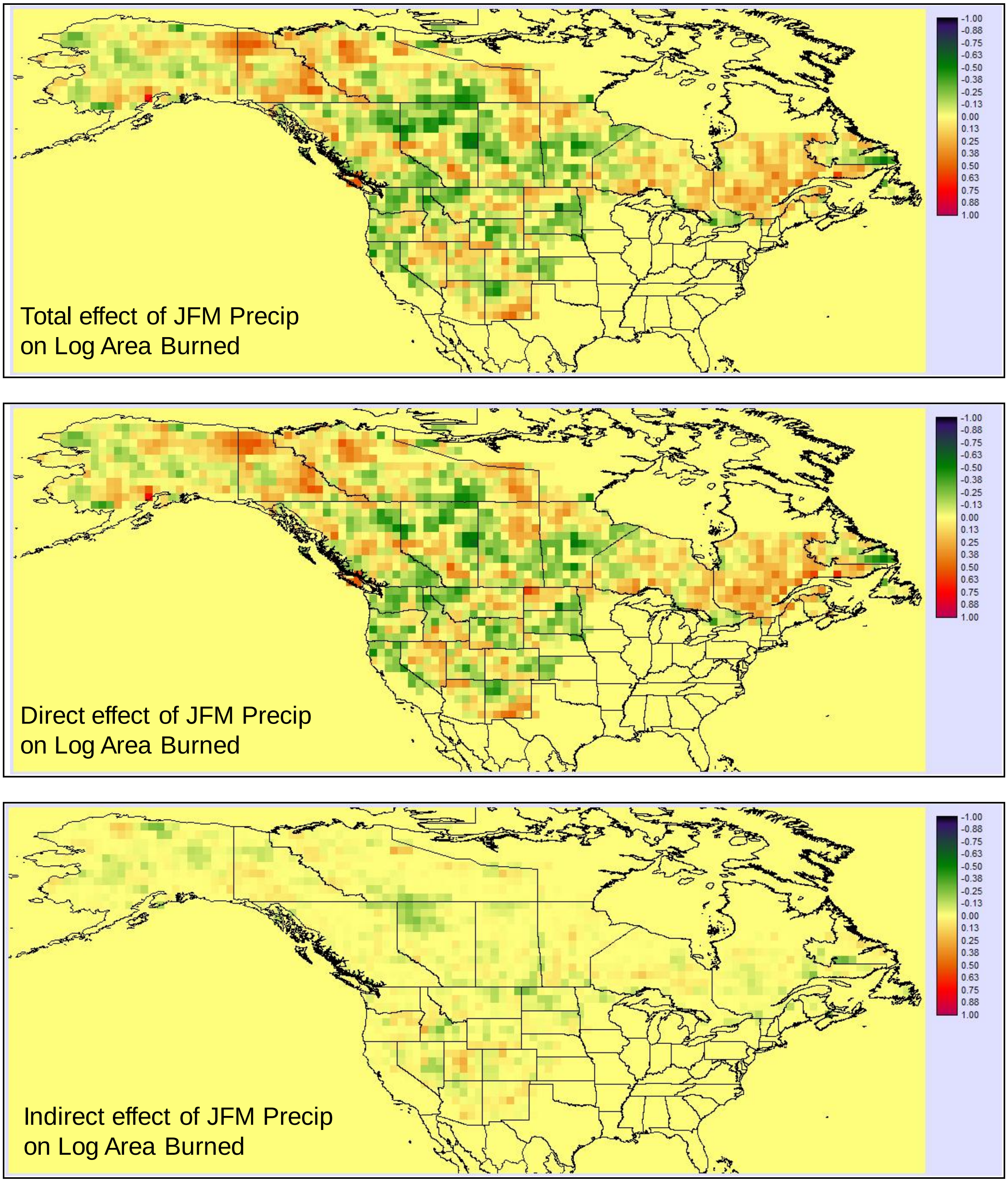
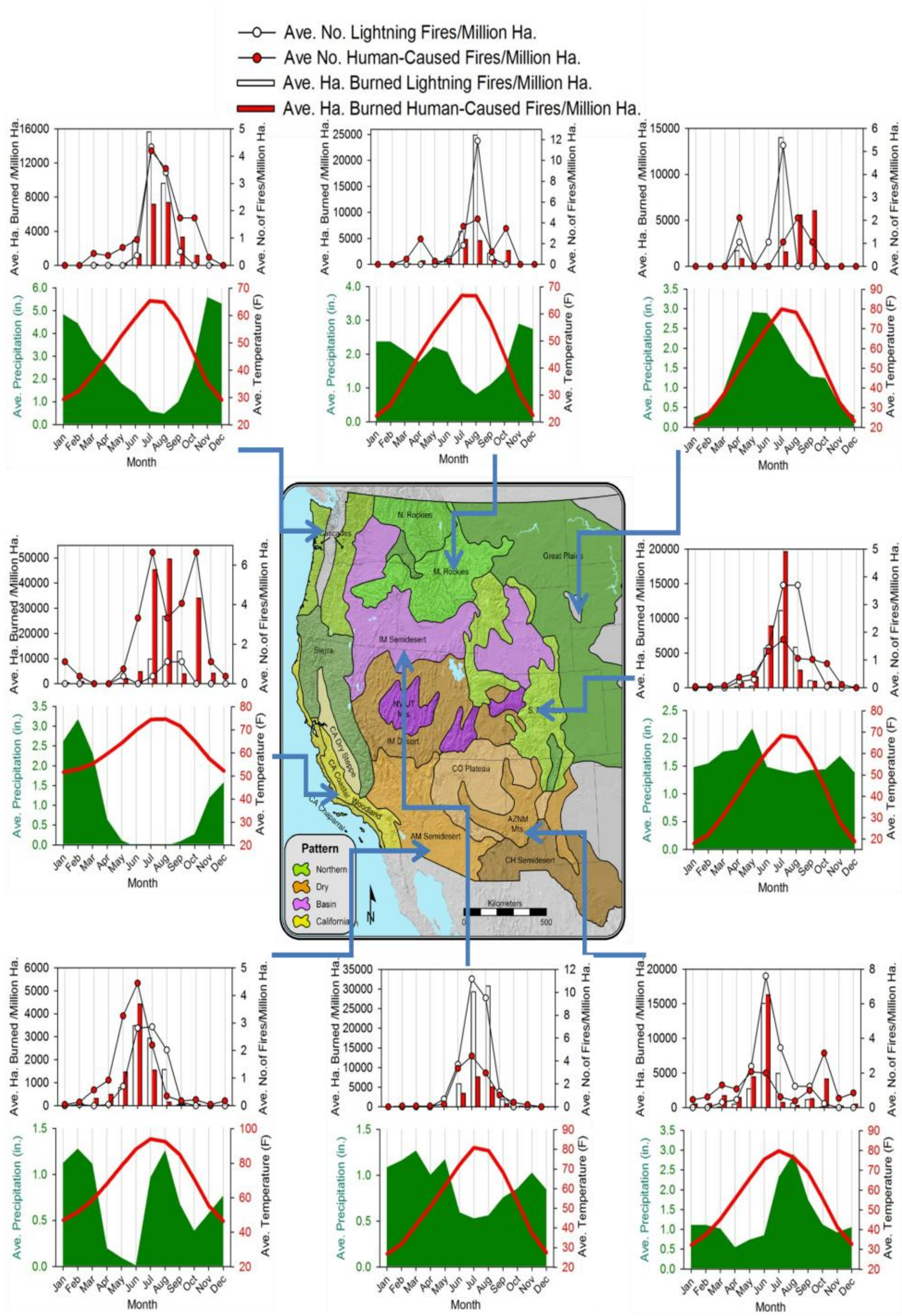


Figure 2.14. Pyroclimograms for eight Bailey ecoprovinces in the western United States. Fires larger than 100 ha for the period 1972-2006 were used. The total areas burned and numbers of fires (by cause) were standardized by the area of each ecoprovince (per million hectares) so that relative comparisons could be made between the y-axis scales. Precipitation and temperature data were from a sampling of the PRISIM data set within each ecoprovince. The ecoprovince map here is modified from Littell et al. 2009.



3. Climate Impacts on Fire Policy

Fire Climate and Fire Management Policy

Our original objectives from proposal: The objectives of this component of the synthesis were to: (1) Reconstruct and synthesize the pathways by which past climate-fire events have shaped policy and decision-support systems for national wildland fire management (*e.g.* Preparedness Levels for resource allocation); and (2) Determine ways to proactively use climate change and fire/climate relationship knowledge to inform to policy and guide decision-support systems.

Methods

Climate-fire impacts on policy

To identify past climate-fire impacts on policy and decision-support systems, we utilized two approaches. First, we combed through numerous texts chronicling the history of wildfire and/or land management in the US. These included several books by fire historian Stephen Pyne, Hal Rothman's history of the National Park Service (A *Test of Adversity and Strength: Wildland Fire in the National Park System*), James Lewis' history of the US Forest Service (*The Forest Service and the Greatest Good: A Centennial History*), Norman Maclean's *Young Men and Fire,* and John Maclean's three books on pivotal fire fatalities (*Fire on the Mountain, Fire and Ashes, and The Thirtymile Fire*).

In addition to books, we reviewed several dozen Incident Reports, the formal investigative report that documents a fire incident resulting in an undesirable outcome with significant repercussions. These incident reports tended to fall into three categories or combination thereof: 1) a fatality event, 2) an escaped prescribed or WFU fire that resulted in private property losses, and 3) significant fire event that was associated with record size, suppression expenditures, duration, or some other characteristic that resulted in either a Fire Order being broken, or a significant Lesson Learned.

We also reviewed current and recent wildland fire policy documentation, including the 1989, 1995, 2001, 2008, and 2009 federal fire policy guides, as well as numerous supporting documents such as Cohesive Strategies, memos of implementation, and GAO reports. We also reviewed numerous peer-reviewed manuscripts, technical reports and other gray literature, and non-fiction essays and articles on fire management history in the US, including previous syntheses of fire policy history by Stephens and Ruth (2005) and a 1986 review of the evolution of fire policy by John Chambers.

Finally, we held 1-to-2 hour informal discussions with five national level fire program managers who shared a combined experience of over 150 years in fire management across four of the five primary federal land management agencies. These individuals included: Dick Bahr (NPS), Tom Zimmerman (USFS), Neil Hitchcock (USFS), Dennis Dupuis (BIA), and Tom Wordell (Predictive Service/NIFC/BLM). The goal of these discussions was not to conduct formal interviews following scripted questions. Instead, we held free-form, directed conversations which revolved around a series of directive questions. These were not asked in order, or in entirety, but instead were asked as appropriate to supplement and keep the conversation flowing. They included:

1. How does climate impact wildland fire management?
2. How has climate affected the development of fire policy?
3. How did the fuels management program develop?
    a. How have the objectives changed over the years?
    b. In response to what?
4. What types of "unofficial" policy changes have occurred over the years?
    a. Have any of these been in response to climate?
5. How has climate impacted area burned over the years as compared to changes in suppression tactics/increase in WUI, etc.?
6. How are current fire policies adaptable to future fire events/changing fire regimes?
7. How are current fire policies NOT sufficiently adaptable or flexible? What needs to change within policy to make it more adaptable to future conditions?
8. How do you think climate information could be used at local, regional and national levels to better support fire management and accomplish objectives?
9. How does current fire policy allow you to integrate what is known about climate variability-wildfire relationships into your fire management?
10. Given your experience, what are some ways you think we can address climate change in fire management?

From our literature review and our discussions, we identified two types of climate impacts on fire policy: direct (top-down) and indirect (bottom-up). For each impact type, we identified events, trends, and resulting policy or changes in management. We then identified the associated climate conditions for that event, season or trend using the WestWide Drought Tracker (WWDT), a web interface tool available from the Western Regional Climate Center that visualizes and allows exploration of the historic PRISM climate data. The WWDT utilizes temperature and precipitation data produced by PRISM to calculate historic drought indices, including the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). We synthesized our climate associations and identified common climate conditions or anomalies associated with different trends or events.

Integrating climate information into decision-support

To identify pathways for integrating climate information into fire policy and decision-support system, we relied both on our discussions with our five interviewees, and on understanding how previous fire science has been applied to policy. In our discussions with our program managers, they individually identified education through the national fire training programs to be the primary method of science integration. They also recommended we review training curriculum for a specific set of courses to determine existing integration of climate information and identify gaps for future integration.

Based on this recommendation, we reviewed curricula for 15 different courses taught at the National Advanced Fire and Resource Institute (NAFRI). The NAFRI library contains course curriculum notebooks dating back to the 1970s, and for many courses includes an annual example, such that changes and the introduction of new materials and information can be temporally tracked through the years.

We utilized the notebooks to identify nine courses where fire-climate relationships are addressed either directly or indirectly. In each of these courses, we traced the initial introduction of the fire-climate segment of the course to either the current year, or to the year the segment died out (approximately half of the courses). In almost all cases, the fire-climate section is tied to a single individual teaching that section of the course, and when the individual stopped teaching the section, fire-climate relationships were dropped from the course.

Thus, we were able to identify courses where fire-climate relationships and the role of climate information in fire management could be both reintroduced, or introduced for the first time. As many of these courses included actual wildfires as case studies, we were able to identify some case studies where climate was a relevant factor but was not addressed by the lesson because it was either a) prior to greater scientific awareness about fire-climate relationships or b) highly focused on a specific aspect of the fire (e.g., a complex personnel challenge, or an emergency interface with the public).

Deliverables from this portion of the project:

1. (2) FACS fact sheets for the RMRS series:
    a. How Climate Affects Fire Policy
    b. Using Fire Climatology: Best Management Practices
2. Climate Impacts on Wildfire Policy and Practice in the U.S.A. A peer-review manuscript (in prep. for *Ecological Applications*)
3. A webinar presentation through the Wildland Fire Lessons Learned Center on using climate information for managed fire: Using Climate Information for Risk Mitigation and Objective Achievement in Managed Fire. April 2011. http://frames.nacse.org/10000/10282.html
4. Presentation (pending abstract acceptance) at the April 17-19, 2012 Human Dimensions of Wildland Fire conference in Seattle, "Climate impacts on Wildfire Policy and Practice"

Ancillary: since one of our interviewees was the USFS R&D lead who directed the WFDSS development and implementation, an additional benefit of this project was a commitment to integrate climate information and support tools into WFDSS to make the information more accessible to users.

4. Science delivery and technology transfer: Decision Support Tools

The technology transfer tools developed from this project include workshops, webinars, publications, analytical tools, presentations, and fact sheets.

Workshops: Two manager workshops are resulting as part of the FACS project. One was a 2-day workshop at the beginning of the project held in Tucson, AZ, in February 2010. Over 25 managers participated in the workshop that focused on manager needs for fire climatology data, tools, and applications. The second workshop will be a half-day workshop to be held in conjunction with the Southwest Fire Ecology conference to be held February 27, 2012, in Santa Fe, NM. The conference abstract provides a description of this workshop: "The workshop will provide hands-on experience with obtaining existing online fire history data and how to use several tools for data analysis and presentation. The focus will be on understanding, interpreting, and using fire history data for management applications, e.g., ecological or vegetation assessments, forest plans, or project level planning needs. Data and tools to be covered include the International Multiproxy Paleofire Database (IMPD), an online repository for fire history data sets; the Fire History Analysis and Exploration System (FHAES), a tool for analyzing and displaying data sets from the IMPD and other sources; the Fire History and Climate Change (FHCC) reference database, an annotated bibliography of fire regime information across the US; and the Fire and Climate Synthesis (FACS) project, an ongoing effort to develop and apply understanding of fire/climate relationships to management needs across western North America. The workshop will begin with a description of types of fire history data sets, how they are collected and analyzed, and some issues with interpretation and use of the data. This will be followed by hands-on exploration of programs and data. Participants should bring their laptops to the workshop to explore the tools and databases we will cover." We plan to amend our report following completion of the February 2012 AFE conference.

Analytical Tools

With the assistance of a computer programmer and statistician, Dr Elena Velasquez, the FACS team developed several new software applications:

Superposed Epoch Analysis. Superposed epoch analysis is a statistical method used to examine the relationship between a continuous variable and a series of events. In many fire history studies, superposed epoch analysis is used to evaluate the influence of climate on fire occurrence evidenced by fire scars on trees. For each fire, climate data from a window of years preceding, including, and after the event is used to evaluate how leading climate may influence fire events.

We revised a commonly used program for applying superposed epoch analysis (EVENT) into JAVA. This new tool, SEA, takes as input two types of data files, event (discontinuous) files and chronology (continuous) files, and generates text, numerical and graphical output files. During testing, the old and new versions of EVENT/SEA were run simultaneously to ensure that the results were similar.

We developed a set of event and continuous series of known properties (e.g., variable wavelength spectral signatures in continuous series; signals in event or lagging years; clustered or evenly-distributed events; few versus many events (event density), ran SEA, and interpreted results. These analyses of series with known properties provide useful guidance about how the properties of their own data sets might influence the results of superposed epoch analysis. SEA can be used in a wide range of applications in dendrochronology, such as the influence of volcanic eruptions on climate (and tree growth) to insect outbreaks on tree growth. It will be distributed to interested users.

Tools for matrix analysis. Recent developments in fire history analysis, including the accomplishments of the FACS project, have increased the potential for analyzing fire scar and climate datasets across multiple scales of space and time (see *Paleofire*, this report). To deal with such unusually large fire history data sets, we developed several tools that facilitate fire history analysis. JOIN is a GUI-interface tool for selecting any combination of input files and for any specified years. The output from JOIN is a composited FHX2 file which can be exported to MATRIX, FHAES, or any other analytical platform that uses this input format.

We next developed a Java tool, MATRIX, which is designed to import fire history records in FHX2 format and convert files to a universal binary format. File selection is via a GUI browser, allowing any combination of multiple files to be selected. The user specifies the range of years to be analyzed (this capability was included to allow data analysis to cover only years with sufficient sample depth, for instance). The user can also filter the fire inputs from the FHX2 files, including any fire, or only fires representing a minimum user-specified number or percentage of recording trees at each site. MATRIX then generates a series of output files, beginning with a master binary matrix (*year* x *site*); these matrices were used to generate the annual fire time series in the *Paleofire* section of this report. The binary format can also be used to generate fire frequencies or mean fire intervals at sites or among composites of any scale.

Synchrony analysis: Similarity analysis is a powerful emerging approach for analysis of fire history data. The output matrices from MATRIX are used for pairwise comparisons of fire history sites and to generate of similarity matrices and cluster analyses, which are a primary tool for grouping large numbers of sites into coherent regional sets. We are continuing to work on development of a clustering tool for fire history analysis. All tools will be distributed to interested users and eventually incorporated into FHAES.

Fact Sheets

Fact sheets are being published as a series of web-only Rocky Mountain Research Station Research Notes, with one editor (Elaine Kennedy Sutherland) and a number of individual authors. They are short (usually one page, front/back), focusing on any number of topics relating to fire and climate. Five are in draft form and being edited. Following is a table of the FACS fact sheets and their status.

About FACS: The Fire and Climate Synthesis	Elaine Kennedy Sutherland
How weather becomes climate	Unassigned

Fire weather vs. fire climatology	Peter Brown
The role of the El Niño-Southern Oscillation and other climate teleconnections in Fire Climatology	Peter Brown
How climate change is affecting fire climate	Peter Brown
Climate, snowpack, and fire	Thomas Kitzberger, Don Falk
Fire regimes versus fire history - drivers of ecosystem dynamics	Tom Swetnam, Don Falk contribute
How climate affects fire policy	Crystal Kolden
Using fire climatology: Best Management Practices	Crystal Kolden
Using Historical Fire Data to Reconstruct Fire Climatology across North America	Don Falk
Developing a "Geography of Fire Climatology" for North America	Don Falk, Thomas Kitzberger
Understanding lagged relationships: long-term effects of climate on fire	Elaine Kennedy Sutherland

MANAGEMENT IMPLICATIONS

Products of the FACS project will be available to the fire and ecosystem management community and may be useful in several ways. Our paleofire synthesis documents the widespread presence of fire on the pre-settlement landscape, and the dominant role of climate in synchronizing west-wide fire years over the past 400+ years. If there is a single take-home message from this synthesis, it is that managers will have to learn to work with, not against, the time-varying influence of climate on widespread fire years; recent experience suggests that it is unlikely that the forces that set up west-wide fire years can be resisted at the scale of individual forests or management units. The FACS analysis of modern fire climatology indicates the prevailing influence of seasonal climate (temperature and precipitation) in annual area burned, with snowpack duration acting as a mediating factor. For managers, the implications are similar to those from paleofire climatology: widespread fire years are set up by regional and subcontinental climate variation, including secular trends due to anthropogenic emissions of greenhouse gases, and are unlikely to be controlled by local fire suppression efforts. Finally, our analysis of the influence of climate change on fire policy suggests both direct and indirect effects resulting in policy shifts. An additional benefit of this project was a commitment to integrate climate information and support tools into WFDSS to make the information more accessible to users.

RELATIONSHIP TO OTHER RECENT FINDINGS

The Fire History and Climate Change (FHCC) project, also supported by JFSP, compiled an extensive bibliography and documentary summary of published information in paleo and modern fire climatology.

FUTURE WORK

The FACS synthesis project has compiled the largest paleofire database ever assembled for western North America, as well as adapting existing modern area burned data for climate analysis. Our initial syntheses of these major data sets are only the beginning of potential insights important to fire science and management. In paleofire, future analyses could include regionalized spatial analysis of fire occurrence and climate teleconnections, as well as the influence of vegetation types, topography, and ignition potential. Modern fire analyses could include more extensive modeling of the effects of future climate change on seasonal temperature, precipitation, snowpack depth and duration, ignition frequency, and seasonal fluctuations in atmospheric circulation.

One possibility for a future version of the pyroclimograph data and graphical tools would be an interface with a fire occurrence database (kept updated) that would allow users to select different time periods and different thresholds of fire sizes (or other criteria) to include in the pyroclimographs for any sub-region. This tool would be useful for assessing changes through time and space as well as for regional analyses of fire seasonality.

DELIVERABLES CROSSWALK TABLE

Deliverable	Status	Additional Deliverables
1. Quantitative time series and spatial analyses of fire-climate patterns.	Complete, summarized in this Final Report.	Fire history software was developed for analyzing the FACS data sets; these will be released to the fire community through FHAES.
2. An interactive multimedia CD or DVD to be published as a RMRS GTR.	DVD is in preparation as of December 2011 and on schedule for production in 2012.	
3. Fire climatology fact sheets.	Two Fact Sheets complete.	Five additional Fact Sheets are in draft and on schedule for publication in 2012.
4. Paper for publication in a peer-reviewed outlet.	12 papers have been published by the PIs through the FACS project to date.	Two additional journal papers are in preparation as of December 2011, including a synthesis of paleofire climatology, and an analysis of factors controlling modern annual area burned.