FINAL REPORT

# Incorporation of Wildland Fuels Information into Landscale Scale Land Use and Planning Processes

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Recent fire seasons have resulted in record area burned and expenditures with attendant loss of life, property, and natural resources. Knowledge about fire ecology has expanded tremendously in recent years, especially as a result of important research into the role of fire in ecosystems, fire effects on organisms (especially plants), and impacts of management activities on the fire environment (especially fuels). Yet, landscape-scale fuel treatments have generally not been implemented across most landscapes, for a variety of reasons. In high frequency-low severity fire regimes, such as ponderosa pine forests in the southwestern US, political pressures may override ecological understanding of the need for widespread fuel treatments. In other areas, such as southern California chaparral, the historic fire regimes may dictate against consideration of large-scale type conversions across a landscape. Fuel treatments have been proposed at the stand or plant community scale to mitigate the costs and losses from wildfires, yet relatively few have been implemented at the landscape scale. Although treatments have been evaluated at specific sites (Pollet and Omi 2002; Omi and Martinson 2002) the cost-effectiveness of landscape treatments is uncertain or unknown.

Landscape scale fuel treatments generally require a broader perspective than discrete projects carried out in a specific stand or area. Planners and managers may differ in their incentives and understanding regarding landscape scale projects. This report summarizes a Joint Fire Sciences Project aimed at documenting the reasons for the relative lack of fuel treatments carried out the landscape scale, as well as insights and recommendations for the future.

Specifically, project objectives were:

1. Analyze problems with incorporating fuel management information into landscape scale land use and planning processes; and
2. Based on the problem analysis develop/examine approaches for incorporating fuel management knowledge in landscape-scale land-use processes.

Methods included the following:

1. Review of pertinent literature;
2. Survey of managers within USDI and USDA responsible for landscape-scale plans;
3. Develop/analyze two prototype spatial models;
4. Compare and contrast prototypes for insight into problems associated with implementing plans at the landscape scale.

## RESULTS

### Literature review

The literature that is available to assist managers and planners with developing and implementing landscape-scale fuel treatment plans is limited. Case studies (e.g., Lynch and others 2000; Kaufmann and others 1999; Omi 1996) provide insights to changes in fuel profiles that have accompanied historic management activities, but may not include concepts that can be generalized elsewhere. In general, the literature identifies the importance of planning at the landscape scale but lacks detail for carrying out this task in other locales, perhaps because specific understanding (and information gaps) varies between landscapes. The various factors to be considered in plan development (and their appropriate weighting) will depend on numerous considerations, including the particular agency, land management objectives, location and size of planning unit, historic fire regime, spatial and temporal distribution of "hot spots" across the landscape, costs, access, and markets. Other issues to be resolved include the size, timing, and placement of treatments across the landscape. Further, criteria for judging the success of landscape-scale plans are either poorly formed or omitted. Finally, the urban interface has become such an overriding concern that lower priorities may be attached to large-scale treatments, especially prescribed fire.

Knowledge of landscape ecology and disturbance history is essential for planning and implementing landscape-scale plans. The effects of historical fire regimes may in some cases be difficult or even undesirable to mimic (Romme and others 2000; Agee 1998), though basic understanding of landscape dynamics and provides a baseline for future management plans (Cissel and others 1999).

Apparently there is no single successful strategy for planning and implementing landscape-scale treatments. In addition to robust planning documents, successful landscape-scale plans require communication and collaborative learning with agencies and publics. Interactive communication approaches covered in the literature include visualizations (Wilson and McGaughey 2000), consideration of social dynamics as well as ecological relations (Schindler 2000), adaptive management (Walters and Holling 1990), among others. Ultimately, long-term large-scale experiments with rigorous follow-up monitoring will be useful (Swanson and Franklin 1992), though there may never be a simple set of prescriptions for the multiple use and value management of complex ecosystems.

## Surveys

Two surveys were conducted as part of this project, both aimed at planners and managers involved with landscape-scale fuel treatments. The first focused on planners and managers involved with planning and/or implementing landscape-scale fuel treatment projects within the USDI and USDA in Colorado, Utah, Arizona, New Mexico, Wyoming, and Oregon. The second survey focused on a smaller group in Colorado with the aim of ascertaining the role of NEPA compliance in carrying out planning efforts.

The first survey explored objectives and constraints for landscape-scale fuel treatments as expressed by 25 managers/planners in the Intermountain West. Highlights included the following trends. Vegetation structure was cited most often as the criterion used to assess the need for landscape-scale plans, followed in decreasing importance by proximity to the wildland-urban interface, fire frequency, hazard analysis, and fuel continuity. Fuel reduction and ecosystem restoration were cited as primary landscape fuel treatment objectives, followed in decreasing order by wildlife habitat manipulation and severity reduction. Fire regimes and desired ecosystem condition were cited most often as reasons for selecting objectives/strategies, followed by fuel measurements and climate information. Fuel management approaches considered at the landscape scale included prescribed fire, mechanical treatment, fuelbreaks, or some combination thereof. Indicators used to assess fuel treatment effectiveness include photo points and field sample plots, followed by expert opinion and models. Air quality, political and social issues, and funding were cited most often as obstacles—staffing, knowledge, and risks were less important. Additional survey details were summarized in Omi (2001).

The second survey (sent out to 20 planners/managers in Colorado) identified three key obstacles to accomplishing landscape ecosystem management projects: 1) Completion of landscape analysis including development of reference conditions and historical range of variability; 2) Development of desired future conditions which are acceptable to a diverse group of scientists, resource managers, business operators, environmental groups, and the general public; 3) Integration of ecosystem science with social concerns to develop an acceptable plan to move a landscape from current to desired future conditions. Details from the second survey were summarized in Omi (2002).

Apparently no standards exist for developing landscape-scale plans within public agencies, although several approaches are possible. One approach is to develop a Landscape plan comprising several site-specific project plans. An example of this approach is the “Upper Blue Stewardship Project” case study on the White River National Forest. A second approach involves completion of a landscape analysis and development of a generalized landscape restoration prescription. This approach was adopted by the San Juan National Forest for its “Ponderosa Pine Forest Partnership” case study on the San Juan National Forest. Yet another approach is to address landscape analysis and management within the context of an umbrella forest plan or resource management plan, as suggested by the planner on the Grand Mesa-Uncompaghre-Gunnison forests.

### Prototype Models

Two prototype spatial optimization models were developed to provide insights into planning considerations. The first examined relationships between a target fire and valued resources to be protected (such as an urban development), separated by fuels of varying flammabilities as affected by management activities. The optimization model objective was to maximize the time required for a fire to spread from the target ignition to the protected resource, subject to cell ignition likelihood, time required to spread through cells, as affected by fuel availability and management constraints. Additional details are included in Hof and others (2000) and summarized in Omi (2001 and 2002).

Rather than rely on a fixed location for a hypothetical target fire, the second model used percolation theory to evaluate the effectiveness of fuel barriers (either treatments or burned areas, for example) established at random across a landscape adjacent to a fire protection area. An underlying assumption of the modeling process relied on the belief that insights would be gained from modeling fire-fuel relations through spatially-correlated, random spatial treatment patterns. The aim of the Monte Carlo simulation procedure was to produce a spanning cluster of treatments (e.g., a fuelbreak) to protect a community from an untreated forest. Insights gained from the simulation process included the large proportion of area requiring treatment, if randomly arranged; and the degree to which clustering increased the landscape treatment fraction. Further, random treatments produced fairly direct spanning fuelbreaks, although managers will need to treat a majority of the landscape in order to randomly create fuelbreaks. Additional details were described in Omi (2003 and 2004) and published in Bevers and others (2004).

## DISCUSSION

Planning for landscape-scale treatments remains a monumental undertaking. Many reasons contribute to general reluctance to undertake large-scale treatment regimens. Part of the reticence may be related to lack of incentives or inconclusive understanding of the need for such treatments. For example, in many systems fuel structures may not be the primary drivers behind the occurrence of large fires. Instead, climate may bear greater responsibility than fuels for the recurrence of conflagrations. In fact, Collins (2004, see Appendix) shows that climate may be the primary driver of large fires throughout the Intermountain West, both during and preceding the 20th century.

Numerous landscape scale management projects have been launched over recent years. All rely to varying degrees on simulation of fire incidence, spread, and effects to anticipate and inform future strategic plans. Examples include plans for the Columbia River Basin, Sierra Nevada Ecosystem, Southern Utah, Quincy Library Group, and South Platte River Basin. In addition, numerous federal national parks and land areas have implemented programs that essentially manage fire on large landscapes. Several processors have been developed to assist with landscape planning efforts including SIMPLLE/MAGIS, FETM, VDDT, among others. The Fire Regime Interval Departure (FRID) database provides useful information for planning and managing fire incidence by lightning and prescribed ignition sources. Approaches such as national fuel condition classes (Schmidt and others 2002) provide guidance for assessing departures from historical norms and may inform spatial strategies for planning treatments across a landscape (e.g., Finney 2001).

## CONCLUSIONS

Conclusions from the literature, surveys, and prototype modeling efforts included the following:

1) Long-term landscape-scale planning, though highly desirable, presents formidable problems;
2) Many problems are non-scientific;
3) Two major management science problems include non-linearity and the randomness of fire-fuel interactions;
4) Monte Carlo simulations that simulate fire behavior and effects across the landscape show promise though model specification and computation problems can be considerable;

5) Much additional research is needed to capture the dynamics of landscape spatial fire-fuel dynamics.

Recent wildfire seasons illustrate that the war with wildfire cannot be won using standard approaches. Landscape-scale fuel treatments offer one tangible hope for moderating the costs and losses from wildfire events, but implementation lags due to formidable knowledge gaps and agency obstacles, both internal and external. Collaborative adaptive learning processes adopted by agencies and affected publics offer additional hope, but successful outcomes will require commitment and resources (human and financial).

In addition, a change in society's view toward fire on the landscape also is needed. Although not intended, the greatest contribution to fuel hazard reduction across a landscape may in fact be related to the incidence of large wildfire incidents in recent years. Thus success in managing landscapes may in fact rely on the extent to which we, as a society, can accept the beneficial impacts of wildfire areas that burn with low severity (e.g., flanks and rear portions) while simultaneously rejecting the detrimental results from prescribed fires that go awry.

## Products

Products from this project included two refereed publications (*Forest Science* and *Canadian Journal of Forest Research*) and a proceedings article for a conference on fuel treatments and ecological restoration. Further, the conference was supported in part with resources from this project. The high visibility and scientific rigor of these outlets represent important contributions to the literature. In addition, written and oral progress reports were provided for the 2001-04 JFSP PI meetings.

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# APPENDIX

# THESIS

# REGIONAL RELATIONSHIPS BETWEEN CLIMATE AND WILDFIRE BURNED AREA AT MULTIPLE SCALES IN THE INTERMOUNTAIN WEST

Submitted by

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In partial fulfillment of the requirements

For the degree of Master of Science

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Spring 2004

COLORADO STATE UNIVERSITY

WE HEREBY RECOMMEND THAT THE THEISIS PREPARED UNDER OUR SUPERVISION BY BRANDON M. COLLINS ENTITLED REGIONAL RELATIONSHIPS BETWEEN CLIMATE AND WILDFIRE BURNED AREA AT MULTIPLE SCALES IN THE INTERMOUNTAIN WEST BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

Committee on Graduate Work

| | | |
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# ABSTRACT OF THESIS

# REGIONAL RELATIONSHIPS BETWEEN CLIMATE AND WILDFIRE BURNED AREA AT MULTIPLE SCALES IN THE INTERMOUNTAIN WEST

The response in yearly burned area to synoptic scale climatic patterns (El Niño/Southern Oscillation and Pacific Decadal Oscillation) varied geographically at both regional and landscape scales. The southern Intermountain West showed the strongest relationship with the Southern Oscillation Index (SOI) in years preceding, and during widespread fire years. I found a strong connection between antecedent Pacific Decadal Oscillation (PDO) index and increased burned area in the northern Intermountain West, and a weak connection between contemporaneous PDO index and burned area in the southern Intermountain West. Burned area on the western slope of the Colorado Rockies was only related to antecedent SOI, while burned area on the eastern slope was only related to contemporaneous SOI. Contemporaneous drought was related to increased burned area throughout the Intermountain West. Furthermore, in most of the study area antecedent wet conditions were associated with increased burned area. These results demonstrate that climatic influences on burned area for the last 75 years in the Intermountain West are similar to those associated with more widespread fire years in historical fire regimes.

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## Introduction

Throughout the reconstructed record of history, the occurrence of fire has been linked with climate. In the Intermountain West, several studies (Littell 2002; Swetnam and Betancourt 1990; Swetnam and Betancourt 1998; Veblen et al. 2000) have found that synoptic scale climatic processes, specifically El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), can promote more widespread fire due to the alteration of moisture availability. Both ENSO and PDO affect moisture availability by influencing precipitation and temperature patterns. These influences on precipitation and temperature can lead to both enhanced fine fuel production and increased net fuel loading.

The oscillation in both processes refers to a shift between warm and cool phases caused by changes in temperatures in the Pacific Ocean. In the Intermountain West the effects on the regional climate caused by these phases of ENSO and PDO are reversed between the southern and northern Intermountain West. During the warm phase of ENSO, or El Niño conditions, and the warm phase of PDO the southern Intermountain West experiences substantially wetter, and slightly cooler, winters, while in the northern Intermountain West winters tend to be warmer and drier than usual (Cayan 1996; WRCC 1998). The effects of the cool phase of ENSO, or La Niña conditions, and cool phase PDO are opposite to those associated with the warm phases. The strength of these phases for both ENSO and PDO varies. As result, during weaker phases of both ENSO and PDO, there may be no discernable effect on climate (WRCC 1998).

Despite the similarity in signals of warm and cool phases, two major differences exist between ENSO and PDO. One difference is in the time scales at which the processes operate. A phase of ENSO lasts 1-2 years, while a phase of PDO last 10-20 years (Mantua 2000a; WRCC 1998). The other major difference is that the effects of ENSO are stronger and more consistent in the southern Intermountain West, while effects of PDO are stronger in the northern Intermountain West.

The climatic influences of ENSO and PDO are not as well understood for the central Intermountain West. The dividing line of the reversal in ENSO and PDO effects runs through the central Intermountain West (WRCC 1998). This creates a high degree of ambiguity as to which signal of ENSO or PDO is evident in this region. In addition to this reversal in effects of ENSO and PDO, the central Intermountain West happens to be the pivotal zone of a north-south reversal in distribution of precipitation (Dettinger et al. 1998). Dettinger et al. (1998) point out that this north-south reversal is not always due to ENSO or PDO effects. The pivotal zone of this reversal is characterized by tremendous variability in precipitation.

The variation in the climatic influences on moisture availability throughout the Intermountain West has strong implications towards climate/fire relationships. Drought often corresponds with more widespread fire. In addition, several studies (Brown and Shepperd 2001; Donnegan et al. 2001; Grissino-Mayer and Swetnam 2000; Swetnam and Betancourt 1998; Veblen et al. 2000) have shown that increased antecedent moisture availability leads to widespread fire. The explanation accompanying this relationship is that increased moisture availability stimulates production of fine fuels. The fine fuels are then dried out by subsequent drought conditions, creating conditions conducive to widespread fire (Grissino-Mayer and Swetnam 2000; Veblen et al. 2000).

These connections between climate and fire have not been found to be regionally consistent. Strong patterns indicating widespread fire years are preceded by increased moisture availability have been found in the southern Intermountain West, and to a lesser extent in the central Intermountain West. This relationship has been verified using different indices of ENSO (Donnegan et al. 2001; Swetnam and Betancourt 1990), as well as an index of moisture availability, the Palmer Drought Severity Index (Brown and Shepperd; Swetnam and Betancourt 1998). In the northern region of the Intermountain West relationships between more widespread fire and indices of ENSO and PDO, as well as the Palmer Drought Severity Index (PDSI), were found to be much weaker or non-existent (Littell 2002).

Most of the studies referenced above relied on fire dates from dendrochronologically based fire histories to determine fire/climate relationships. In many systems in the Intermountain West fire scars are readily available prior to the late 1880s and early 1900s (Littell 2002; Swetnam et al. 1999; Veblen et al. 2000). The availability of fire scars that post date the turn of the century is very limited due to changes in fire regime patterns caused by fire exclusionary policies. As such, only slim inferences may be drawn from these types of studies about current climate/fire relationships.

Several studies have examined more recent climate/fire relationships (Simard et al. 1985; Swetnam and Betancourt 1998; Westerling et al. 2003). These studies used yearly burned area statistics compiled from multiple federal agency records that extend from the early 1900s to 2000. This study attempts to build on these recent studies that have explored the relationship between yearly burned area and climate during the period since inception of fire record keeping. This study differs from the previous studies, in that it involves multiple indices of climate to ascertain regional differences in climate/fire relationships. By using multiple indices I hope to identify which climatic signals are most important in relating to burned area in the Intermountain West, and whether or not the relative importance of these indices varies regionally. If strong climatic signals are related to burned area, managers can use these signals to provide some indication of burned area potential for a given fire season. Given the variation in the effects of different climatic influences throughout the Intermountain West (Dettinger et al. 1998), I would expect to find regional differences in the response of burned area to climate. Thus, the identification of regional differences could be extremely important in planning management actions for potentially extensive or less-extensive fire seasons.

Based on the studies mentioned previously, I expect that ENSO fluctuations will have a much greater influence on burned area in the southern Intermountain West than in the northern Intermountain West. Fluctuations in PDO may play a lesser role in establishing interannual fire/climate relationships in the Intermountain West due to the longer time scale at which it operates (Mantua et al. 1997). However, I hypothesize that the influence of PDO on burned area will be greater in the northern Intermountain West, where the connection between PDO and moisture availability has been established in previous studies (Cayan 1996; Mantua et al. 1997).

I presume that drought will be associated with increased burned area throughout the Intermountain West. More long-term drought may be more important in conditioning fuels in the denser, more closed canopy, forest types in the northern Intermountain West (Westerling et al. 2003). In contrast, antecedent moisture availability will likely play a more important role in relating to burned area in the southern Intermountain West, where forests tend to be more open and fuel accumulation tends to be more responsive to moisture availability (Westerling and Swetnam 2003). Climate/fire relationships in the central Intermountain West are not as well understood. I am unsure if, and how, burned area in this region relates to ENSO or PDO.

In addition to using multiple climatic indices, this study assesses regional differences in climate/fire relationships at multiple spatial scales. I expect that an analysis of climate/fire relationships at a finer scale will unveil relationships that would otherwise be masked by doing the same analysis at the larger scale. If this is the case, the application of regional scale climate/fire relationships for fire management is limited to regional scale planning. In order to use such relationships for sub-regional scale planning, a finer spatial scale may need to be studied.

In exploring the previously stated objective I will be able to compare the results from this study to climate/fire relationships established in studies of historical fire regimes. This will aid in assessing the relevance of information from these fire history studies for managing fire regimes. In doing so, I hope to gauge the degree to which current climate/fire relationships are within or outside the historic range of variability.

I expect that under current forest conditions climate, in particular antecedent climate, may play less of a role in influencing burned area. This hypothesis is based on the fact that current fuel conditions in the southern and central Intermountain West far exceed those established in studies of historic range of variability (Brown et al. 1999;

Cooper 1960). With increased fuel loads, widespread fire may be less dependent on fuel accumulation (Brown and Shepperd 2001). As a result, the relative importance of antecedent moisture in enhancing fine fuel build up may be reduced under current fire regimes.

## Methods

### Study Area and Climate Regions

The study area includes 8 states in the interior western US: Idaho, Montana, Wyoming, Colorado, Utah, Nevada, Arizona, and New Mexico. For the purposes of this study, the area that encompasses these 8 states is referred to as the Intermountain West. Previous studies (Dettinger et al. 1998; Mock 1996) have noted considerable climatic variability throughout the Intermountain West region. In order to recognize this variability in climate and its associated impacts on climate/fire relationships, I divided the study area into 3 climatic regions based on air masses that predominate in the winter and summer, after Mitchell (1976).

The northern region (Mitchell's region II) includes Idaho, Montana, and Wyoming (Figure 1). This region is influenced by frequent intrusion of arctic air from the north and northwest. The southern boundary of this region represents a boundary between two air masses. The northern air mass is influenced by east-west winds, whereas winds in the southern air mass are much less organized (Mitchell 1976). The two regions to the south of the northern region experience relatively similar temperature patterns, but differ in moisture patterns. The central region (Mitchell's region V) includes Nevada, Utah, and northwest Colorado. This region is characterized by drier summer air due to lack of summer precipitation. The southern region (Mitchell's region VI) includes most

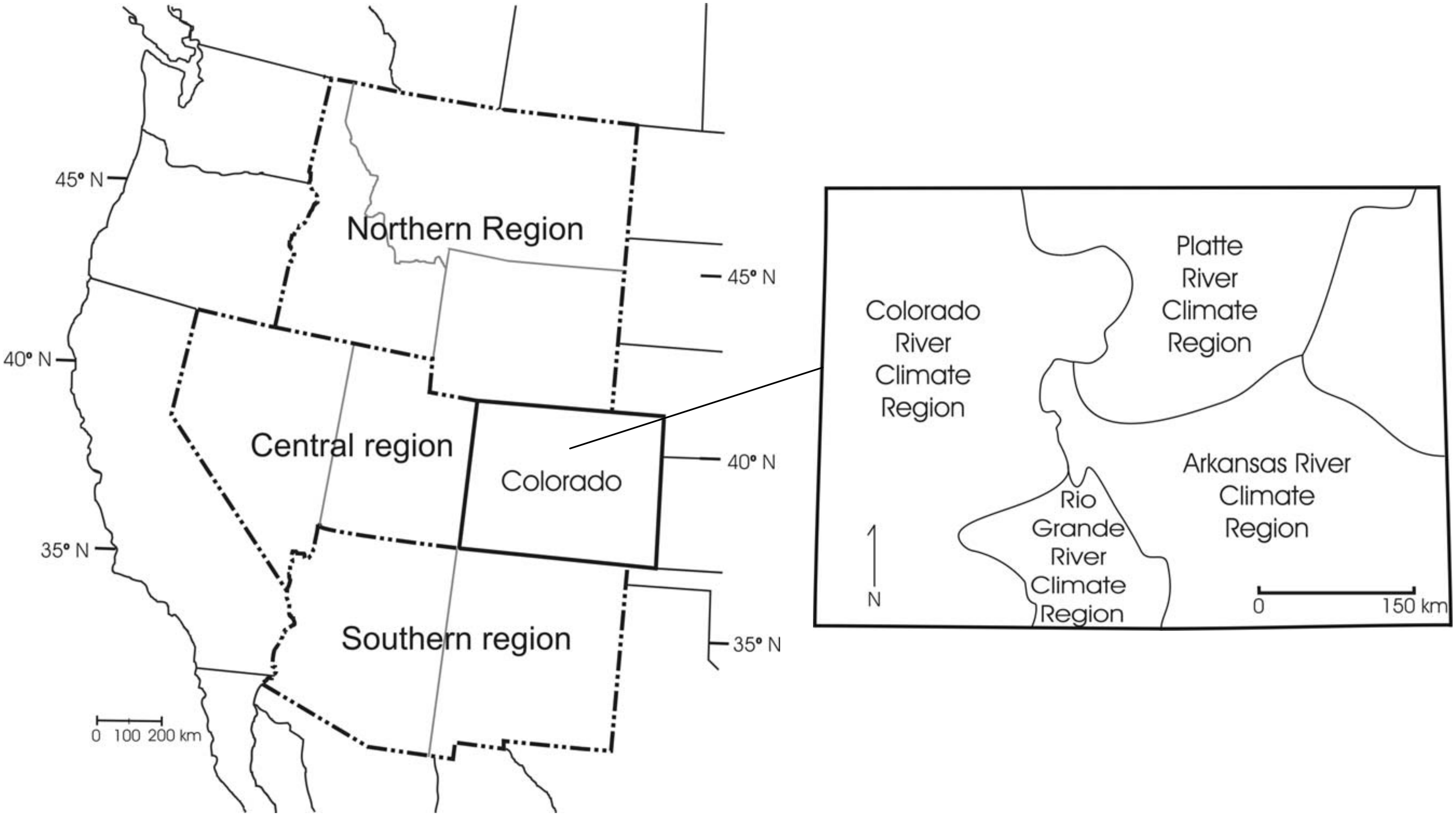

Figure 1. Climate regions for the Intermountain West and Colorado. Intermountain climate regions are based on air mass boundaries identified by Mitchell (1976). Colorado is not included in any of the Intermountain climate regions. Colorado climate regions are based on divisional climate data from the Western Regional Climate Center, and represent major watershed boundaries in Colorado

of Colorado, New Mexico, and Arizona. This region differs from the central region because it is influenced by the summer monsoons. As a result, the summer air in this region tends to be more moist than that of the middle region (Mitchell 1976).

The boundaries between these 3 climate regions in the Intermountain West correspond fairly well with state boundaries, with Colorado being the only exception. Mitchell's boundary between the central and southern region cuts through Colorado, leaving the southern and eastern portion of the state in the southern region, and the northwest portion in the central region. To address this inconsistency, I excluded Colorado from both the central and southern regions (Figure 1). It was not possible to obtain data on fire statistics that were more geographically explicit than individual state totals before 1956. As a result, I could not partition Colorado into the central and southern climate regions, and keep the full length of the fire statistics time series (1926-2002). I opted to only report results from the Intermountain climate regions with Colorado excluded from the analysis, although I did perform the same analysis including Colorado in both the central and southern regions.

The regionalization of the Intermountain West is an attempt to get at larger scale variations in climate/fire relationships. Conducting this type of analysis at a larger scale may mask some of the more intricate climatic fluctuations throughout the Intermountain West. This is especially true given the tremendous spatial heterogeneity in precipitation timing and amounts in mountainous areas (Mock 1996). To discern climatic influences on burned area at a finer scale from those at the Intermountain scale, I chose to look at just the state of Colorado. Several reasons warrant greater scrutiny on Colorado. Colorado lies in the latitudinal zone (40° N) at which the north-south seesaw of precipitation pivots (Dettinger et al. 1998). The high degree of variability in precipitation patterns in this pivotal zone means that Colorado could be affected by either extreme of the north-south contrast in precipitation. The combined effect of being located at this pivot point, the extensive mountainous terrain, and the fact that Mitchell's (1976) climate regions split the state, all suggest a high potential for variability in precipitation in Colorado. A finer scale analysis of Colorado will yield a higher degree of resolution as to how this variability in precipitation is realized geographically in terms of climate/fire relationships.

As with the Intermountain scale, Colorado is sub-divided into its own climate regions. These regions are based on the drainage basins for 4 major western US rivers, which originate in Colorado: the Colorado River, Arkansas River, South Platte River, and the Rio Grande. The boundaries between these drainage basins are used by the Western Regional Climate Center as climatic regions for divisional climate data (Figure 1). The different sources of atmospheric moisture for each region, as well as the rain shadow influence on the eastern slopes, create a marked east-west contrast in precipitation regimes (Doesken 2002).

The Colorado River climate region (CR) includes the portion of Colorado that is west of the continental divide. The primary source of atmospheric moisture for the CR region is the Pacific Ocean. The moisture is carried east from the Pacific Ocean by the jet stream. Eastward moving storms drop most of their moisture in this region, leaving little moisture for regions on the eastern slope of the Colorado Rockies (Doesken 2002). The 3 climate regions on the eastern slope: Arkansas (AR), Platte (PL), and the Rio Grande (RG), receive most of their moisture from the Gulf of Mexico, and to a lesser extent, the Gulf of California (McKee et al. 2000). This difference in moisture sources leads to seasonal differences in maximum precipitation. For the CR, the maximum precipitation occurs in the winter and early spring, versus summer for both RG and AR, and late spring to early summer for the PL (McKee et al. 2000; Mock 1996).

## Historic Burned Area

The fire data I use in this study is total burned area per year. Burned area is examined, rather than other indicators of fire, such as fire occurrence, because climate affects the extent of fire more than number of fires. In fact, fire occurrence may tend to reflect social behavior more than it reflects climatic processes (Brenner 1991).

The yearly totals for burned area at the Intermountain scale were compiled from USDA Forest Service publications of Wildfire Statistics (USDA 1998). Wildfire Statistics publications provide statewide totals for every year from 1926-1997. These reports summarize total yearly burned area for all federal, state, and private land for every state in the US. The publication of Wildfire Statistics ceased in 1997. From 1998-2002, I obtained statewide totals for yearly burned area from the USDA Forest Service (for state, private, and Forest Service lands) and the National Interagency Fire Center (for all Department of Interior lands). I summed up these data from both sources to get yearly total burned area for each of the states included in the Intermountain climate regions. I then summed state totals to get yearly total burned area for each of the three climate regions. The length of the burned area time series for all Intermountain regions is 76 years (1926-2002).

The yearly burned area statistics for the Colorado regions were obtained from 3 sources: published fire reports from 1956-1986 (USDA 1987), Kansas City Fire Access

Software from 1980-2002 (KCFAST 2002) and fire statistics from individual National Forest Fire Management Officers 1970-2002. If discrepancies existed between these 3 sources for the overlapping years I used the fire statistics from the Fire Management Officers, which claimed to be corrected.

The boundaries for the 4 climate regions in Colorado were consistent with National Forest boundaries. Burned area statistics for the CR were compiled from the following national forests: the Routt, White River, Grand Mesa, Uncompahgre, Gunnison, and San Juan. The same statistics for the AR were compiled from the Pike and San Isabel National Forests, along with the Comanche National Grassland. For the PL, the burned area statistics were compiled from the Arapaho and Roosevelt National Forests, along with the Pawnee National Grassland. The statistics for the RG consisted of yearly burned area from just the Rio Grande National Forest. The length of the yearly burned area time series was 46 years for all 4 regions (1956-2002).

## Climatic Indices

Due to the influences of ENSO and PDO on climate in the Intermountain West, I chose to use indices of both processes in relating climate to yearly burned area. The index of ENSO used is the Southern Oscillation Index (SOI). This index is based on differences in standardized sea-level pressure between Tahiti and Darwin, Australia. Sea-level pressure shifts between Tahiti and Darwin. As a result, this difference in sea-level pressure indicates the magnitude and direction of Southern Oscillation (NOAA 2003a). Negative values of SOI most often correspond with El Niño conditions, and positive values with La Niña conditions. Values of standardized SOI typically range from -3 to 3. However, during very strong El Niño events, such as the 1982-1983 event, the standardized values of SOI were as low as -4.6.

I obtained monthly values of SOI for every year in the fire statistics time series (NOAA 2003a). Northern winter (December, January, February) values of this index were used because this is the season when maximum pressure anomalies occur (Swetnam and Betancourt 1990).

The PDO index used in this analysis consists of a set of standardized values based on monthly sea-surface temperature anomalies in the North Pacific Ocean (Mantua 2003). Just as with SOI, I used the northern winter (December, January, February) values because the wintertime signature of PDO is the strongest (Cayan 1996). The PDO index ranges from -3 to 3, with positive values corresponding with warm phase of PDO, while the negative values correspond with the cool phase of PDO.

In addition to using SOI and the PDO index, I found it necessary to use another climatic index, Palmer Drought Severity Index (PDSI), to capture interannual variability in available moisture. PDSI is based on precipitation and temperature, and is a measure of moisture status over prolonged periods, which accounts for precipitation, evapotranspiration, and soil moisture conditions (Palmer 1965; Rollins et al. 2002). PDSI values usually range from -6 to 6 with positive values corresponding with wetter conditions, while negative values correspond with drought conditions.

The temporal scale used for PDSI differs from that of the PDO or ENSO indices. Where I used the winter averages for both the PDO index and SOI, for PDSI summer values are more optimal for studying fire/climate relationships because the summer values capture the moisture availability prevailing during the Western fire season (Baisan and Swetnam 1990; Swetnam and Betancourt 1998). To aid in determining which summer month to use in the analysis I used the program DendroClim 2002 (Biondi 2002). The outputs from this program provide values for the correlation between the burned area time series and each of the 12 months from the PDSI time series. I used these correlation values to determine the month most highly related to yearly burned area (see Table 1). The month chosen was the PDSI value used for each year in the fire statistics time series. This month varied between regions, ranging from July (for the southern region), to August (for the northern region and RG), to September (for the central region, AR, CR, and PL).

Table 1. Sample output from DendroClim 2002 (Biondi 2002) correlating burned area for the northern region with Palmer Drought Severity Index (PDSI). In this instance August was the month selected for the northern region PDSI time series.

| *Month* | *Jan* | *Feb* | *Mar* | *Apr* | *May* | *Jun* | *Jul* | *Aug* | *Sep* | *Oct* | *Nov* | *Dec* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Correlation value | -0.05 | -0.08 | -0.13 | -0.18 | -0.25 | -0.28 | -0.35 | -0.43 | -0.39 | -0.32 | -0.30 | -0.29 |

For the climate regions in the Colorado analysis I used the Standardized Precipitation Index (SPI), in addition to using PDSI. The SPI is based on current and historical precipitation data, and can be computed for different time scales. McKee et al. (2000) explain that SPI is the simplest yet the most robust index for describing drought patterns. I did not use SPI for the analysis at the Intermountain scale because statewide SPI data were not available.

As with the PDSI, the SPI is computed monthly. However, unlike the PDSI, the SPI is available at multiple time scales for every month. In other words, for any given month, there are SPI values for just that month, the last 3 months, 6 months, 9 months, etc. As a result, I used the same method with the DendroClim program as I did with

PDSI to determine the month, and scale that best related with the burned area time series for each region. The month chosen ranged from August (for the PL), to September (for the AR, and RG), to October (for the CR), at the 9 month scale for all regions.

The SOI and PDO index do not vary geographically for a given year. For any given year the winter SOI and winter PDO index values will be the same for each region. On the other hand, the yearly PDSI and SPI values do vary regionally. I obtained statewide PDSI time series for each of the states in the Intermountain climate regions from the Western Regional Climate Center (WRCC 2003). I averaged the statewide yearly values of PDSI to then get yearly PDSI for each of the climate regions. For the climate regions in Colorado I used specific values of PDSI and SPI for each region from divisional climate data (NOAA 2003b; WRCC 2003).

**Statistical Analyses**

I used two different statistical methods to analyze relationships between yearly burned area and the different climatic indices. The first method involves lagged regression using an autoregressive error model. I constructed lagged variables for each of the previously mentioned indices for 3 years prior to every year from 1926-2002. The mathematical expression for this model is:

$$Y = \alpha + \beta_0 x_0 + \beta_{-1} x_{-1} + \beta_{-2} x_{-2} + \beta_{-3} x_{-3} + \varepsilon \qquad (1),$$

where $Y$ is the response in burned area, $\alpha$ is the intercept and $\beta_0, \beta_{-1}, \beta_{-2}, \beta_{-3}$ are the slope parameters for current ($x_0$) and lagged years ($x_{-1}, x_{-2}, x_{-3}$) for a given climate index, and $\varepsilon$ is the error term. (This relationship was tested for each of the climate indices mentioned in the previous section). I ran this analysis using the Autoreg Procedure from the computer software package SAS® (SAS 2003). This procedure adjusts for serial autocorrelation in the burned area time series data to account for lack of independence of the regression error terms. The error terms were assumed to have an autoregressive structure with up to 3 terms (Brockwell and Davis 2002).

Before I ran the time series analysis I detrended what appeared to be an exponential increase over time in the burned area time series for each region, at both scales. Each time series was log transformed then fitted with a linear trend line. I then used the residuals, or deviations from the fitted line, from each region to run as the burned area time series in the autoregressive model. I did this because I was interested in getting the near-term lagged correlation structure. If the time series were not detrended the long term trends will tend to dominate the correlation structure. Figure 2 shows the residual burned area time series for each region at the Intermountain and Colorado scale, respectively. No bowing or abrupt change points are evident in these plots, indicating that the linear detrending was adequate. In addition, the detrended log burned area time series were nearly normally distributed for every region, whereas the original data were highly right skewed. Detrending was not necessary for the climatic indices because the indices are standardized (Mantua 2000b; NOAA 2003a; NOAA 2003b; WRCC 2003). The outputs from the analysis provide slope estimates and p-values for the main effects of the current and lagged indices on the regression of yearly burned area. The relationships between yearly burned area and the contemporaneous values of the climatic indices, along with values for each of the 3 years prior to all years in the burned area time series, were determined using the slope estimates. Each slope is the estimated change in log area burned for a unit change in one lagged year of a particular index, holding the other

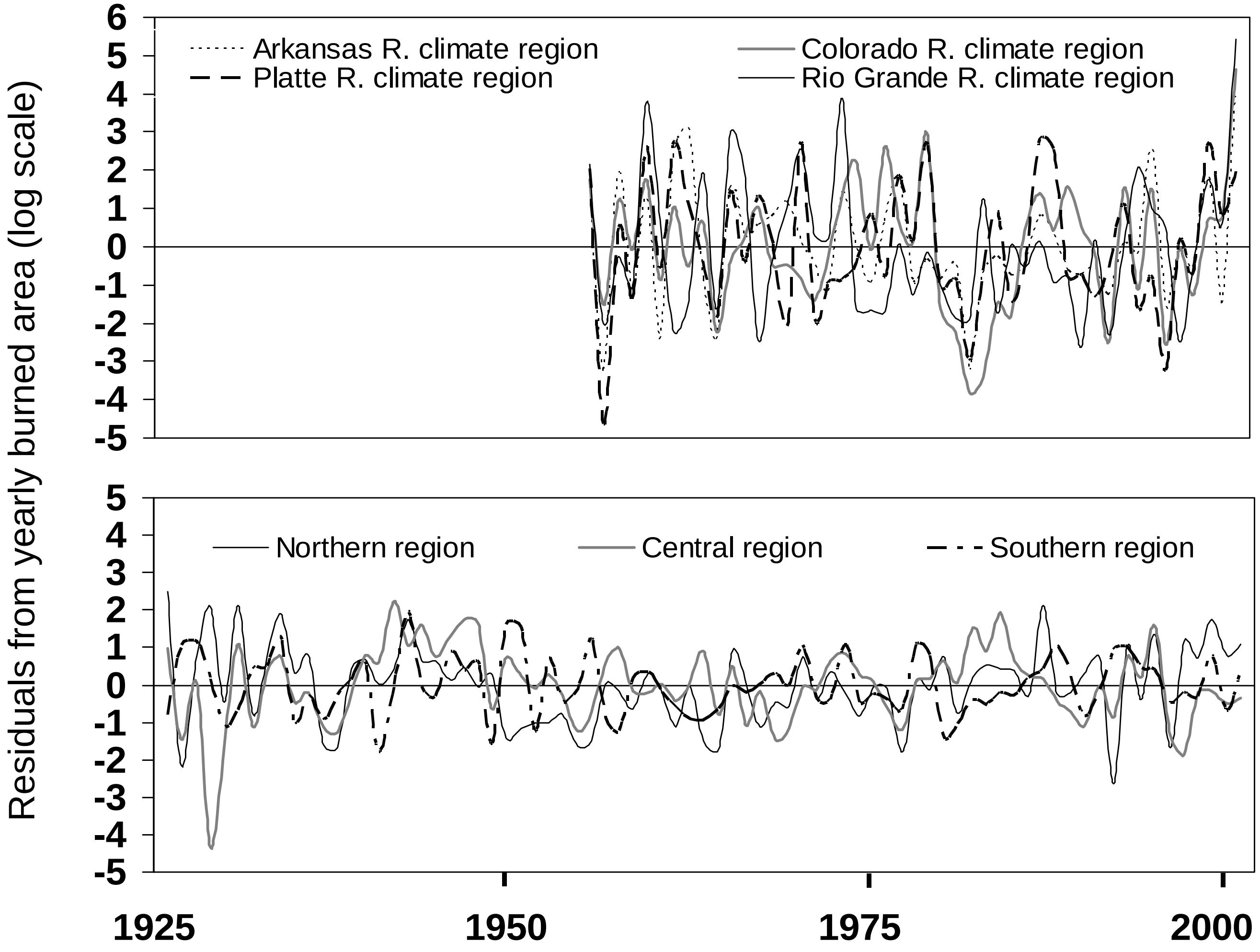

Figure 2. Colorado (top) and Intermountain (bottom) climate regions-yearly burned area (log scale) residuals from linear detrending.

lagged years for that index in the model constant. I used a backward selection, starting with lag -3, to eliminate model parameters with a p-value >0.10. Once a model parameter was identified with a p-value ≤0.10, all parameters having shorter lags (-2,-1, 0) were retained in the model. This is based on a hierarchical modeling procedure, which was also used in eliminating autoregressive coefficients from the model. The importance of individual lagged climate index parameters was judged by the size of the p-values associated with each parameter. Table 2 identifies both the number of autoregressive coefficients and the lagged climate index parameters retained in the final model for all regions using each climatic index.

The second statistical method I used, Superposed Epoch Analysis (SEA), analyzes the relationship between identified fire years and mean climatic conditions surrounding these fire years (Grissino-Mayer and Swetnam 2000; Swetnam 1993). SEA compares a set of fire years to the window of climate index values leading up, in this study each of the 3 years prior, to and including each year in the set. The set of fire years I used in this study were the 10 most extensive fire years, based on the residuals from the detrended time series. The decision to use the 10 most extensive fire years is based on a similar type of analysis done by Swetnam and Betancourt (1998).

The SEA uses a bootstrapping method, based on 1000 Monte Carlo simulations, to provide confidence intervals for mean climatic conditions around the identified fire years. In each simulation, the number of randomly selected years equals the number of fire years, which are 10 for each set. The confidence intervals are based on a normal distribution, and serve to provide statistical significance on the relationship between fire years and the climatic indices mentioned previously.

Table 2. Information on final model selection from the autoregressive analysis. The AR1, AR2 and AR3 indicate whether the 1, 2 or 3 autoregressive coefficients were retained in the final model. In some cases no autoregressive coefficients were retained in the final model, indicated by no AR. The lagged climate indices that were retained in the final model are in parentheses. A single dash (-) indicates that the relationships were not tested.

| | *Intermountain climate regions* | | | *Colorado climate regions* | | | |
|---|---|---|---|---|---|---|---|
| | Northern region | Central region | Southern region | Arkansas river climate region | Colorado river climate region | Platte river climate region | Rio Grande climate region |
| Southern oscillation index | AR3<br>(none) | AR1<br>(-2, -1, 0) | AR2<br>(-2, -1, 0) | AR1<br>(-1, 0) | AR3<br>(-3, -2, -1, 0) | AR1<br>(0) | no AR<br>(0) |
| Pacific decadal oscillation index | AR3<br>(-2, -1, 0) | AR2<br>(none) | AR2<br>(none) | - | - | - | - |
| Palmer drought severity index | AR3<br>(-1, 0) | AR1<br>(-3, -2, -1, 0) | no AR<br>(-2, -1, 0) | AR1<br>(-1, 0) | no AR<br>(0) | AR3<br>(-3, -2, -1, 0) | no AR<br>(-1, 0) |
| **Standardized precipitation index** | - | - | - | no AR<br>(-1, 0) | AR3<br>(-1, 0) | AR3<br>(-1, 0) | no AR<br>(-2, -1, 0) |

Given that the data for the burned area statistics are continuous it seems that more certainty can be placed in climate/fire relationships established using the regression model because it uses the entire data set to develop relationships. This is in contrast to the event based SEA, which in this case only looks at 10 years of the fire statistics data set. The one advantage of looking at the 10 largest fire years is that the SEA can identify the climatic conditions that lead up to and occur during just these extensive fire years. The conditions that occurred around these more extreme fire years could differ from those identified by the regression model, and would be important to incorporate in planning for large fire years.

## Results

### Intermountain climate regions

#### *SOI*

Figures 3a and 3b show the relationships between increased burned area and SOI for the regression model and the SEA, respectively. The difference in the vertical axes between figures reflects the two different analyses. The results reported from regression model are slope estimates. The interpretation of these slope estimates is the change in log area burned per unit change in SOI. The results from the SEA are simply the mean SOI values from the 10 extensive fire years. Despite the difference in units for the vertical axes similar relationships can be inferred from the results reported in the two figures.

Both analyses show very similar relationships between SOI and increased burned area, but differ with respect to statistical significance (Figures 3a and 3b). Only the southern region shows significant relationships with SOI. As indicated by the regression model, increased burned area in the southern region is preceded at the -2 ($p$=0.003) and

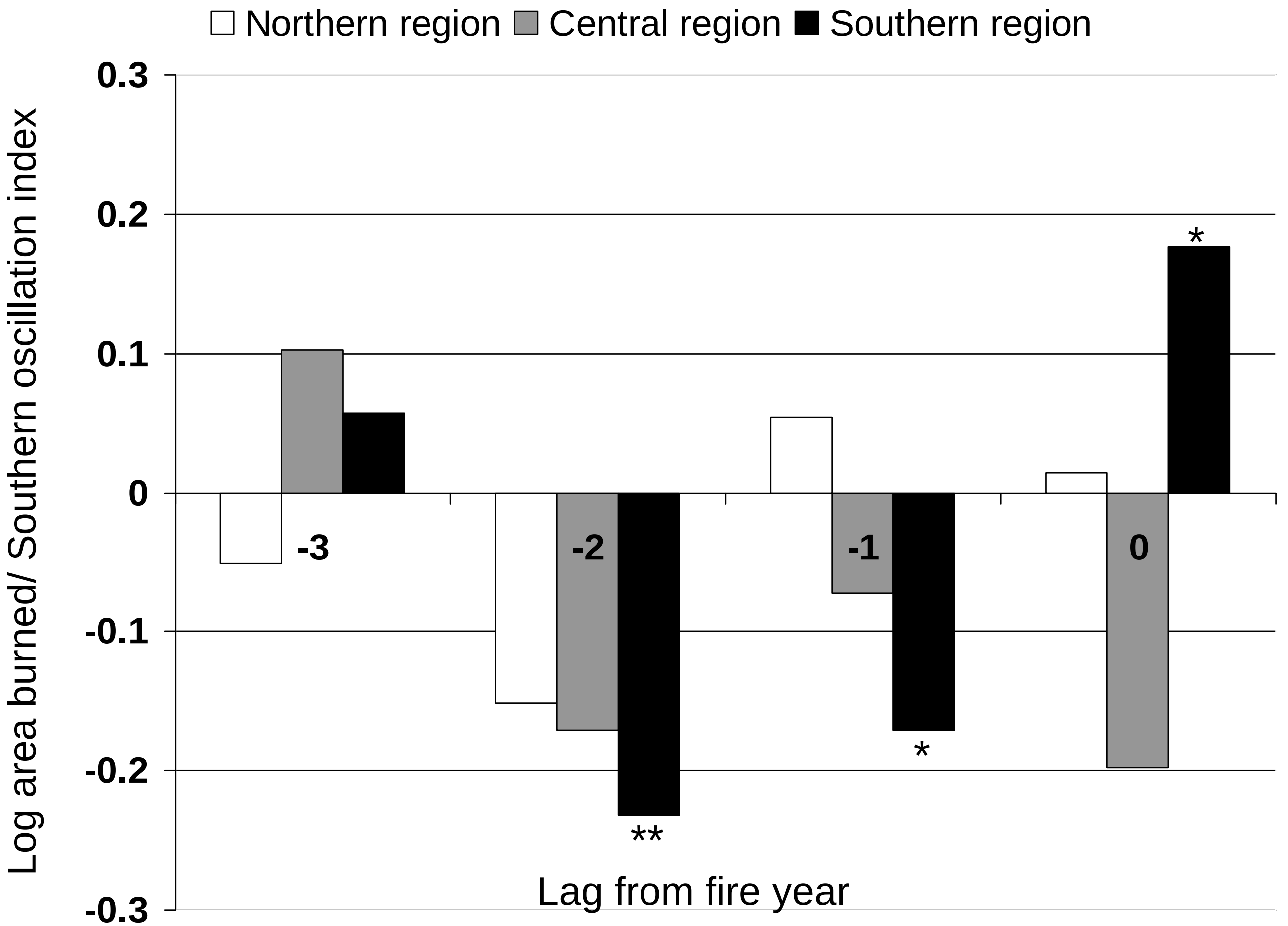

Figure 3a. Intermountain climate regions-slope estimates (in log scale) from autoregressive model using yearly burned area and winter (Dec, Jan, Feb) Southern Oscillation Index. Slope estimates are reported from backwards selection. Slope estimates eliminated from the final model (if p>0.10) are reported though subsequently removed. Significance is based on p-values from the autoregressive model (1). Significance at p<0.05, p<0.01, and p<0.001 are denoted with single, double, and triple asterisks, respectively.

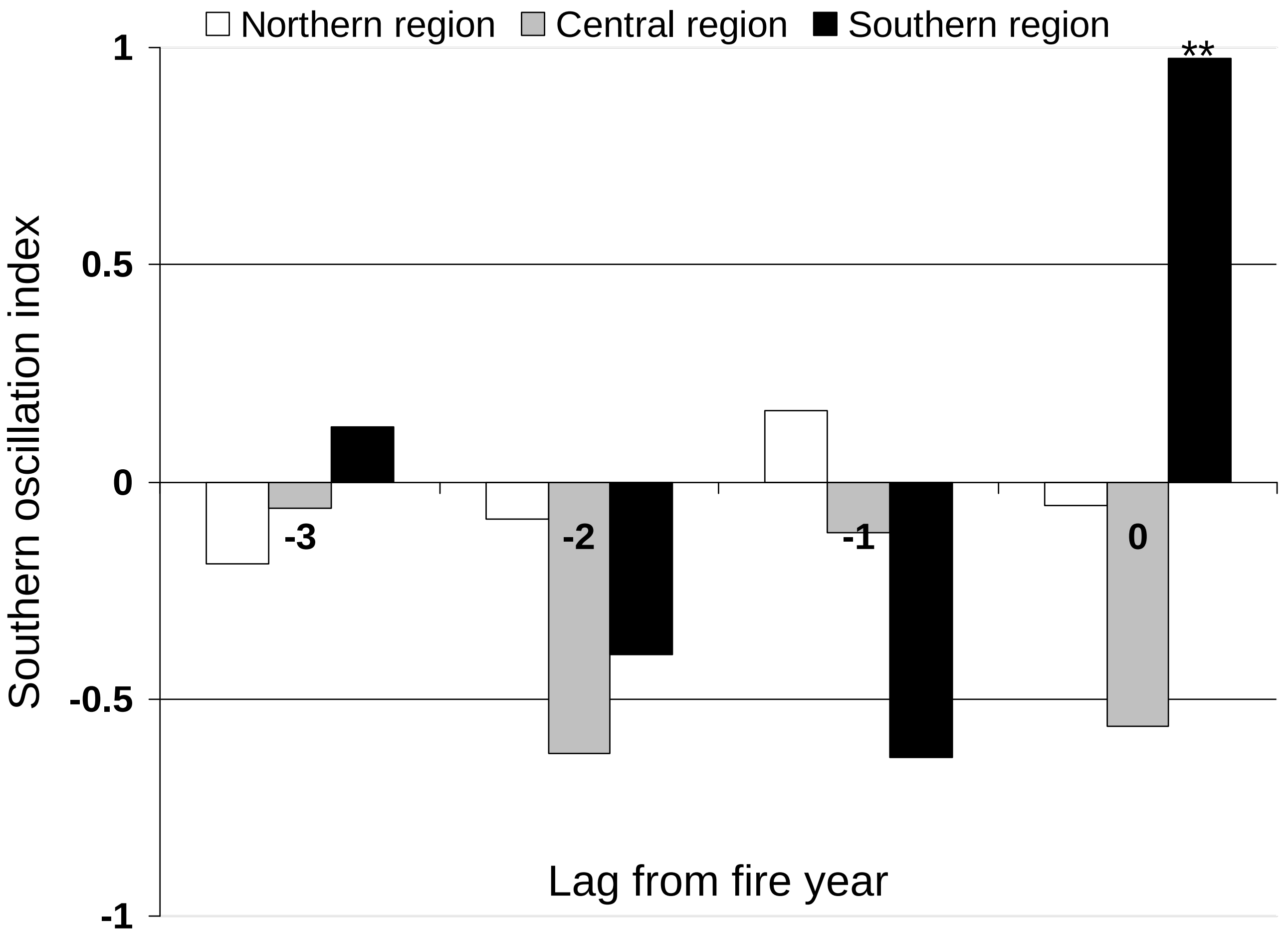

Figure 3b. Intermountain climate regions-mean winter (Dec, Jan, Feb) Southern Oscillation Index values for the 10 <u>highest</u> fire years. Significance is based on Monte Carlo simulations from Superposed Epoch Analysis. Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

the -1 (*p*=0.023) year lags by negative SOI, or El Niño conditions. There is also weak evidence for a negative relationship with SOI for the central region at the -2 (*p*=0.09) and the 0 (*p*=0.054) year lags. For the southern region, the relationship between SOI and burned area switches to positive at the 0 year lag, while for the same lag the central region shows a weak negative relationship. Relationships with SOI for the Northern Region are very weak or non-existent for all lag years.

### *PDO*

The connection between PDO and burned area appears to be strongest in the northern region (Figures 4a and 4b). The regression model yields the only significant positive relationship with PDO for the northern region, which is at the -2 year lag (*p*=0.004). The SEA shows a similar positive association at the -2 year lag for the northern region, but the relationship is not significant (*p*=0.14). The two analyses also differ with respect to the negative relationship with burned area at the 0 year lag for the southern region. The SEA identifies a significant (*p*<0.05) negative relationship, while the regression model identifies a very weak (*p*=0.29) negative relationship. Burned area in the central region is weakly (*p*=0.054) related to PDO at the -2 year lag, according to SEA. However, no such relationship is identified in the regression model.

### *PDSI*

The relationship between PDSI and the burned area time series is much stronger than that of the other climate indices. Both the regression model and the SEA with extensive fire years yielded strong -1 year and 0 year lag relationships (Figures 5a and 5b). The regression model shows highly significant (*p*<0.0001) positive relationships at -1 year lag for all regions. The SEA confirms this relationship at the -1 year lag, but only

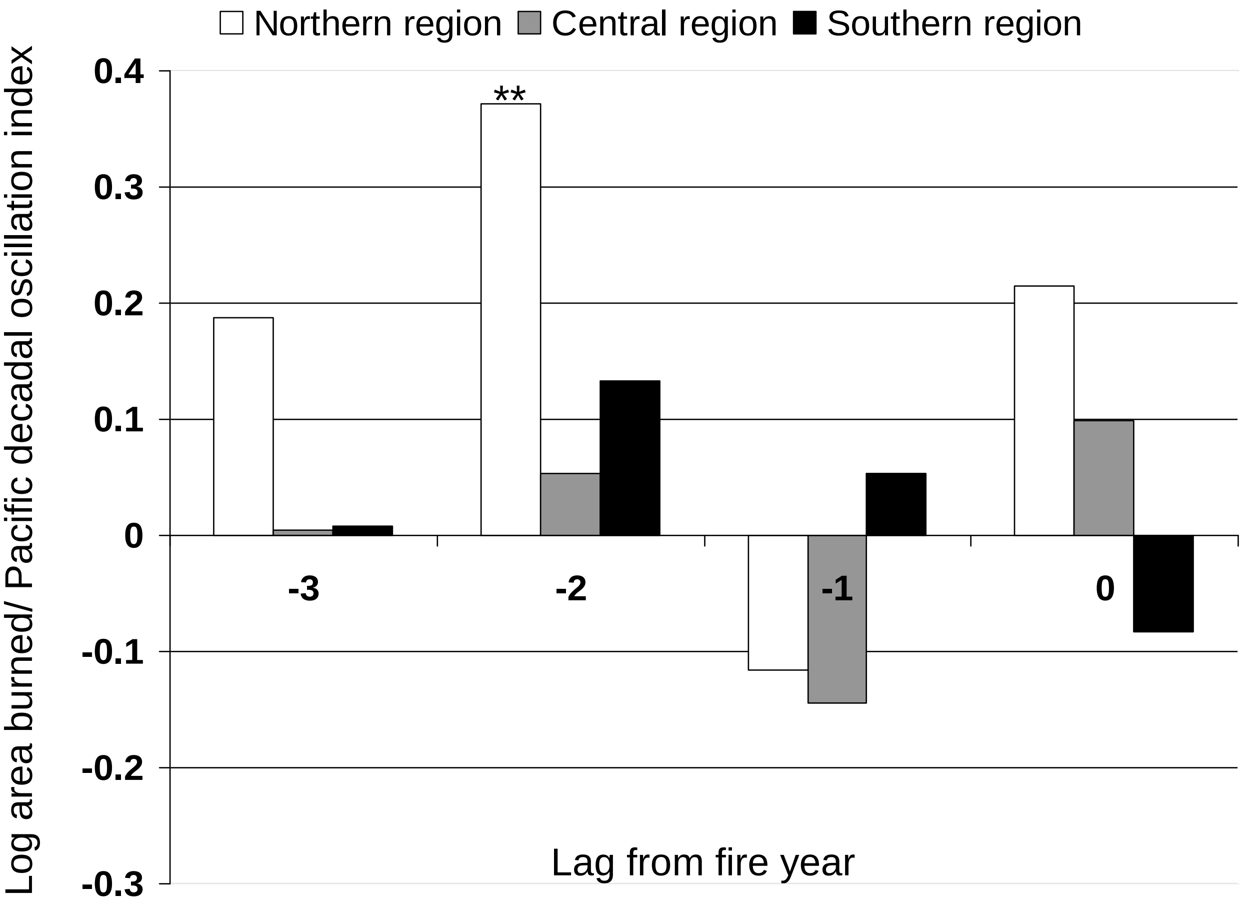

Figure 4a. Intermountain climate regions-slope estimates (in log scale) from autoregressive model using yearly burned area and winter (Dec, Jan, Feb) Pacific Decadal Oscillation Index. Slope estimates are reported from backwards selection. Slope estimates eliminated from the final model (if $p>0.10$) are reported though subsequently removed. Significance is based on p-values from the autoregressive model (1). Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

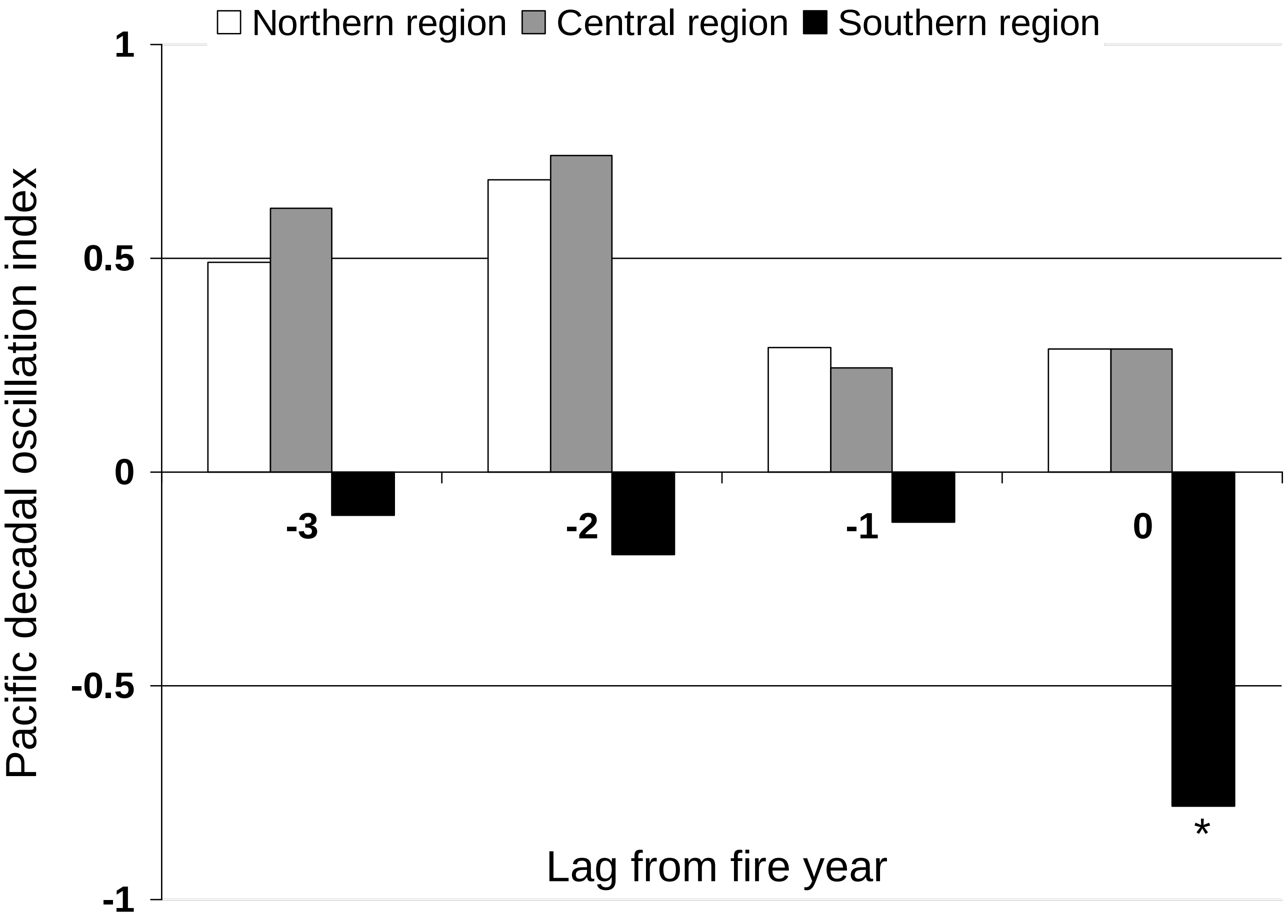

Figure 4b. Intermountain climate regions-mean winter (Dec, Jan, Feb) Pacific Decadal Oscillation Index values for the 10 highest fire years. Significance is based on Monte Carlo simulations from Superposed Epoch Analysis. Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

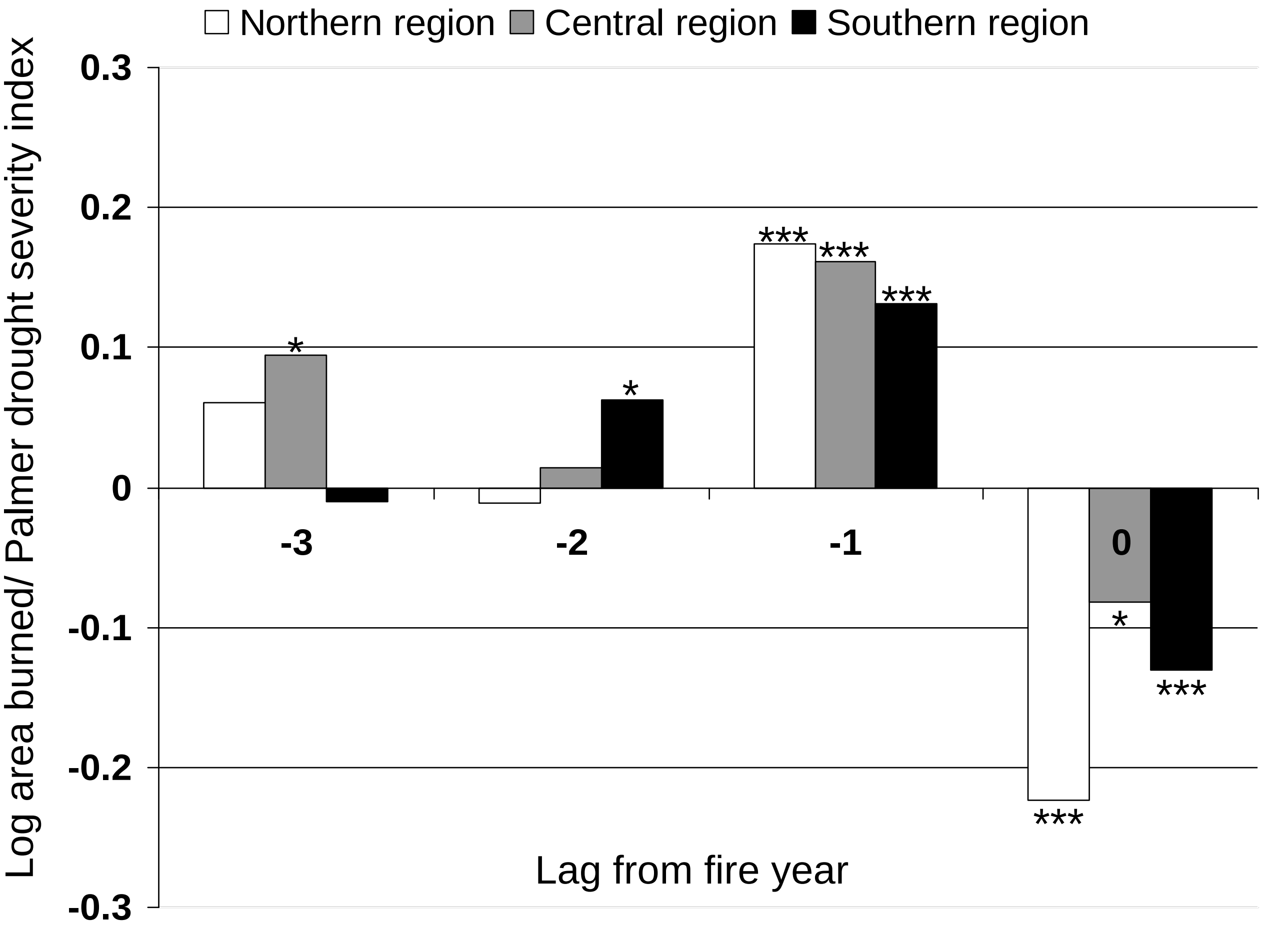

Figure 5a. Intermountain climate regions-slope estimates (in log scale) from autoregressive model using yearly burned area and monthly Palmer Drought Severity Index. Slope estimates are reported from backwards selection. Slope estimates eliminated from the final model (if p>0.10) are reported though subsequently removed. Significance is based on p-values from the autoregressive model (1). Significance at p<0.05, p<0.01, and p<0.001 are denoted with single, double, and triple asterisks, respectively.

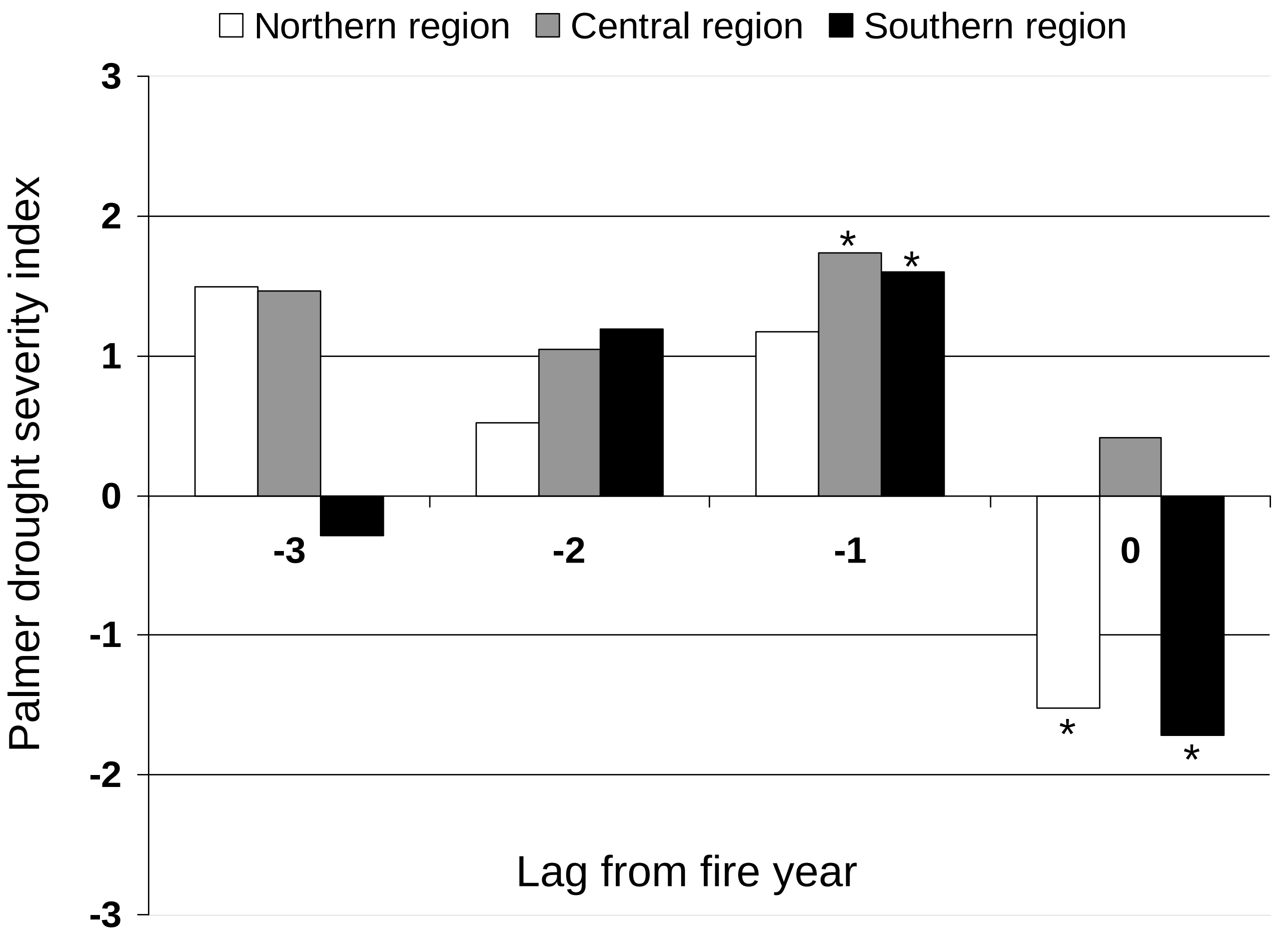

Figure 5b. Intermountain climate regions-mean monthly Palmer Drought Severity Index (PDSI) values for the 10 highest fire years. Significance is based on Monte Carlo simulations from Superposed Epoch Analysis. Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

the central and southern regions are significant ($p<0.05$). The relationship between PDSI and burned area is reversed at the 0 year lag. Both the regression model ($p<0.0001$) and the SEA ($p<0.05$) identify this negative relationship for the northern and southern regions, while only regression model shows the same negative relationship (p=0.033) for the central region.

In addition to the strong reversal identified in the relationships at the -1 year and 0 year lags, there are significantly positive relationships at the -3 year lag for the central region ($p=0.013$) and -2 year lag for the southern region ($p=0.026$). Both analyses confirm these positive relationships, however, only the regression model identifies the significance. The only real disagreement between the regression model and SEA is with respect to direction of the 0 year lag relationship for central region. The regression model indicates a significant ($p=0.032$) negative relationship, while the SEA indicates a slightly positive relationship.

## Colorado climate regions

### *SOI*

The regression model and SEA with the extensive fire years do not show similar general trends (Figures 6a and 6b). The regression model indicates positive relationships for most regions, at all lags. These positive relationships are significant at the -1 ($p=0.022$) and -3 ($p=0.008$) year lags for the CR, and 0 year lag for the AR ($p=0.046$) and PL ($p=0.02$). The SEA identifies no strong trends or significant relationships, only a weak negative relationship for the CR, PL, and RG at the -2 year lag, which the regression model shows to be negative for just the PL.

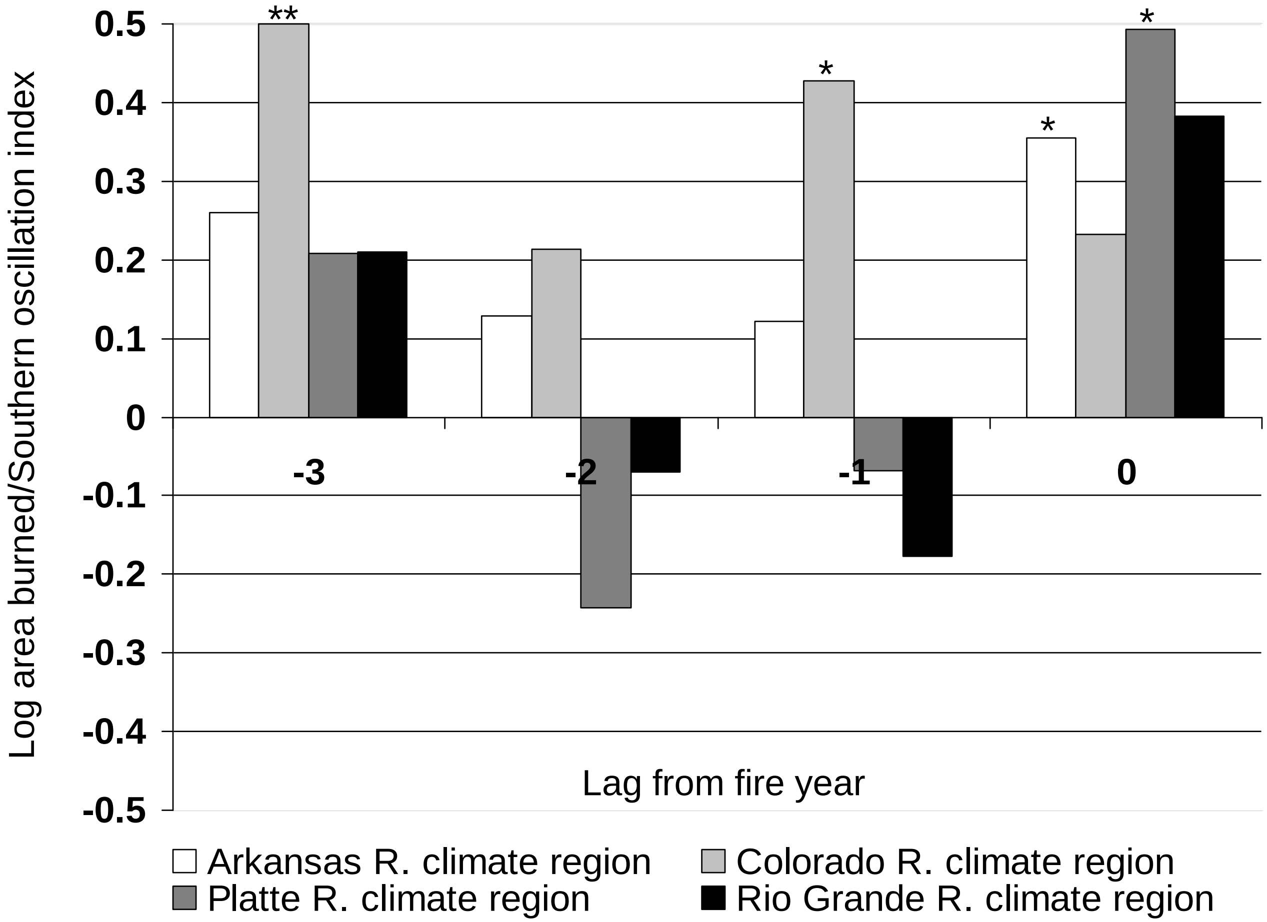

Figure 6a. Colorado climate regions-slope estimates (in log scale) from autoregressive model using yearly burned area and winter (Dec, Jan, Feb) Southern Oscillation Index. Slope estimates are reported from backwards selection. Slope estimates eliminated from the final model (if p>0.10) are reported though subsequently removed. Significance is based on p-values from the autoregressive model (1). Significance at p<0.05, p<0.01, and p<0.001 are denoted with single, double, and triple asterisks, respectively.

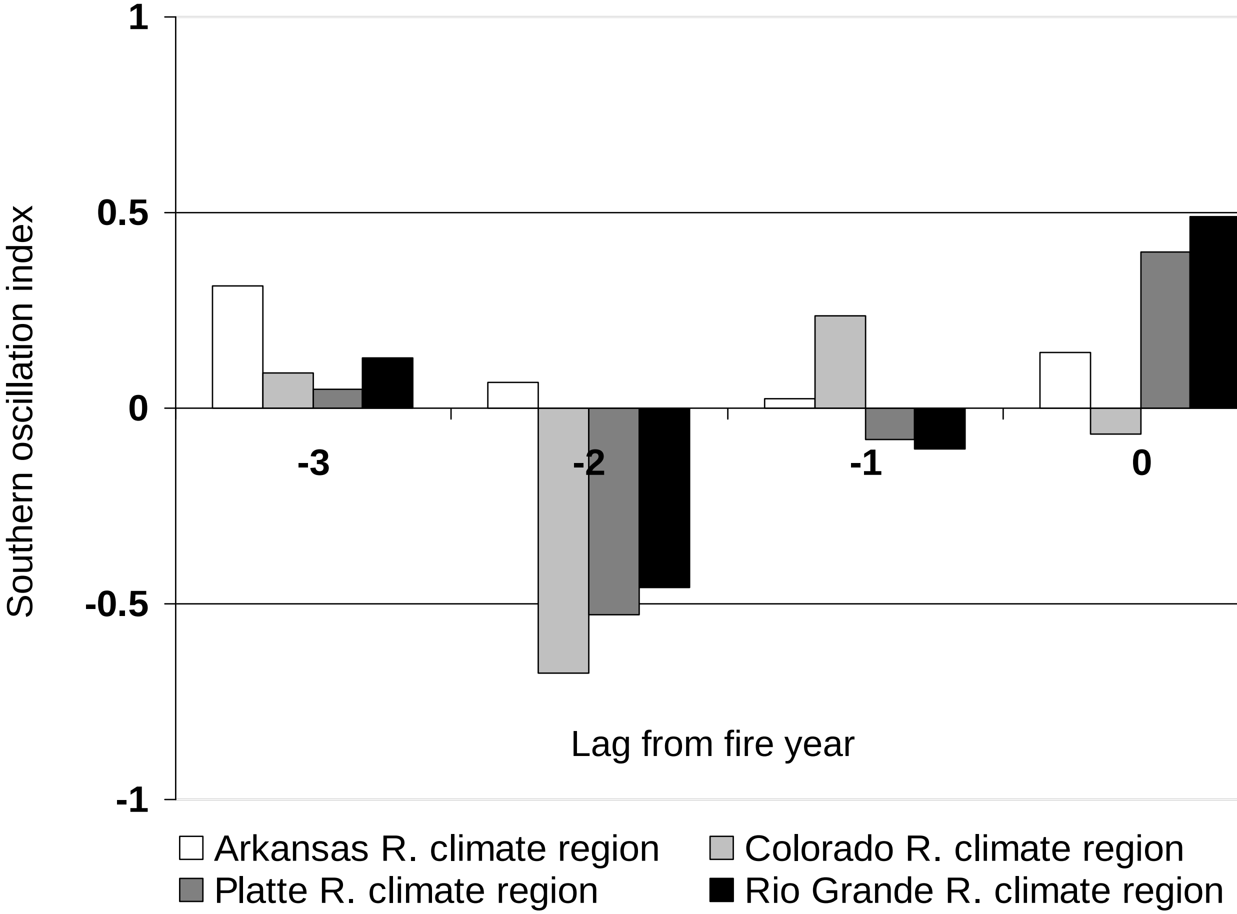

Figure 6b. Colorado climate regions-mean winter (Dec, Jan, Feb) Southern Oscillation Index values for the 10 highest fire years. Significance is based on Monte Carlo simulations from Superposed Epoch Analysis. Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

### *PDO*

I found no relationships whatsoever between PDO and burned area for any of the Colorado climate regions. As such, no figures are included.

### *SPI*

Both analyses show strong evidence for a negative relationship between SPI and widespread fire at the 0 year lag for all regions (Figures 7a and 7b). The regression model shows this relationship to be highly significant ($p<0.001$) for all regions. The SEA confirms this significant ($p<0.05$) relationship for all regions except CR. In addition to the significant relationship at the 0 year lag, the regression model identifies a significantly positive relationship for AR ($p=0.002$) and PL ($p=0.041$) at the -1 year lag and for RG ($p=0.049$) at the -2 year lag. The SEA only verifies this significant ($p<0.05$) positive relationship for the AR at the -1 year lag.

### *PDSI*

The relationships between PDSI and increased burned area for all regions are very similar to those using SPI (Figures 8a and 8b). Again, the regression model shows a negative relationship at the 0 year lag which is highly significant for AR, CR, PL, ($p<0.0001$) and RG ($p=0.003$). Only AR ($p<0.01$) and CR ($p<0.05$) are significant at the 0 year lag using SEA. As with SPI, the relationships change to significantly positive at the -1 year lag for AR ($p=0.0001$) and PL ($p=0.016$). The AR is the only region to show this same significant ($p<0.01$) relationship from the SEA. This positive then negative relationship at the -1 and 0 year lag with both PDSI and SPI is only evident in both analyses for the AR. The PL shows a positive then negative relationship with both PDSI and SPI, but significance is only identified by the regression model.

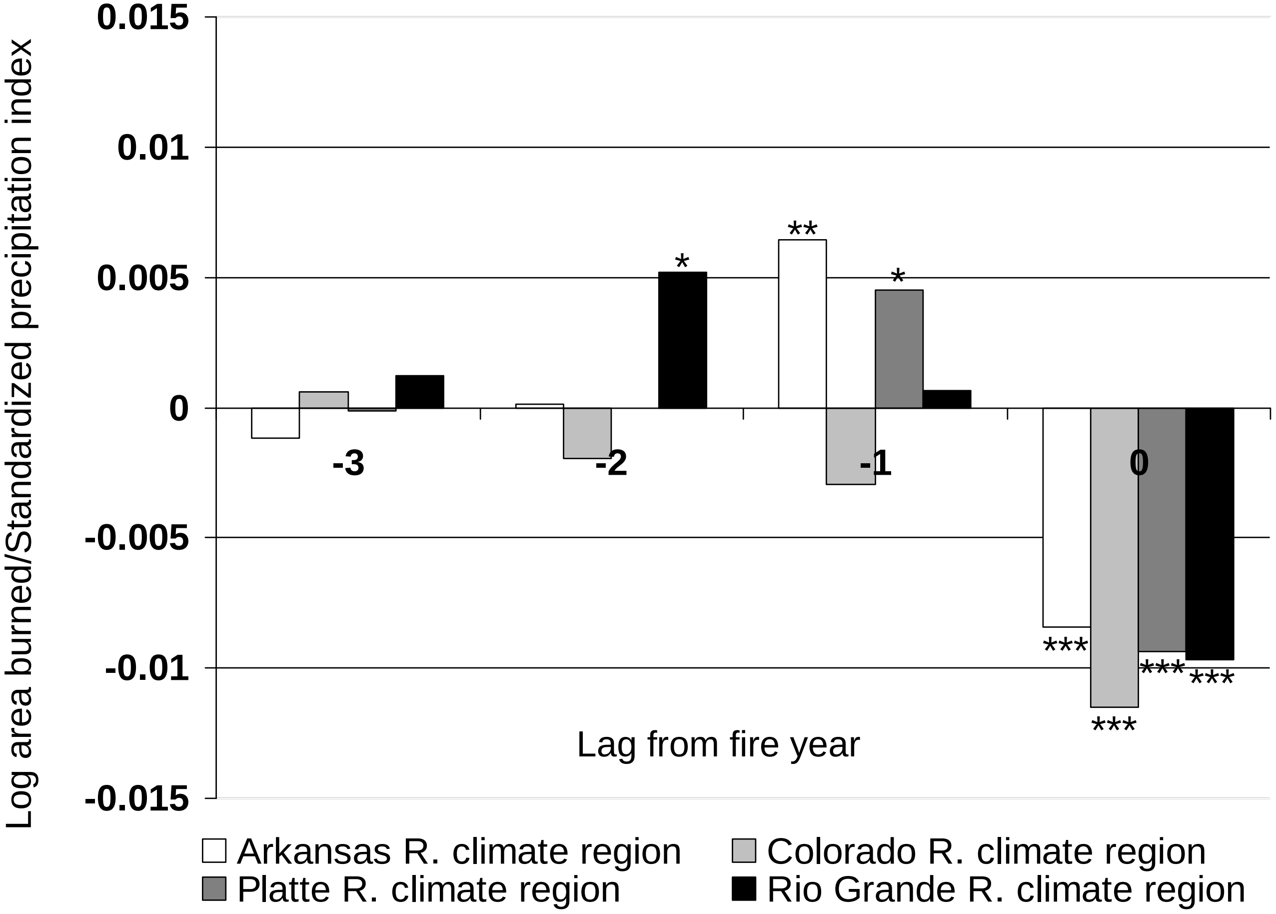

Figure 7a. Colorado climate regions-slope estimates (in log scale) from autoregressive model using yearly burned area and 9-month Standardized Precipitation Index. Slope estimates are reported from backwards selection. Slope estimates eliminated from the final model (if p>0.10) are reported though subsequently removed. Significance is based on p-values from the autoregressive model (1). Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

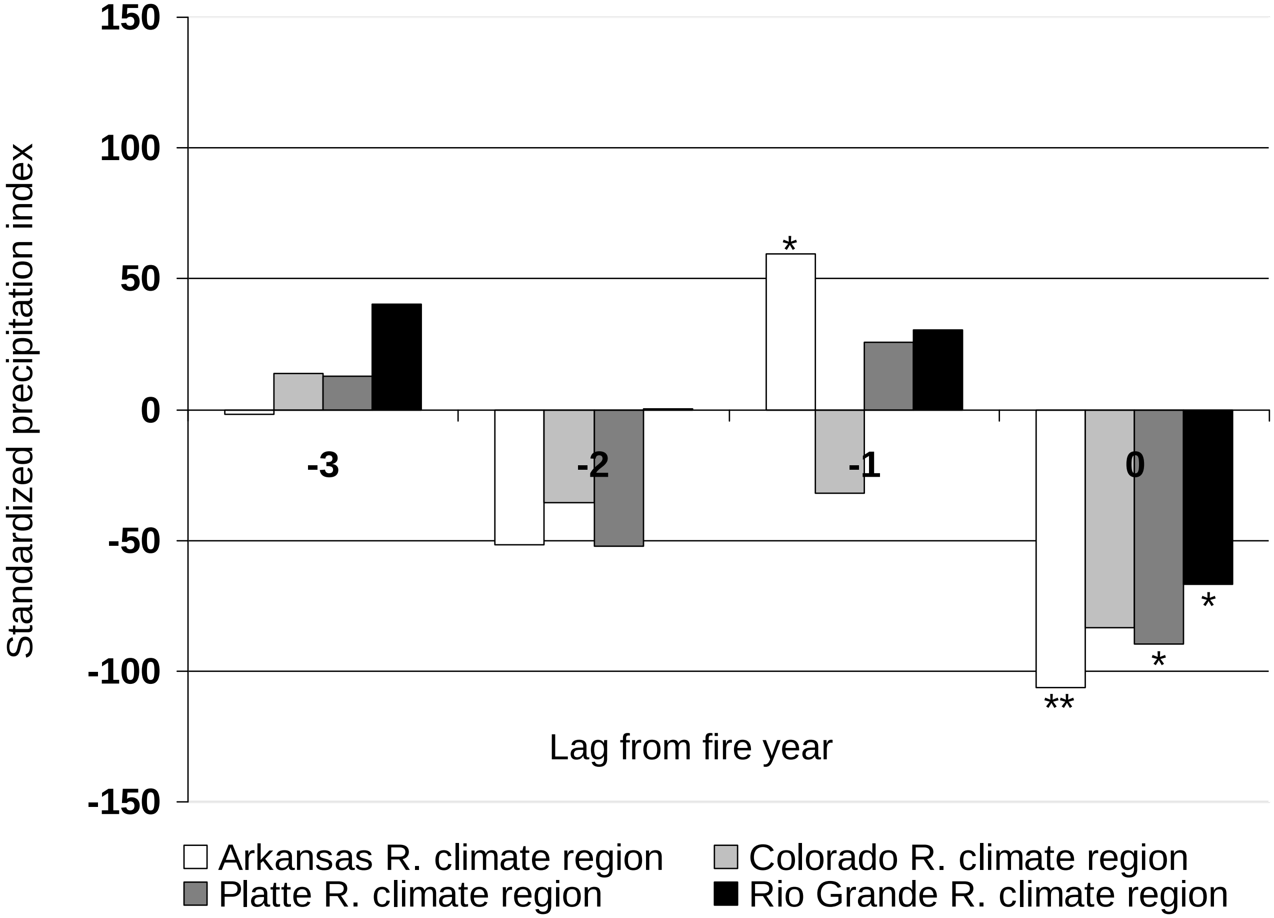

Figure 7b. Colorado climate regions-mean 9-month Standardized Precipitation Index values for the 10 highest fire years. Significance is based on Monte Carlo simulations from Superposed Epoch Analysis. Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

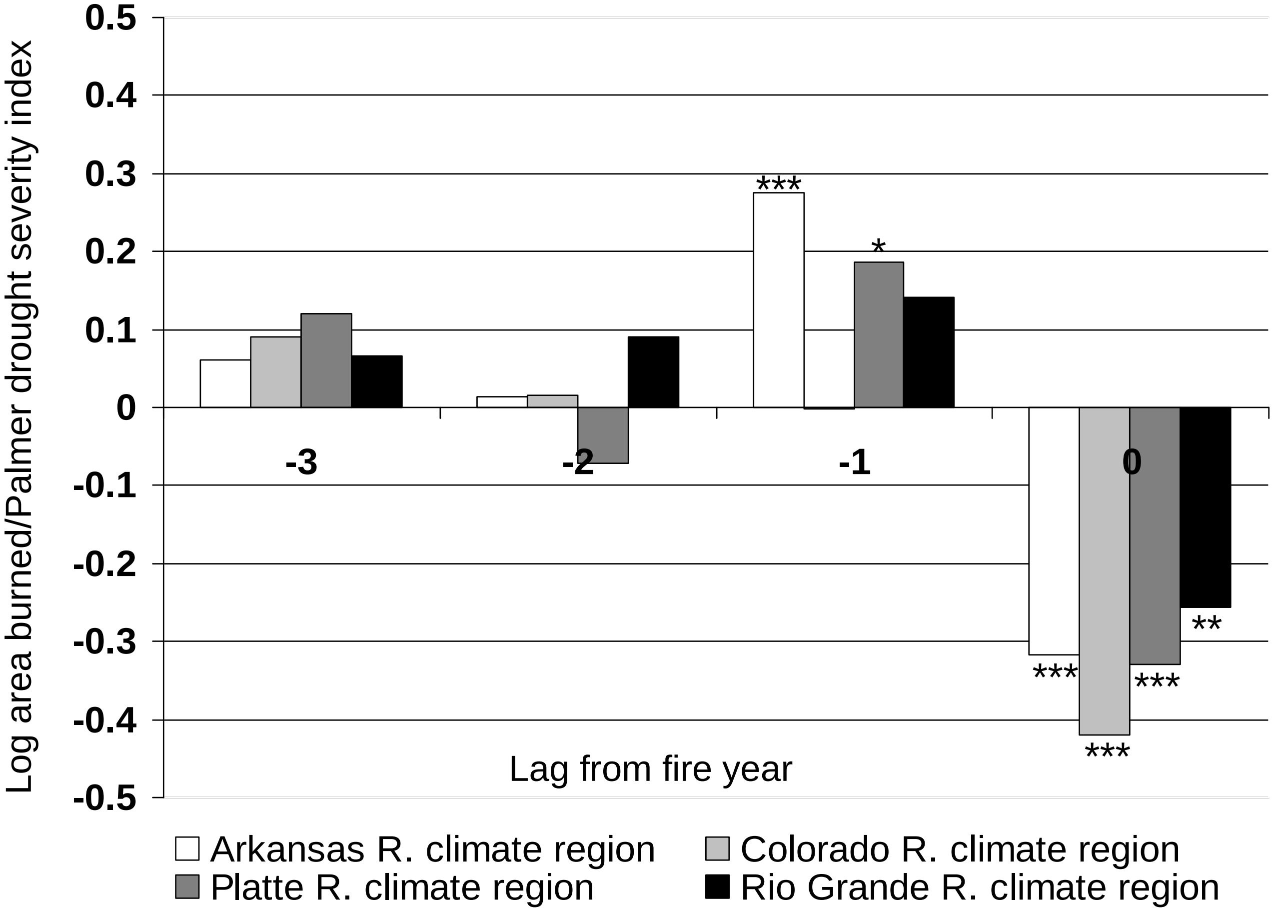

Figure 8a. Colorado climate regions-slope estimates (in log scale) from autoregressive model using yearly burned area and monthly Palmer Drought Severity Index. Slope estimates are reported from backwards selection. Slope estimates eliminated from the final model (if p>0.10) are reported though subsequently removed. Significance is based on p-values from autoregressive model. Significance at p<0.05, p<0.01, and p<0.001 are denoted with single, double, and triple asterisks, respectively.

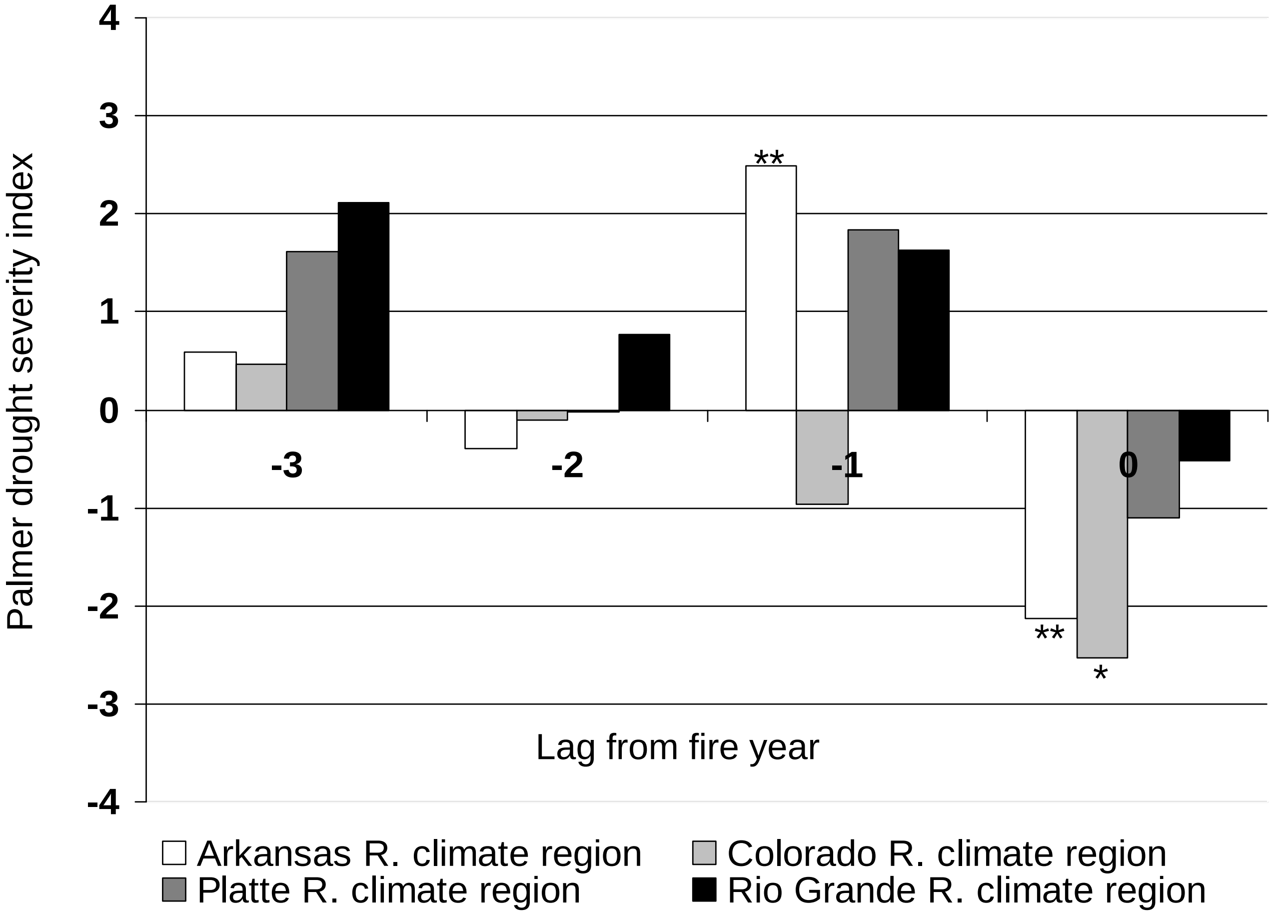

Figure 8b. Colorado climate regions-mean monthly Palmer Drought Severity Index values for the 10 highest fire years. Significance is based on Monte Carlo simulations from Superposed Epoch Analysis. Significance at $p<0.05$, $p<0.01$, and $p<0.001$ are denoted with single, double, and triple asterisks, respectively.

## Discussion

### ENSO-burned area relationships

The variability in climate throughout the Intermountain West is indeed expressed in the regional differences in climate/fire relationships found in this study (Table 3). This was not unexpected. Previous work by Simard et al. (1985) demonstrated regional differences throughout the entire US in the relationships between fire activity and ENSO. The only strong connection they found was in the southeastern US, indicating that fire activity decreased during El Niño events. Swetnam and Betancourt (1990) confirmed the same relationship for the southwestern US, and further identified that increased burned area corresponds with La Niña conditions.

The results from this study are consistent with my expectations regarding the regional differences in the relative importance of ENSO in relating to burned area. For the Intermountain climate regions, the only statistically significant relationships found with SOI and burned area were in the southern region (Figure 3a and 3b). The reduced moisture availability in the Southwest associated with positive SOI, or La Niña conditions, most likely explains the positive relationship at the 0 year lag. This relationship was expected based on previous work (Swetnam and Betancourt 1990). What may be of more interest is the significant lagged relationship with antecedent SOI identified in Figure 3a. This shows that years with increased burned area in the Southwest tend to follow 2 consecutive years of El Niño conditions. This verifies a similar pattern in the Southwest identified in previous studies using both

Table 3. Summary table identifying only significant ($p<0.05$) relationships between burned area and all climatic indices from either the regression model or the SEA with extensive fire years. The direction of the relationships is indicated by positive (+) or a negative (-) sign. The abbreviations for the climate indices are as follows: PDO (Pacific Decadal Oscillation), PDSI (Palmer Drought Severity Index), SOI (Southern Oscillation Index), and SPI (Standardized Precipitation Index).

| | *Intermountain climate regions* | | | | | | *Colorado climate regions* | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Northern region | | Central region | Southern region | | | Arkansas River climate region | | Colorado River climate region | | Platte River climate region | | Rio Grande climate region |
| Lag year | PDO | PDSI | PDSI | SOI | PDO | PDSI | SOI | PDSI or SPI | SOI | PDSI or SPI | SOI | PDSI or SPI | PDSI or SPI |
| -3 | | | + | | | | | | + | | | | |
| -2 | + | | | - | | + | | | | | | | + |
| -1 | | + | + | - | | + | | + | + | | | + | |
| **0** | | - | - | + | - | - | + | - | | - | + | - | - |

dendrochronologically based fire dates (Grissino-Mayer and Swetnam 2000; Swetnam and Betancourt 1998), and dates based on documentary fire records (Kitzberger et al. 2001). The explanation offered by these studies, that the enhanced production of fine fuels under El Niño conditions leads to more widespread fire due to increased amounts of available fuel under drier La Niña conditions is confirmed in this study.

This pattern of more widespread fire following the reversal in phases of ENSO does not appear to hold true for the central region. Although the relationships between SOI and yearly burned area in the central region are only weakly statistically significant, they warrant some discussion. The SOI/burned area connection at the 0 year lag is opposite that of the southern region, indicating that more area burns under El Niño conditions. This is difficult to explain given that the latitude at which ENSO effects are reversed runs right through the middle of central region, or northern Great Basin (Dettinger et al. 1998). This is further compounded by the fact that the burned area in the central region shows the same negative relationship with SOI at the -2 year lag that the southern region does.

One plausible explanation for the negative SOI/fire relationship in the central region might be that increased burned area in the Great Basin area may be associated with more prolonged periods (1-2 years) of the warm phase of ENSO. This interpretation is not supported in any previous work that I am familiar with. In fact, these findings, and the suggested interpretation, contradict the proposition made by Westerling and Swetnam (2003) that increased burned area in what they call the Mountain states (Nevada, Utah, Colorado) coincides with La Niña conditions (warm phase of ENSO).

Increased burned area in the Colorado climate regions seems to be related quite differently to SOI. Figure 6a shows that antecedent SOI is only related to burned area in the CR. This suggests that prolonged (1 to 3 years) La Niña conditions lead to more widespread fire on the western slope of the Colorado Rockies. Increased burned area on the eastern slope of the Colorado Rockies (AR and PL) is only related to contemporaneous La Niña conditions, which for this area is correlated with warmer, drier springs (Veblen et al. 2000). Previous work on fire/SOI relationships (Veblen et al. 2000) also shows that contemporaneous La Niña conditions correspond with dendrochronologically based fire dates for the eastern slope of the Colorado Rockies. However, for the same area, Donnegan et al. (2001) found that antecedent SOI (3 years prior) was negatively related to dendrochronologically based fire dates, which I did not find in this study.

Both Veblen et al. (2000) and Donnegan et al. (2001) explain that the effect of El Niño (negative SOI) on the eastern slope of the Colorado Rockies is similar to that in the Southwest meaning increased spring precipitation and reduced spring and fall temperatures. As a result, they hypothesize that these conditions stimulate production of fine fuels, which when followed by dry conditions create more available fuel to aid widespread fire. However, neither study shows the strong connection between more widespread fire and the reversal in phases of ENSO that previous studies (Kitzberger et al. 2001; Swetnam and Betancourt 1990) have shown in the southern Intermountain West. Veblen et al. (2000) did not find a significant relationship between antecedent SOI and widespread fire years, and Donnegan et al. (2001) found no significant relationship with contemporaneous SOI. These discrepancies, along with the findings from my study, suggest that the ENSO/fire connection is not as strong in Colorado as it is in the Southwest.

The fact that the SOI/fire relationships identified in the regression model were not confirmed using the SEA (Figure 6b) tends to detract from the confidence in the regression model results. However, the lack of any substantial relationships from the SEA results brings up an interesting point. Choosing the 10 most extensive fire years out of a 46 year fire statistics time series most likely includes some years in which burned area was not extensive enough to detect SOI signals. If I had chosen to identify less than 10 extensive fire years the sample size for constructing mean SOI conditions around the set of fire years would be reduced, which could lead to increased variance among the means and wider confidence intervals. As a result, SEA may not be an appropriate method for looking at SOI/fire relationships for a shorter fire statistics time series.

No such relationship, either positive or negative, with SOI and burned area can be drawn from this data with respect to the northern region. The weaker signal of ENSO in the northwestern US described by Dettinger et al. (1998) most likely explains this lack of an ENSO/fire relationship. This is also supported by a non-existent connection between SOI and dendrochronologically based regional fire years from Montana (Littell 2002).

### PDO-burned area relationships

As expected, the northern region did have a strong positive relationship with PDO (Figure 4a). Both the regression model and the SEA confirm this relationship to be strongest at the -2 year lag. (However, only the regression model identifies this lag as significant). The warm phase of PDO (positive PDO index) corresponds with lower precipitation and reduced snowpack in the northwestern US (Mantua et al. 1997). This positive -2 year lag relationship with the PDO index suggests that more widespread fire years may be linked to a drying effect on the fuels initiated several years previous by the warmer phase of PDO. Littell (2002) found a similar positive lagged relationship between the PDO index and dendrochronologically based fire years in Montana. However, the only significant relationship he found used regional fire years that occurred just during the warm phase of PDO.

In addition to the lagged relationship detected in the northern region, PDO appears to be associated with widespread fire years in the southern region (Figure 4b). At the 0 year lag, the SEA indicates this relationship to be significantly negative, while the regression model indicates a weakly negative and non-significant relationship. Regardless of this discrepancy between methods this negative relationship offers compelling implications. First, it shows that the cool phase of PDO, which tends to cause warmer, drier conditions in the Southwest, does coincide with widespread fire years. This is consistent with the previously mentioned strong positive (La Niña) SOI/fire relationship at the 0 year lag for the southern region. Second, the negative PDO/fire relationship in the southern region is the possible signature of an interaction between PDO and ENSO in the burned area data. It is believed that the phases of PDO can affect the strength of ENSO events (Westerling and Swetnam 2003). In the Southwest, it appears that the cool phase of PDO can strengthen the effect of a La Niña event. In other words, years under the cool phase of PDO and the warm phase of ENSO (La Niña) can be even warmer and drier than La Niña conditions alone. Given that yearly burned area in the southern region is significantly related to positive SOI and negative PDO, it is very likely that the interaction of these phases of PDO and ENSO will likely lead to years with even more widespread fire (Westerling and Swetnam 2003).

The lack of agreement in the results from regression model and SEA with respect to the PDO index most likely reflects the longer temporal scale of PDO. The fact that the SEA only looks at mean PDO conditions around 10 fire years may limit the ability of the analysis to detect the more long term changes in the phases of PDO. The regression model may be better at detecting these longer changes in phase, but may not be optimal because it is looking at interannual PDO/fire relationships. Perhaps a method that is designed to look at decadal changes in burned area is more appropriate for assessing PDO/fire relationships.

### Moisture availability-burned area relationships

The fact that at the Intermountain scale the southern region is the only region to show a significant relationship at the -1 or 0 year lag, using either the PDO index or SOI, limits the utility of these indices to relate PDO or ENSO to near term yearly burned area for the central and northern regions. The PDSI appears to have far better connections with near term burned area for not only the northern and central regions, but the southern region as well (Figures 5a and 5b). The highly significant positive (indicating wet conditions) relationships at the -1 year lag (Figure 5a), coupled with the significantly negative (indicating drought conditions) relationships at the 0 year lag, suggest that increased burned area for all regions is associated with a wet/dry sequence. Previous work (Swetnam and Betancourt 1998; Westerling and Swetnam 2003) has only identified this wet then dry association with more widespread fire for the Southwest, and to a certain extent, Colorado (Veblen et al. 2000), based on both yearly burned area statistics and dendrochronologically reconstructed fire dates. As with the explanation of the El Niño/La Niña sequence, this wet/dry sequence is most likely associated with increased burned area because of the increase in available fuel following the dry period.

The SEA results, and to a lesser extent the results from regression model, with PDSI (Figures 4a and 4b) suggest that this dry period at the 0 year lag is less important in the central region. This suggestion differs from my expectation that current drought conditions would be related to increased burned area throughout the Intermountain West. Westerling et al. (2003) confirm this lack of a strong relationship between increased burned area and contemporaneous climate for the Great Basin area. I submit that this lack of relationship at the 0 year lag for the central region indicates that this area may be dry enough to burn most years, but what leads to increased burned area is the production of fuel associated with the antecedent moisture conditions. Perhaps the explanation behind this relationship with antecedent moisture and not with contemporaneous moisture is in part due to the abundance of cheatgrass (*Bromus tectorum*) in the Great Basin area (Humphrey and Schupp 2001). Cheatgrass is an annual, which could allow for it to take advantage of the increased moisture by producing more seed for future generations. The establishment of these future generations adds to the fuel load, creating a potential for increased area burned following a year of increased moisture availability. This could also explain why this study identifies that increased burned area in the Great Basin area seems to be associated with El Niño conditions. Addressing this hypothesis will most likely require finer spatial resolution than that of this study.

The apparent wet/dry sequence in the northern region is more anomalous relative to reports from previous studies. Westerling and Swetnam (2003) proposed that increased burned area in the Northwest tends to be associated with more prolonged dry periods. The fact that in this study I found a significantly positive -2 year lag with PDO also supports their finding. The strong and very significant wet then dry relationship between PDSI and yearly burned area in the northern region seems to contradict the notion that increased burned area is associated with prolonged dry periods. This relationship with a prolonged dry period is not seen in Figures 5a or 5b at either the -2 or -3 year lag for the northern region. Apparently, increased burned area in the northern region depends on the same progression of increased production of fine fuels, followed by subsequent drying, to create more available fuel, as is shown for the southern regions. However, the lack of a strong relationship with antecedent moisture from the SEA suggests that during the most extensive fire years in the northern Intermountain West, only current year drought conditions are important.

The Colorado climate regions also show that a wet/dry sequence is important in relating burned area to climate. However, there appears to be a stark contrast in the relative importance of this wet/dry sequence between the eastern and western slopes of the Colorado Rockies. The relationships between both indices of moisture availability (PDSI and SPI) and the CR, which encompasses the western slope, show that increased burned area is only related to contemporaneous dry conditions. On the eastern slope, the AR and PL, and to a lesser extent RG, show that increased burned area is related to the sequence of increased moisture availability at the -1 or -2 year lag then reduced moisture availability at the 0 year lag.

This difference in the dependence of antecedent moisture availability between the eastern and western slopes of the Colorado Rockies suggests that there are different processes that lead to more widespread fire on each slope. On the eastern slope fine fuel accumulation may be more important in determining more widespread fire years, whereas drought alone may be more important on the western slope.

Even within the eastern slope of the Colorado Rockies this study identifies some notable variation. The only positive relationship I found for RG was at the -2 year lag with the regression model using SPI. In addition, the relative strength in the positive relationship at the -1 year lag for the AR is greater than that of the PL. This is verified by the higher significance in the relationships with both SPI and PDSI, and the fact that both the regression model and SEA confirm significant relationships at the -1 year lag for the AR (Figure 7a, 7b, 8a, 8b). This suggests that in addition to the east-west disparity with respect to the importance of antecedent moisture in Colorado, there may also be a north-south gradient in importance of antecedent moisture. This study is not the first to identify such a gradient for the eastern slope of Colorado. Brown and Shepperd (2001) found that antecedent moisture at the -1 and -2 year lags was associated with dendrochronologically based fire dates in southern Colorado. However, for sites in central Colorado and southern Wyoming antecedent moisture was not related to fire dates, only contemporaneous drought conditions. They attribute these findings the fact that in the northern sites fuel was not limiting, thus fuel accumulation was not as necessary to allow widespread fire. This is similar to the argument I present for the findings on the western slope of the Colorado Rockies.

The fact that the relative importance of antecedent moisture in leading to widespread fire varies geographically is most likely a result of differences in forest types. Previous work (Sherriff et al. 2001) has shown that antecedent moisture was not associated with fire years in the high elevation subalpine forests of Colorado. However, Sherriff et al. (2001) did find that fire years were associated with contemporaneous drought. The explanation they offered for this lack of a relationship with prior moisture conditions is that the persistent snowpack in these higher elevation forests usually allows for fine fuel accumulation in most years. It is my contention that the dominant fire regimes of the forests on western slope, and to a lesser extent the north-eastern slope, of the Colorado Rockies resemble those of the subalpine forests studied by Sherriff et. al (2001), thus explaining the geographic differences I found in this study with respect to antecedent moisture. Further research is needed to directly assess how climate/fire relationships change between different vegetation types.

As expected, the finer scale analysis (Colorado climate regions) did yield variations that were masked at a larger scale (Intermountain climate regions). The climate/fire relationships observed when I included Colorado was in both the central and southern regions at the Intermountain scale did not differ substantially from the relationships reported from each region without Colorado. This emphasizes the importance of performing an analysis of climate/fire relationships at finer spatial scales. The differences in the climatic signals of SOI and the moisture indices in the responses of burned area between the western and eastern slopes of the Colorado Rockies offer a compelling contrast that would not have become apparent at the Intermountain scale. Furthermore, the climate/fire relationships identified for the climate regions in Colorado appear to be somewhat unique compared to the relationships associated with each of the surrounding Intermountain regions.

I would suspect that a finer scale analysis of climate/fire relationships throughout the Intermountain West would uncover some other important exceptions to the regional relationships identified in this study. This may be particularly true in extensively mountainous areas where an east-west slope ‘rain shadow’ effect exists. The east slope of the Rockies in Montana and to some extent Wyoming could have very different climate/fire relationships from those for the Idaho Rockies. By aggregating burned area over the all of Idaho, Montana and Wyoming the ability to detect this potential east-west slope difference is lost. This could be an explanation for the lack of a more long term drought signal in the burned area for the northern region. Perhaps future research at a finer spatial scale could indicate whether or not these differences are realized in climate/fire relationships.

### Management implications

The findings from both the Intermountain and the Colorado climate regions carry considerable importance with respect to fire management in the Intermountain West. The relationships identified can be used by fire managers for planning. This is especially true given our increasing ability to predict climatic anomalies, such as drought and more extreme fluctuations in ENSO (Clarke and Van Gorder 2001; Panu and Sharma 2002). Management actions, along with decisions regarding staffing levels and equipment deployment could change depending on previous and current climatic conditions. For example, the climatic conditions for most regions leading up to and including the 2000 fire season were very similar to those identified in this study as relating to more widespread fire.

The signals of increased potential burned area for the 2000 fire season were evident in the climate indices used in this study. The positive PDSI and SPI values for 1999, and in some regions 1998, indicated wetter than average conditions just prior to 2000 for most regions. In addition, the positive SOI in 1998 revealed the presence of a substantial El Niño event. Both of these indices pointed towards a likelihood for increased fine fuel accumulation due to antecedent precipitation, especially in the southern region. The positive winter SOI value in 1999 and 2000 indicated that La Niña conditions followed this El Niño event. To complete the wet then dry sequence, in the spring of 2000 the threat of substantial drought over much of the Intermountain West was becoming more apparent.

Had the climate/fire relationships identified in this study been available to resource managers prior to the 2000 fire season, management decisions could have incorporated this increased potential for widespread fire into their planning. Managers might have chosen to apply prescribed fire treatments or wildland fire use extremely judiciously. This highlights the importance of using both long-term (climate) and short-term (weather) conditions in planning for prescribed fire and wildland fire use. In addition, if funding could have been made available, fire managers may have benefited from increased staffing levels. The increased staffing levels could allow for quicker response in initial attack and accelerated fuel reduction activities in high risk areas.

The relationships identified in this study as leading to increased burned area cannot be taken as absolute predictive relationships. The relationships are better utilized as guides to aid managers in decision making. Extreme drought on its own, which for most regions was not recognized in this study as relating to widespread fire, has tremendous potential for influencing burned area. The 2002 fire season is a good example of how extreme drought led to extensive burned area. Using the relationships from this study, extensive burned area in 2002 would not have been expected. There was no wet then dry reversal evident from either PDSI or SOI prior to the 2002 fire season. The average or slightly less than average moisture availability in 2001, followed by extreme drought in 2002, did not seem to allow for much fuel accumulation. However, the burned area for every region in 2002, like 2000, was among the highest 10 years for the entire fire statistics time series we used.

The 2002 fire season draws attention to an important point in determining climate/fire relationships. Extreme drought may supercede all other climate/fire relationships. This is evident in the regional widespread fire years identified by previous fire history studies, such as 1851 in Colorado and the Southwest (Brown et al. 1999; Swetnam and Baisan 1996), and 1800 in Montana (Littell 2002). Both of these years were extreme drought years that were preceded by average moisture availability in 1850 and 1799, for their respective regions (Cook et al. 1999). In this sense, the 2002 fire season was not unprecedented relative to historic widespread fire years.

In addition to the management implications associated with preparing for years with increased area burned, the relationships identified in this study can be used for planning management actions during less extensive fire years. For example, a dry year followed by a wet winter/spring may create conditions where increased fire use, either prescriptively or through wildland fire use, may be more appropriate. Furthermore, during potentially less extensive fire seasons a greater proportion of the suppression crews could be assigned to fuel treatment activities.

## Conclusion

The examples of the 2000 and 2002 fire seasons, along with the high degree of correspondence between the climate/fire relationships established in this study and those from fire history studies, suggest that climate continues to play a similar role as it did historically in determining widespread fire years. These findings are especially intriguing given the dramatic changes we have seen in the 20th century with respect to climate (Mann et al. 1999) and vegetation/fuels (Brown et al. 1999; Cooper 1960). Furthermore, the similarity between current and historical relationships is surprising given that the current relationships are based on burned area and the historical relationships are based reconstructions of point occurrences of fire. This similarity is contrary to what I expected, and serves as one piece of evidence suggesting that our current fire regimes are not that different from the historical range of variability.

The climate/fire relationships shown in this study identify the regional and temporal dependence of climatic processes on yearly burned area in the Intermountain West. By testing the relationships against each of the climatic indices (SOI, PDO, PDSI/SPI) I have identified variation in the relative importance of the climatic processes that lead to widespread fire throughout the Intermountain West. The most definitive relationships between climate and burned area are in the southern Intermountain West. Both PDSI and SOI confirm that the same sequence of lagged and current climate leads to widespread fire. In the northern Intermountain West the connection between burned area and both PDO and PDSI also shows a response to multiple climatic signals. Apparently, only moisture availability, as indicated by PDSI, has strong connections with burned area in the central Intermountain West.

As with the southern Intermountain West, signals of both SOI and PDSI are evident in the burned area for Colorado. The lagged relationships with PDSI and SPI, and the consistency between the relationships with contemporaneous SOI and PDSI, suggest that the climate signal in the burned area is strongest on the eastern slope of the Colorado Rockies. The lagged relationship with SOI for western slope, which is not confirmed by either PDSI or SPI, suggests a weaker connection between climate and burned area.

Regardless of the strength in the connections between burned area and climate, the findings from the Colorado climate regions emphasize the importance of finer scale information. In terms of planning fire management actions, these findings suggest that the scale at which the relationships identified in the study are applied is critical. The regional climate/fire relationships may not be the most accurate relationships to incorporate into planning for an individual national forest. A more appropriate use of regional relationships is for planning at the regional scale.

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