Historic and future wildfires in the Southern Rockies Ecoregion, USA

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Abstract

Wildfires play a necessary and formative role in the processes that have created the Southern Rockies Ecoregion (SRE). The occurrence of wildfires is influenced mainly by precipitation and temperature, which control fuel growth and fuel moisture. Climate change in the SRE has already been shown to increase temperatures, bringing warmer springs with earlier runoff and longer fire seasons. It is critical to quantify likely changes in burned areas because increasing wildfire extent and intensity would affect safety, livelihoods, and landscapes in multiple ways. We summarized the historical wildfire record in the National Forests of the SRE from 1930 to 2006 and showed an order of magnitude increase in the annual number of fires recorded over the full time period and in the occurrence of large fires since 1970. Using temperature and precipitation variables, our model of percent burned area in the SRE accounts for 48% of the variability over the period 1970-2006. Applications of this model with data from two downscaled GCMs, for IPCC SRES climate scenarios A2 and B1, and for the time periods 2010 to 2040 and 2041 to 2070 generally show increasing trends in burned areas, with the most severe increases occurring during the second time period. The results provide important information to natural

resource managers and planners to assist in wildfire management, land use planning, and water resource management.

Additional keywords: wildfires, climate change, downscaled climate data, fire model, Southern Rockies Ecoregion.

1. Introduction

Wildfires play a formative role in ecosystems of the Southern Rockies Ecoregion (SRE) by affecting plant and animal ecology. In human terms, the loss of life and damage to property and resources that wildfire can cause, as the 562 km^2 Hayman Fire demonstrated in 2002, is substantial (Graham, 2003). Property losses from wildfire are increasing as available rural land is developed; indeed, 39% of houses in the conterminous US are now in the wildland-urban interface (Radeloff *et al.*, 2005; Theobald and Romme, 2007). Other effects and resource losses can be substantial. For example, wildfires can alter geomorphology and hydrology resulting in increased erosion and reduced water quality (EPA, 2000; Moody and Martin, 2001; Shakesby and Doerr, 2006), and subsequent costly maintenance problems for water storage and processing facilities (Palmieri *et al.*, 2001; Graham, 2003). The increasing risk to property and other resources, and the growing need to use fire wisely to maintain ecological health, both point to the importance of understanding how changes in the principal drivers of wildfire may alter the likelihood of future wildfires.

The occurrence and natural extent of wildfire is mainly controlled by weather, in particular, temperature and precipitation, which affect fuel growth and moisture content (Gedalof *et al.*, 2005; Cary *et al.*, 2009). Climate change, by altering weather patterns, is likely to affect the natural regimes of fire extent, frequency, and severity (Flannigan *et al.*, 2005). Coarse scale studies suggest that global climate change will alter spatial distributions of wildfires, causing increased likelihood of fires in some areas and decreases in other areas (Krawchuk *et al.*, 2009).

In the western US, patterns of fire occurrence are strongly related to seasonal changes in precipitation, temperature, and soil moisture, which reflect moisture availability and the demands of evapotranspiration (Bartlein, 2003). During the 1980s and 1990s, warmer winter and spring temperatures caused snow to melt earlier and spring runoff to end sooner. During this time period, summers in the West became longer and drier, fire seasons lengthened (Westerling *et al.*, 2006), the number of days of high fire danger in much of the West increased (Brown *et al.*, 2004), and the numbers of wildfires increased due to changes in annual and seasonal precipitation and temperature (Westerling *et al.*, 2006).

The size of burned areas in the southwestern US is related to the climatic patterns of the El Nino Southern Oscillation (ENSO) (Swetnam and Betancourt, 1990), which is characterized by relatively moist El Niño years followed by drier La Niña years. For example, in the ponderosa pine forests of the Colorado Front Range, herbaceous vegetation grows more prolifically during El Niño years of relatively high precipitation rates. This additional vegetative growth provides fine fuels that, when dried during the drier springs of La Niña years, encourage the spread of wildfire (Veblen *et al.*, 2000). Hence the inter-annual variability in moisture, related to ENSO, can be more conducive to wildfires than drought alone (Veblen *et al.*, 2000; Sibold *et al.*, 2006).

In recent years, general circulation models (GCMs) characterizing the earth's climate have been refined to include regionally and temporally important factors such as ENSO and the Pacific Decadal Oscillation (PDO) (Cañon *et al.*, 2007; Cañon *et al.*, submitted). Improvements in downscaling data from GCMs have generated data of fine enough spatial scale to be used as input to watershed-scale models (Hay, 2000; Wood, 2004; Cañon *et al.*, submitted). Hence events such as wildfire that are strongly influenced by weather can be projected using the downscaled climate change data.

The goals of this study were to summarize the historic wildfire extent in the SRE, to develop a burned area model, and use the model to estimate the region's future extent of wildfire under climate change. We developed the model based on the relationship of climatic factors to area burned by recent wildfires (1970-2006) and used the model to estimate future burned area given downscaled climate forecasts from two GCMs. Having adopted a much smaller area than Westerling et al. (2006) did in their study of the western US, we were able to examine the historic fire record more carefully, including data on all past fires (rather than just large, >400 ha fires), and to model at a finer spatial scale.

2. Description of the SRE

Our study area is defined as the SRE (Bailey *et al.*, 1994) plus a 50 km buffer to prevent the edge effects commonly encountered in GIS processing and we call this SRE50. The SRE covers much of mountainous central Colorado plus parts of northern New Mexico and southern Wyoming in the United States, and comprises an area of almost 144,000 km^2 (Bailey *et al.*, 1994) (Figure 1). Elevations in the SRE range from 1000 m to 4400 m. Mean annual precipitation for the years 1971-2000 ranges from 170 mm at the lower elevations to 1600 mm in the mountains. Mean annual temperatures for 1970-2000 range from -4° to 13° C. Vegetation in the SRE includes prairie, shrublands, and pinyon-juniper woodlands at the lower elevations, mountain forests at the mid-elevations, and alpine tundra at the highest elevations. The SRE contains the headwaters of several major rivers of western and central North America, including the Colorado, Platte, Arkansas, and Rio Grande rivers. About 60% of land in the SRE is owned by federal and state agencies, with 41% of the total managed by the US Forest Service (USFS) and 12% by the Bureau of Land Management.

3. Methods

Our basic approach in this study was to develop a model of the past relationship of weather to wildfire extent and then use that model in light of projections of future weather to estimate future wildfire extent. A critical need, therefore, was to acquire and synthesize data on past wildfires. All available spatial data for wildfires were obtained from eight national forests within the SRE50 for the period 1930 to 2006 as point locations, and we obtained 95 fire polygons from the Geospatial Multi-agency Coordination (GEOMAC) website for 2000 to 2007.

The data required multiple processing steps before they could be used in this study. Duplicate fires in the GEOMAC dataset were deleted when a fire point within a fire polygon had at least two of three conditions: the same fire name, fire area or size class, and year of occurrence. We used centroids from the GEOMAC fire polygons to represent fire locations to match the fire points from the USFS. The multiple GIS layers of fire incidence were appended to create a single burned area layer which contained the locations, fire size class or area burned, and year of the fire. About 4% of wildfires were deleted as they lacked a year and fire size or USFS size class and so lacked the key information for modeling. USFS designated fire size classes range from the smallest A (< 0.001 km^2) to the largest, G (> 20.2 km^2) (Table 1). Fires for which only a size class was listed (2%) were assigned the median size for fires in that class. Location precision was a concern as about 34% of the points were hand digitized from unknown data sources, while 1% were originally located to the nearest quarter, half or full section by the Public Land Survey System. Another 13% of the points were located using GPS or a combination of hand digitizing and GPS and 17% were located using the personal computer historical analysis technique. The data sources of the remaining 38% of points are unknown. About 7% of points were deleted because they were outside of federally owned lands that we used to calculate the total available land to burn.

We restricted our analysis to the period from 1970 to 2006. We removed early years of data because observation and detection of wildfires improved dramatically over the first decades of the 1930-2006 period, which skewed the estimation of burned area towards later years. The remaining 37 years of data, 1970 to 2006, was judged to still be long enough to accommodate variability in climate. In addition, we retained only fire points that were on National Forests and BLM within the SRE50. The resulting dataset contained 16,105 fires for 1970-2006 (Figure 1). Note that we did not distinguish between human- and lightning-caused fires, as data on fire causes were not available for most of the fires.

The response variable of our model was wildfire extent, which we characterized as the percent of National Forests within the study area that burned in a given year (BA%). Because the BA% distribution is skewed, with large values being relatively uncommon, we log transformed BA% to ensure a normal distribution when developing models relating weather to burned area.

The predictor variables for the burned area models were derived from monthly precipitation and temperature data available from PRISM (Daly *et al.*, 1994) at a 4 km^2 resolution for the SRE for 1968 to 2006. Twenty-five predictor variables were developed from the weather data, consisting of seasonal and annual values for current year and prior year precipitation and temperature, plus two- and three-year running averages of precipitation and temperature where a running average is across the current fire year and a prior year or two. Data for prior years were used to capture the multi-year effect of precipitation and temperature on fuel moisture and fine fuel availability. Seasonal estimates were computed for the following threemonth periods, selected to match the temporal resolution of the GCM-based data: winter (January - March), spring (April - June), summer (July - September), and autumn (October - December). For each variable, averages were calculated over the area of the six selected vegetation types within the SRE50 for each year. In the relatively short time frame that we proposed to model, topographic variables at 4 km^2 resolution would be unlikely to change hence they were not used in the model process.

We initially intended to generate separate models by vegetation type because wildfire frequency and severity typically varies by vegetation type. We grouped land cover data from the LANDFIRE existing vegetation type (EVT) data (Landfire, 2006) into 13 types (Table 2).[1] Over 95% of fire location points occurred on six vegetation types, all with over 500 fires for 1970-2006 (Table 2). These six vegetation types were lodgepole pine (LP; *Pinus contorta*), low elevation forest (LEF), middle elevation forest (MEF), high elevation forest (HEF), riparian/wetland (RW), and shrub/grassland steppe (ST). Consequently, our analysis was focused on areas of the SRE50 owned by the USFS and BLM that contained fire data points and that were covered by one of these six vegetation types. The 900 m^2 EVT data were upscale to 4 km^2 resolution to match the weather data using the majority class type. Initial attempts to develop sensible and significant models of burned area by vegetation type proved fruitless, most likely because of the coarse resolution of the wildfire data described above and the small area occupied by some of the vegetation types (Table 2). As a result, we combined the data for the six vegetation types into a single model for the SRE. Use of the single vegetation layer precluded the option of directly modeling fuels or accounting for recovery periods following fire.

[1] The classification was performed using NatureServe Explorer, accessed in 2008 at: http://www.natureserve.org/explorer/.

Linear ordinary least-squares regression was used to model the relationships between the log transformed BA% and the predictor variables. The final model was selected using the best average of the following metrics: R^2, p-value, delta from 10-fold cross validation, and the Nash-Sutcliffe efficiency coefficient.

Climate data from downscaled GCMs for years 2006 to 2070 were used to develop future estimates of the predictor variables. The UK Meteorological Office (UKMO) HadCM3 and the Max Planck Institute (MPI) ECHAM5 GCMs datasets were chosen from among 16 available GCM datasets because they best modeled the historic El Niño Southern Oscillation (ENSO) and pacific decadal oscillation (PDO) weather patterns of the southwestern US (Dominguez *et al.*, 2010). The downscaled GCM data were prepared by Canon et al. (submitted) at the 4 km^2 resolution using statistical methods.[2]

We selected downscaled weather data for the A2 and B1 emission scenarios (Nakicenovic *et al.*, 2000). The A2 scenario assumes that there will be high population growth with slow economic development and slow technological change (IPCC, 2007), and this scenario generally results in relatively high increases in temperature. The B1 scenario assumes that the global population peaks in the middle of the 21st century, and then declines, with economies becoming more service and information oriented (IPCC, 2007), and this scenario generally results in relatively low temperature increases. Thus, the two selected scenarios tend to bracket the range in projected future temperature. With the two scenarios each modeled with the two GCMs for two time frames (2010-2040 and 2041-2070), we have eight scenario-GCM combinations that each produce estimates of future weather for the SRE.

[2] The downscaled data were obtained in 2008 at the following site: http://www.sahra.arizona.edu/research_data/SAHRAGeoDB.

Our comparison of PRISM and downscaled GCM data for years spanning 2006 indicated a bias in the GCM data. Hence the downscaled GCM data were adjusted by the difference (GCM minus PRISM) in the decadal averages about 2006 for each variable. The bias correction resulted in, for example, differences of 149 mm and 179 mm being added to the ECHAM5 and HadCM3 A2 annual precipitation data, respectively, and differences of 1.9° and 2.5°C being subtracted from the ECHAM5 and HadCM3 A2 annual temperature data, respectively. The historical and adjusted projected precipitation and temperature are shown in Figure 2 for the A2 scenario.

Using the bias-corrected downscaled estimates of the selected weather variables, projections of BA% were computed for each scenario-GCM combination. Using the variable weather data, 30 iterations were calculated for the eight timeframe and scenario-GCM combinations.

Given the right-skew of the BA% projections, the Kruskal-Wallis rank test was used to detect whether there were differences in BA% between the GCMs and between scenarios. As there were differences, the Wilcoxon rank-sum test was then used to investigate the differences between BA% distributions between the GCMs and scenarios.

4. Results

We first summarize what we learned about the historical fire record of the SRE, showing how the number of fires and the fire size distribution changed over the 1930-2006 period. Then we present our model of burned area based on data for 1970-2006, showing how weather variables area related to burned area. Finally, we present the analysis of how climate change is likely to affect future burned area.

4.1. Wildfires 1930-2006

As seen in the fire size class distribution for the SRE50 area of Table 3, the smallest fires are the most frequent, with classes A and B together accounting for 96% of all fires. In contrast, the larger classes D, E, F, and G together account for only 1% of the fires but 96% of the total fire area. The annual average number of recorded fires increased by an order of magnitude from the 1930s to the 2000s, from 47 wildfires per year for the period 1930-1950 to 417 for the period 1991-2006 (Table 3). The percent of the total burned area also increased over the 1930-2006 period, rising from 1.4% in the earliest period to 81.6% in the most recent period (Table 3). The increase in burned area is evident in distribution of fires by size class, as the number of large fires began increasing in the 1971-1990 period. That increasing trend continued in the most recent time period (1991-2006), which has the largest number and largest percent of fires in classes E, F, and G. Since it is likely that large fires were always detected and reported, the data probably reflect a real increase in the number of large wildfires.

For all seven fire size classes, the mean fire area exceeds the median fire area, suggesting an overall skewed fire size distribution (Table 1). This is particularly true in unbounded class G where the mean fire area of 97 km^2 is nearly twice the median fire area (50 km^2).

During the 1970-2006 period, fires were most common in lower and drier forest areas, with 31% of the fires in low elevation forests and 36% in mid elevation forests, and least common in higher and/or wetter areas, with only 5% in lodgepole areas and 3% in riparian/wetland areas (Figure 3, Table 2). Burned area was greatest in shrub/steppe and mid elevation forest, which each contain 26% of the total burned area in the SRE50, and lowest in the lodgepole (7%) and riparian/wetland (3%) areas (Table 2). In lodgepole pine few fires would be expected during a given 37-year period because of the long fire return interval (Romme, 1982).

In riparian or wetland areas, the higher moisture content of the fuels and the low-lying nature of riparian areas would tend to limit fires.

Improved detection methods, enhanced accessibility to remote locations (to both start and detect fires), an increasing population with an interest in remote property, and management policies that favored fire exclusion and suppression all have probably contributed to the increase in the number and size of recorded wildfires. A key question here is whether a change in climate might also have contributed, as the work by Westerling et al. (2006) has shown it did for the western US as a whole. Visual examination of Figure 2a suggests that annual precipitation did not show any substantial trends over the historic time period. In contrast, Figure 2b indicates an increase in temperature for the latter half of the historic period and this coincides with an increase in fires in larger size classes (Table 4).

4.2. The wildfire model

The log transformed BA% showed the strongest bivariate relationships with spring temperature and the following five precipitation variables: previous autumn precipitation, spring precipitation, summer precipitation, annual precipitation, and three-year running average precipitation (Table 4). Together these variables control seasonal or annual fuel moisture and the abundance of fine fuels. These variables, along with others listed above, were used to generate various models of BA%. Using our multiple criteria for selecting models, we selected the following model (R^2 = 48%, p = 0.00006):

BA% = [10^(–2.379 + 0.079*sprT – 0.008*prevautP – 0.006*avgsumP + 0.158*2yrprevT)]*100

where sprT = spring temperature, prevautP = previous autumn precipitation, avgsumP = summer precipitation, and 2yrprevT = the average of annual temperatures for the burn year and year prior to the burn. As expected, BA% is positively associated with spring and two-year average temperature, and negatively associated with summer and previous autumn precipitation.

4.3. Climate change and wildfires

The mean annual BA% over the period 1970-2006 for the SRE50 was 0.44%. Mean annual BA% projections show substantial increases which vary from 0.48% for the A2 scenario modeled using the HadCM3 GCM to 0.98% for the B1 scenario using the ECHAM5 model (Table 5). Compared with a maximum historic BA% 7.5% in 2002, projected maximums range from 3.65% to 6.75% across the four scenario-GCM combinations (Table 5).

Differences in projected BA% among the results from the four different scenario-GCM combinations were found to be significant using the Kruskal-Wallis rank-sum test (chi-square = 14.2, p = 0.003). Projected mean annual BA% was higher using the ECHAM5 GCM data, with annual means of 0.75% for A2 and 0.98% for B1, than using the HadCM3 GCM data, with annual means of 0.48% for A2 and a mean of 0.73% for B1 (Table 5). The difference in projected BA% for the two GCMs for the A2 scenario was found to be significant using the Wilcoxon rank-sum test (p = 0.02). The HadCM3 A2 scenario was generally wetter than the ECHAM5 A2, with increases of 29% and 16% for summer precipitation and previous autumn precipitation, respectively (Table 6). Differences in spring temperature were less than 1°C with the HadCM3 data being slightly warmer and differences in two-year mean temperature were less than 1°C for the downscaled ECHAM5 and HadCM3 data. Projected BA% of the two GCMs for the B1 scenario were not significantly different (p=0.16), as the temperatures were quite similar, and summer and previous autumn precipitation values differed by only 12 mm and 10 mm, respectively, from ECHAM5 to HadCM3.

BA% projections for the two scenarios obtained using the HadCM3 model (with means of 0.73% for B1 and 0.48% for A2) were significantly different based on the Wilcoxon test ($p=0.02$). The reason for this may be that temperature variables showed the largest increases for the HadCM3-A2 scenario while summer and previous autumn precipitation for the B1 scenario were substantially lower than for the A2 scenario (Table 6). Projected BA% of the two scenarios using the ECHAM5 model were not significantly different ($p=0.14$).

The BA% projections showed consistently higher values for the second of the two timeframes, that is, 2041-2070 (Table 7). There was an exponential increase and a broader range of values in the second timeframe for both A2 and B1 scenarios (Figure 4). The second timeframe means showed larger percent increases for the A2 scenario from the first time frame as would be expected from the scenario, 2.7% for ECHAM5 and 1.7% for HadCM3, when compared to the B1 increases of 2.3% and 1.6% for ECHAM5 and HadCM3 respectively (Table 7). However in terms of the overall increase in BA%, the B1 scenario had the highest annual mean at 0.98% ECHAM5 and this is surprising because it had the lowest temperature for the previous 2yr although it had second highest spring temperature, however, it also had the second lowest precipitation values. We suggest that this high BA% results from fuels that would be drier due to lower precipitation during the previous autumn and warm spring temperature, and that this combination would increase the likelihood of start and spread of fires.

5. Discussion

Our analysis of the effects of weather on the number and extent of wildfires is confounded by the substantial changes that have occurred in fire detection, monitoring and measurements. Increases and changes in the distribution of human population in the SRE may have led to more fires being started as well as being detected. Fire detection has improved over the years; for example, fires now may be detected and monitored by satellite so that burned area can be measured on a daily basis. Because of such changes, we decided to use the wildfire record since only 1970, which incorporates modern methods of fire detection but is a long enough period to account for more than thirty years of climatic variability.

Another change that has occurred is in fire management paradigms. Since the early decades of the 20th century, wildfires have been actively suppressed by public land management agencies. Many years of fire exclusion and suppression have probably altered the structure, composition and fuel loads of forests, which may have caused build ups of fuels and greater potential for wildfire (Kauffman, 2004; Stephens, 2005). This scenario may be particularly relevant in low elevation forests, which have a shorter return interval than do subalpine and lodgepole pine forests (Romme *et al.*, 2006). However, the perceptions of the role of fire and fire management have changed radically. A beneficial role of wildfire, that of maintaining heterogeneity in many forest and grassland ecosystems, is now recognized (Bisson *et al.*, 2006). The 1995 Federal Wildland Fire Management Policy recognizes fire as an "essential ecological process and natural change agent" (NIFC, 1995). The changes in wildfire management have been relatively recent and have probably not yet had an appreciable effect on fire incidence in the SRE, but continued efforts to allow and use fire may gradually change fire behavior from what it would have been without these new approaches. Our projections of future burned area under climate change will overestimate burned area to the extent that the changes in policy are effective in altering future fire patterns compared with the 1970-2006 period.

The accuracy of the burned area model developed here is constrained by the 1970-2006 fire data in three ways. First, we did not distinguish between human- and lightening-caused fires, as fire cause was not listed for most fires in the data set. Human-caused fires tend to occur along highways and closer to developed areas, so they may not reflect weather patterns as clearly as do lightening caused fires (Bartlein, 2003, 2008). Second, the coarse resolution of the fire data may limit the accuracy of the burned area model because fire points were located by different methods with varying levels of accuracy and precision. For example, some points were located only by section or quarter section in the Public Land Survey System so that their presence inside or outside a national forest boundary would determine whether or not the fire was used to develop the model. Lastly, for fire points without a listed fire area, we assigned a fire area equal to the median of the fires in the respective fire size class, which introduces some error in the burned area estimates for the year.

Although the climate data sets provide the best available data for our purposes, it must be remembered that both data sources provide modeled estimates that necessarily rely on assumptions. Uncertainty in the PRISM data comes from the interpolation of measured precipitation data and regression equations based on local topography (Daly *et al.*, 1994). GCMs model regional climate at large scale; the estimates are then downscaled statistically to account for local spatial and temporal variations. It is impossible to know, for example, how accurately the GCMs characterize extremes of weather, such as those that produced the multi-year drought during which the Hayman and several other large SRE fires occurred.

Comparisons of our results are possible with two recent studies of large areas that included the SRE. First, Westerling et al. (2006) found that burned area in forested areas of the western US was 6.5 times greater from the mid-1980s to 2003 than from 1970 to 1986. Our data for the SRE50 indicate a 5.5-fold increase in percent burned over the same time period (Table 7), suggesting that the SRE is roughly representative of average western conditions. Second, for forested areas of the Rocky Mountain region over the period 1996 to 2005, Spracklen et al.

(submitted) estimated an annual burned area of only 0.02%, compared with our estimate for the same period for the SRE50 of 1.18%. Similarly, Spracklen et al. project an average annual burned area for 2046-2055 of only 0.04%, far lower than our projection for the same period for the SRE50 of from 0.48% to 1.06% depending on which scenario-GCM combination is used (Table 7).

It is interesting that the two previously mentioned studies used the same data sets with different spatial extents and it is unfortunate that we are not able to compare their results directly because it seems that Westerling's proportional results for the mid 1980s-2003 generally agreed with ours but Spracklen's results for 1996-2005 were much lower. The likely reason for this difference was that we determined the total burned area on selected portions of federally owned land, which included grass and shrub land, not just forests, and that may be why our BA% values are substantially higher. It is uncertain what effects ensued from the differences in data resolution. Other differences in the data used by Spracklen et al. and those used in the current study may also account for the discrepancy, for example, Spracklen et al. used only fires greater in area than 400 ha and we used all available fires. In addition, subalpine fir, which is the predominant vegetation type in the northern Rockies, is comparable to high elevation forest (HEF) and lodgepole pine (LP) in the southern Rockies. HEF/LP are relatively uncommon in the SRE, accounting for only 27% of the area; the dominant types of the SRE are the ST, LEF, and MEF types, which together comprise 70% of the area (Table 2; Figure 3). Subalpine fir and HEF/LP burn much less frequently than the dominant SRE vegetation types, resulting in a lower mean burned area for the Rockies as a whole.

In recent years, burned areas in the SRE have been exceptionally high. To see this, consider that the annual average BA% is 0.16% for the 1970–1995 period but 1.18% for the more recent period of 1996-2005. The latter value is actually larger than any of the mean annual BA% projections for 2010-2070, where the largest mean BA% is 1.06% for the HadCM3-B1 combination. The SRE experienced a severe drought during part of the 1996-2005 period, along with some of the largest wildfires in the recorded history of the area occurred. The year 2002 was the worst year, with three particularly large fires: the Hayman, the Ponil, and the Missionary Ridge fires which burned 594 km^2, 394 km^2, and 391 km^2, respectively, in Colorado and New Mexico (GEOMAC).

Uncertainties remain regarding the relative contributions of years of fire suppression and the beginnings of climate change to burned area trends in the SRE. Accurately separating the effects of vegetation and climate change would require more detailed data than we were able to obtain, with fuel management or treatment histories to match the timeline of wildfires and weather related variables. As climate change progresses, researchers will be able to obtain more data on the likely trends and magnitudes of precipitation and temperature and further refine burned area models. However, the relation of burned area to weather in the SRE is fairly clear. When combined with expected changes in climate, this relation suggests further increases in burned area. This finding is particularly important because of the increasing numbers of people and structures moving into the wildland-urban interface that need to be protected. Land managers will need to understand how to allocate resources and manage fuels for protection and further research is needed to help with these adjustments.

The burned area model developed here is specific to the SRE but the methodology could be applied in other areas to understand the broad effects of future climate on burned areas. Further, the burned area model could be improved by incorporating a fire-spread model to determine specific burned areas, and by accounting for fire recovery periods, allowing vegetation to recover and progress through seral stages. This improvement would more realistically account for the likely effect of climate change on vegetation and determine the ability of forests to re-grow in areas where they have thrived since the last climate change.

6. Conclusion

The period from 1930 to 2006 saw substantial increases in the numbers and burned areas of wildfires in the SRE. Although some of these increases are attributable to improved fire detection, and some are probably due to an increase in the incidence of human-caused fires, and the changing climate especially during the latter years of the period. We developed a model to examine the effects of precipitation and temperature on burned area in the SRE along with projections of future weather in light of expected climate change to estimate future burned area. Estimates of future burned area differ depending on which future emission scenario one adopts and on the model used to project future weather, but all combinations of scenarios and models we developed show an increase in burned area, especially after 2040. Although there is some uncertainty in our results, the general implications for fire management are clear. With both burned area and human population increasing in the future (Theobald and Romme, 2007), the pressures for enhanced management of fires and fuels will necessarily intensify.

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Table 1. Fire area class with range of areas and for the SRE50, median and mean areas for 1930 to 2006 (Source of area classes: National Wildfire Coordinating Group).

Fire area class	Fire area in km^2 (acres)	Median fire area (km^2)	Mean fire area (km^2)
A	< 0.001 (<0.25)	0.0004	0.001
B	0.001- 0.04 (0.25 to 10)	0.004	0.01
C	0.04 – 0.40 (10 to 100)	.08	0.12
D	0.40 – 1.2 (100 to 300)	0.7	0.71
E	1.2 – 4.0 (300 to 1000)	1.8	2.1
F	4.0 - 20.2 (1000 to 5000)	11	11
G	> 20.2 (> 5000)	50	97

Table 2. Fire data for the period 1970-2006 by land cover and land use area in the SRE50.

LULC Description	Abbreviation	Percent of land area	Number of fires	Percent of burned area
Shrub/ Grassland steppe	*ST	43	1797	26
Low elevation forest	*LEF	12	4961	18
Mid elevation forest	*MEF	12	5794	26
High elevation forest	*HEF	6	1278	20
Lodgepole pine	*LP	2	872	7
Riparian/wetland	*RW	2	543	3
Barren/open water/ snow/ice	BWS	2	252	
Agriculture/pasture and open space	AOS	2	242	
Agriculture –cultivated crops, irrigated	ACI	3	261	
Alpine tundra	AT	1	61	
Low intensity development	LID	0.4	33	
Mid intensity development	MID	0.2	4	
High intensity development	HID	0.04	0	
Total			16098	

* Indicates a vegetation type with over 500 fires, our cutoff for development of burned area models.

Table 3. Number of fires and percent of total fire area by fire size class in the SRE50.

Time period	A	B	C	D	E	F	G	Total number of fires	Number of fires per year	Percent of total burned area
1930-1950	672	254	56	3	4	2	0	991	47	1.4
1951-1970	1283	797	53	9	5	0	0	2147	107	1.7
1971-1990	5374	2597	283	47	9	11	3	8324	416	15
1991-2006	4653	1721	183	44	34	13	19	6667	417	82
Totals	11982	5369	575	103	52	26	22	18129		
Percent of total number of fires	66	30	3.2	0.6	0.3	0.1	0.1			
Percent of total burned area	0.2	1.1	2.3	4.9	4.5	13	74			

Table 4. Loglinear relationships between percent burned area and predictor variables ($p < 0.1$). P is precipitation and T is temperature.

Predictor variable	R^2	p-value
Previous autumn P	0.36	0.0001
Spring T	0.23	0.0030
Annual P	0.23	0.0032
Spring P	0.21	0.0046
Average 3yr P	0.14	0.0252
Summer P	0.09	0.0715

Table 5. Summary of projected annual BA% for the period 2010 to 2070 for the four GCM-scenario combinations. S.D. is the standard deviation; C.V. is the coefficient of variation.

	ECHAM5 A2	ECHAM5 B1	HADCM3 A2	HADCM3 B1
Mean	0.75	0.98	0.48	0.73
S.D.	0.91	1.24	0.60	0.87
Median	0.37	0.60	0.27	0.43
Minimum	0.08	0.06	0.02	0.04
Maximum	4.70	6.75	3.65	5.36
C.V.	1.1	1.3	1.3	1.2

Table 6. Climate data means for the predictor variables for historic data (1971-2006) and future data (2010-2070).

	Spring T (°C)	Summer P (mm)	Previous autumn P (mm)	2yr Previous T(°C)
1971-2006	8.2	156	132	4.6
HADCM3 B1	10.0	178	115	6.3
HADCM3 A2	10.6	191	148	6.6
ECHAM5 B1	10.0	166	125	6.2
ECHAM5 A2	9.9	148	128	6.4

Table 7. BA% annual means for RM forest (Spracklen et al, submitted), forested western USA (Westerling et al., 2006), SRE historic and modeled data (for SRE forest and grassland).

	RM forests	West	SRE50				
			Historic	HADCM3		ECHAM5	
	A1B			B1	A2	B1	A2
1970-2006			0.44				
Mid 1980s – 2003		6.5 times 1970-1986	5.6 times 1970-1986				
1996-2005	0.02		1.18				
2046-2055	0.04			1.06	0.59	0.92	0.84
2010-2040				0.41	0.26	0.46	0.32
2041-2070				1.05	0.70	1.50	1.19
2010-2070				0.73	0.48	0.98	0.75

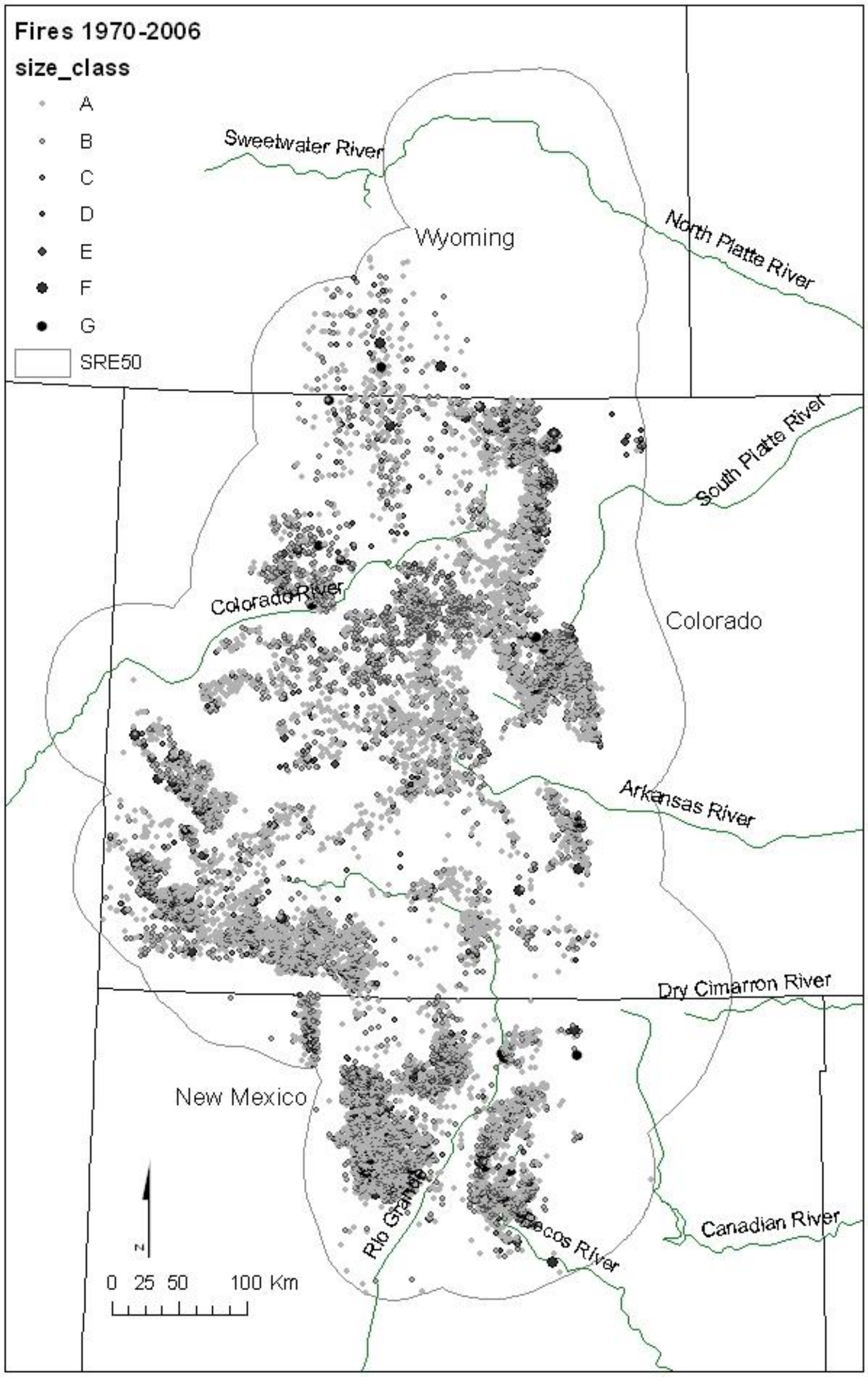
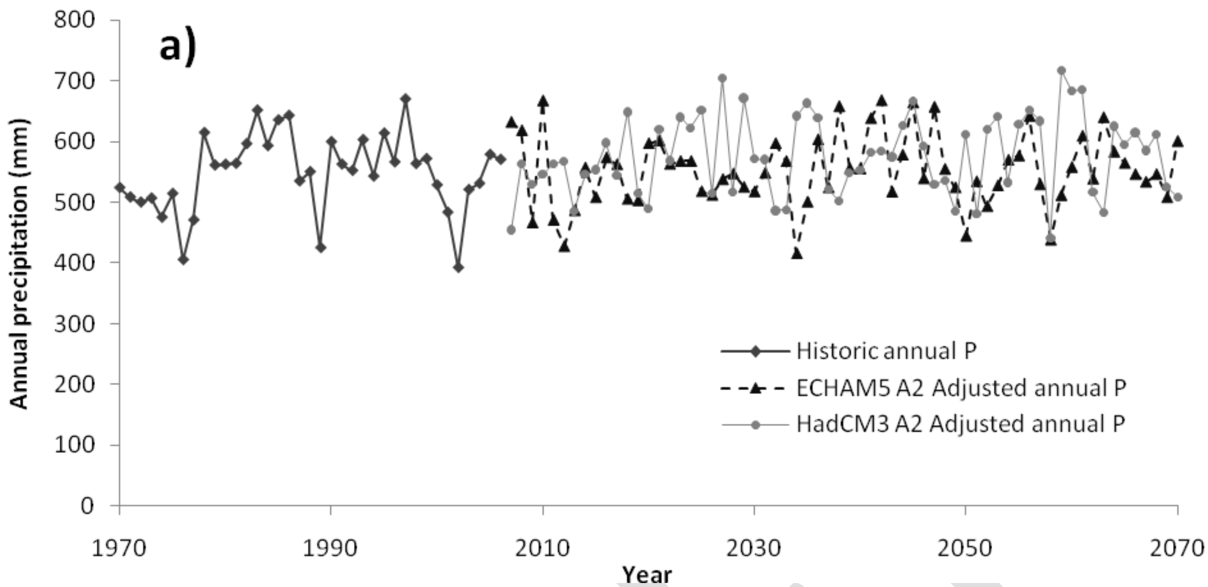


Figure 1. Wildfire locations by area class in the Southern Rockies Ecoregion with 50 km buffer (SRE50) from 1970 to 2006.



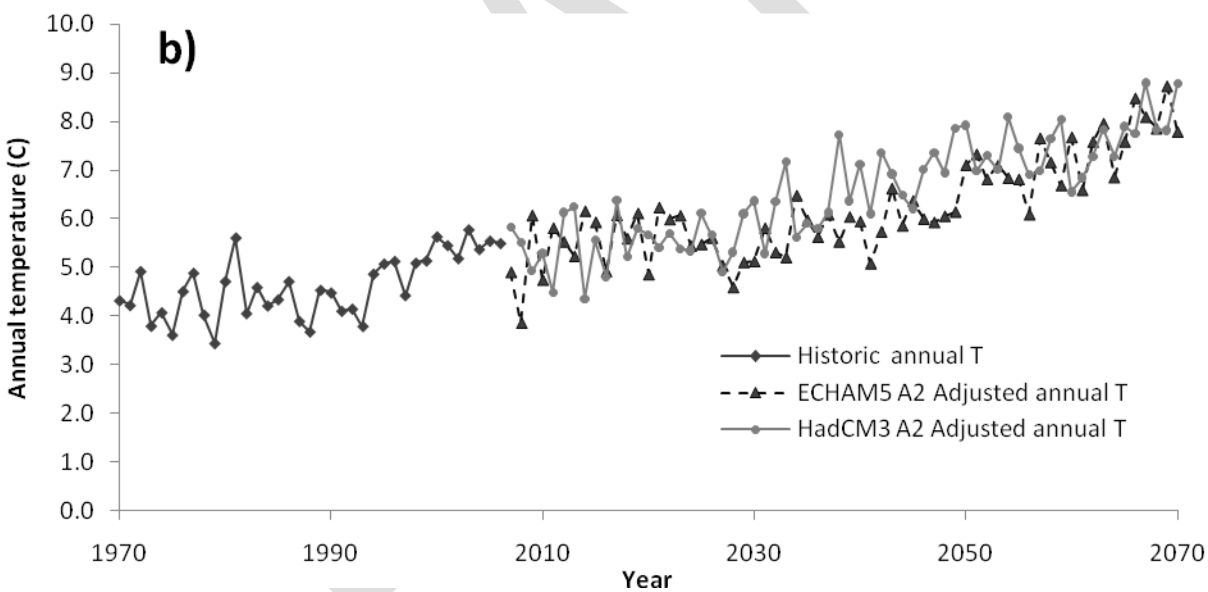


Figure 2. Historic data for 1970-2007, downscaled, adjusted ECHAM5 and HadCM3 A2 scenario 2007 to 2070 for a) annual precipitation and b) annual temperature.

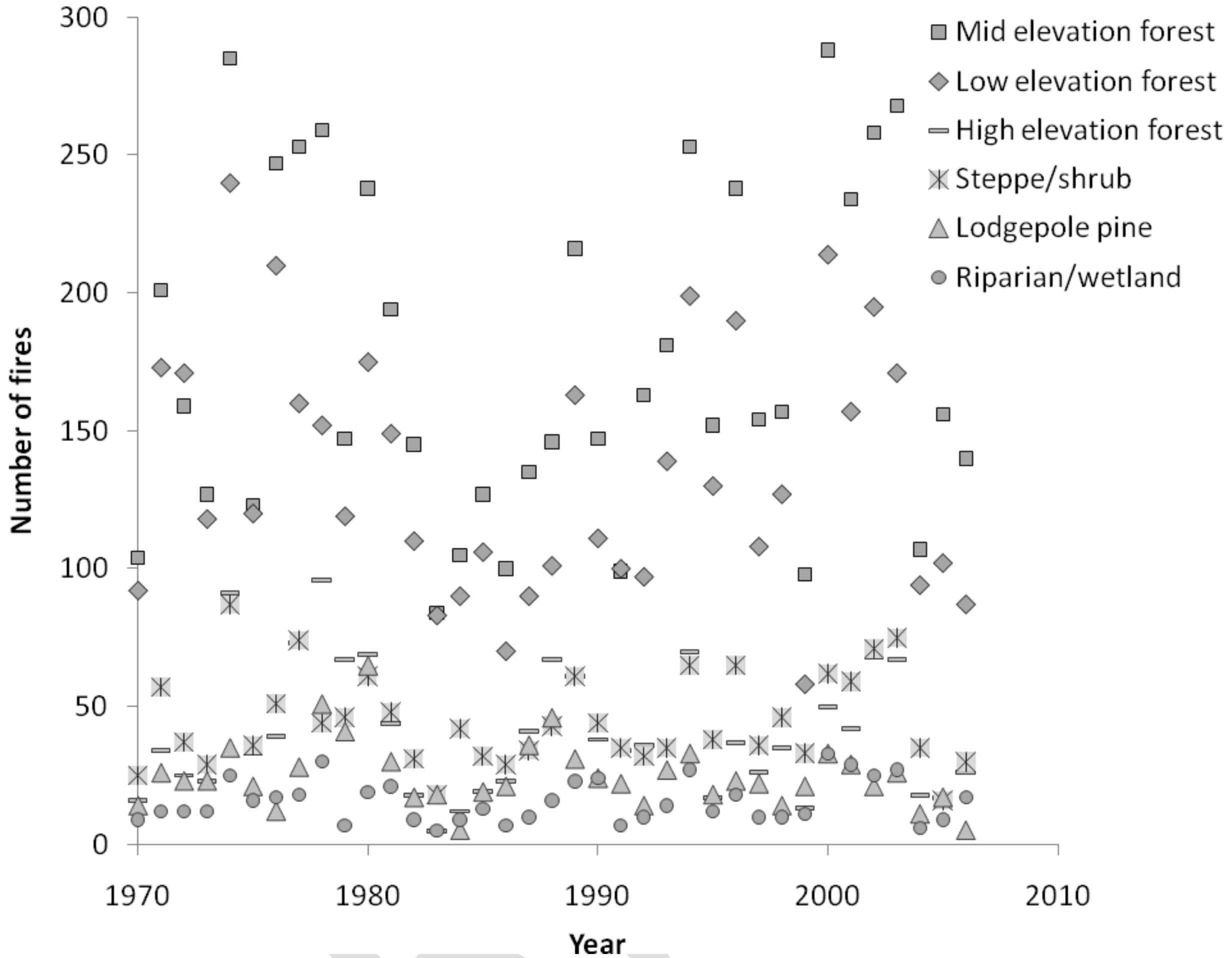


Figure 3. Annual number of fires by vegetation type: 1970-2006.

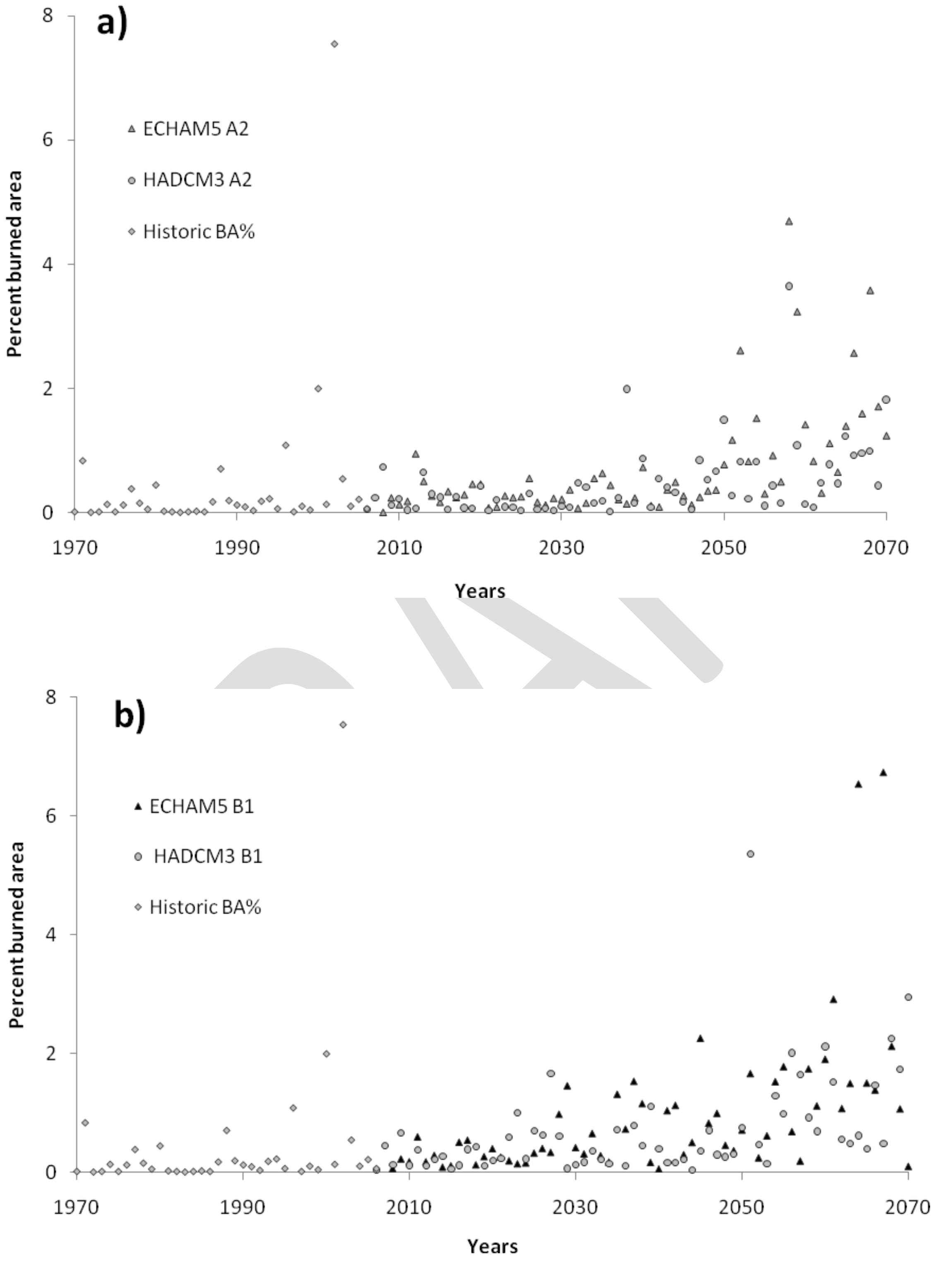


Figure 4.Percent burned area (BA%) for the historic period 1970-2006, and projected BA% using downscaled ECHAM5 and HadCM3 data for 2010 to 2070 and for a) scenario A2 and b) scenario B1.