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THE IMPACT OF CLIMATE CHANGE ON WILDFIRE SEVERITY: A REGIONAL FORECAST FOR NORTHERN CALIFORNIA *

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Abstract. We estimated the impact of climatic change on wildland fire and suppression effectiveness in northern California by linking general circulation model output to local weather and fire records and projecting fire outcomes with an initial-attack suppression model. The warmer and windier conditions corresponding to a $2 \times CO_2$ climate scenario produced fires that burned more intensely and spread faster in most locations. Despite enhancement of fire suppression efforts, the number of escaped fires (those exceeding initial containment limits) increased 51% in the south San Francisco Bay area, 125% in the Sierra Nevada, and did not change on the north coast. Changes in area burned by contained fires were 41%, 41% and –8%, respectively. When interpolated to most of northern California's wildlands, these results translate to an average annual increase of 114 escapes (a doubling of the current frequency) and an additional 5,000 hectares (a 50% increase) burned by contained fires. On average, the fire return intervals in grass and brush vegetation types were cut in half. The estimates reported represent a *minimum* expected change, or best-case forecast. In addition to the increased suppression costs and economic damages, changes in fire severity of this magnitude would have widespread impacts on vegetation distribution, forest condition, and carbon storage, and greatly increase the risk to property, natural resources and human life.

1. Introduction

Wildfires are an integral component of ecosystems throughout the world. Fires affect the value and condition of forest, range, and fishery resources as well as ecosystem services such as clean water, recreation, and carbon sequestration. Wildfires – particularly those that escape initial containment efforts – also pose a risk to people and property, particularly at the rapidly growing wildland-urban interface (Keeley et al., 1999).

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The paleo record and historical data show that changes in wildfire frequency are closely linked to changes in climate. Several recent studies tracking trends over the past century have found that fire frequency (Clark et al., 1990; Brown and Swetnam, 1994) and area burned (Flannigan and Van Wagner, 1991) correlated with air temperature, leading to increased concern over the potential impact of climate change on wildfire severity.

Research applying predictions of general circulation models (GCMs) has consistently found that predicted climate change will lead to increases in the frequency of weather conditions associated with high wildfire hazard. In these analyses – conducted for boreal forest, tropical forest, and coastal sage scrub – a double-CO_2 climate led to changes in weather-related indices of potential fire intensity and rate of spread (e.g., Flannigan and Van Wagner, 1991; Stocks et al., 1998; Beer, 1988; Bergeron and Flannigan, 1995; Simard and Main, 1987), increases in fire ignitions (e.g., Malanson and Westman, 1991; Goldhammer and Price, 1998), and lengthening of the fire season (Wotton and Flannigan, 1993).

Because they were based on weather indices and not actual fires or fire behavior in specific locations, these studies did not take into account the complex interaction of wildfires and suppression or the skewed probability distribution of fire severity, in which large and extreme fires are rare and small fires are common. They did not, as a result, simulate changes in area burned or the mitigation potential of fire suppression.

While the correlation of climate and wildfire has been established, predicting fire outcomes is more difficult. Climatic change has the potential to affect multiple elements of the wildland fire system: fire behavior, ignitions, fire management, and vegetation fuels. In areas where suppression is practiced, however, fire outcomes are more sensitive to fire behavior than any other parameter (Dimitrakopoulos, 1985). Modeling the wildland fire system is complicated by the spatially and temporally heterogeneous distribution of wildfires, the disproportionate influence of a small number of extreme fire events, and the fact that the level of fire suppression effort varies with fire behavior and location. Much of the likely impact can be estimated by modeling climate-fire behavior and fire behavior-suppression interactions.

This paper presents estimates of the likely impacts of climate change using a geographically explicit model that estimates the behavior of individual fires as a function of fuel type, slope, and weather. It links the fire behavior estimates with population density and fire suppression protocols to simulate initial attack, area burned in contained fires, and the number of escapes (fires that grow too large to be contained by initial attack firefighting resources). To focus on the effect of climate change, we used a *ceteris parabis* analysis in which determinants of fire other than weather are held constant between present day and $2\times CO_2$ scenarios.

Our modeling approach, the Changed Climate Fire Modeling System (CCFMS, Fried and Torn, 1990), extended what was learned from previous studies in four important directions. (1) Fire suppression is handled endogenously and is integral to the model. (2) Predicted changes in fire danger indices are modeled to produce fire size distributions, which make it possible to estimate the frequency of extreme events (i.e., escapes). (3) The full suite of relevant climate variables – temperature, wind, humidity and precipitation – are integrated in the model. This is important because some aspects of climate change (e.g., increases in humidity) tend to produce slower spreading fires while others (e.g., lower precipitation and faster winds) will have the opposite effect (Torn and Fried, 1992). (4) Predictions are generated at a comparatively fine geographic scale, thus facilitating analysis by vegetation type or population density. For example, the impact of climate change differs by vegetation fuel types, due in part to the effect of fuel type on fire intensity and, mainly, to the greater importance of wind speed in the fire spread rate calculations for grass fuels, as compared to brush and forest (Torn and Fried, 1992). We present results of CCFMS analyses in three areas of California, and an interpolation that covers most of the northern two-thirds of the state.

California is a useful case study for climate change impacts because wildfire is of critical ecological and economic importance in the state. California contains a broad continuum of ecosystems from mesic to xeric where fire plays an important role and it has extensive areas of wildland-urban interface. More than half of the most damaging fires in the U.S. over the past 170 years occurred in California, and the state leads the nation in wildfire-related economic losses. A guiding objective of this work was to generate results that would be useful to a diverse audience (e.g., natural resource managers, fire protection planners, policymakers, and insurance companies). Thus we have included a high degree of geographic specificity in the model structure and a reporting framework that is compatible with many kinds of secondary impact analysis. We provide quantitative estimates of changes in fire behavior (rate of spread and burning intensity) and two types of modeled outcomes for individual fires: area burned (if a fire was contained) or the prediction that a fire escaped containment efforts.

2. Methods

2.1. MODELING APPROACH

CCFMS bridges differences in the spatial and temporal scales of climate model output and historical fire data to model fire behavior, fire suppression, and, ultimately, the outcomes of individual fires. We modeled representative fires to arrive at precise estimates of the frequency of escapes and other statistics that cannot be estimated by modeling average fire characteristics (Fried and Torn, 1990).

Under the current climate, escapes are rare: between 1961 and 1997, only 0.03–0.5% of ignitions in California resulted in escapes (CDF, 1998). But escapes are much more likely to generate losses: over the past 40 years, one out of every 10 escapes has led to injury/fatality or the destruction of buildings (CDF, 1998).

Moreover, losses generated by some escapes are so large that this category of fire accounted for over half of the fires where loss of buildings or human lives occurred, and well over half of the property value lost to fire in California over this period. The area burned by escapes cannot be modeled or accurately predicted because of the variability in terrain, burning conditions, and suppression intensity encountered by fires that exceed the escape limits. However, the number of escapes is a crucial measure of severity, because these are fires that can become large and damaging. Moreover, the *change* in escape frequency is a robust measure of the likely impacts, because it is comparatively insensitive to shortcomings in the model structure and potential errors in parameter estimates.

Fire behavior and outcomes are sensitive to general circulation model (GCM) choice (e.g., Flannigan and Van Wagner, 1991; Stocks et al., 1998; Torn and Fried, 1992). In CCFMS, climate change scenarios based on the Geophysical Fluid Dynamics Laboratory GCM (GFDL, Manabe and Wetherald, 1980) produced the greatest increase in wildfire severity and those based on UKMO GCM (now Hadley GCM, Wilson and Mitchell, 1987) generated the smallest increase. The scenario used in the present analysis is based on the relatively conservative Goddard Institute for Space Sciences (GISS, Hansen et al., 1983) GCM, which was intermediate (though closer to UKMO than to GFDL).

Fried and Torn (1990) describe the modeling approach in detail. To capture the direct influence of climatically-induced changes in weather, CCFMS (1) adjusts local, daily, historical weather data according to percentage changes in the relevant climate statistics predicted on a monthly, regional basis by the GISS GCM; (2) simulates fire behavior for six years of historical fire occurrences under both historical and climate-change adjusted weather data; and (3) simulates growth and suppression for a set of representative fires for each climate scenario. It does not directly address the effects of climate change on plant growth or ignitions, which would tend to increase the overall damage from wildfires for a given level of suppression intensity.

Wildfire was modeled under the historical climate and with a climate change weather data set. The day, time, slope, vegetation, location, and number of fires were the same under each climate scenario. The total number of fires was not altered because over 90% of wildfires in the analysis area are started by people.

2.2. ANALYSIS AREA

Most of California has a Mediterranean climate with summer drought. The fire season extends from June to October in the northern portion of the state. Annual precipitation increases moving north through the state, and, thanks to nearly-omnipresent coastal fog, summer temperatures fall sharply approaching the coast. Vegetation mosaics are controlled by a combination of synoptic climate, elevation, aspect and edaphic factors and have evolved under the ongoing influence of sto-

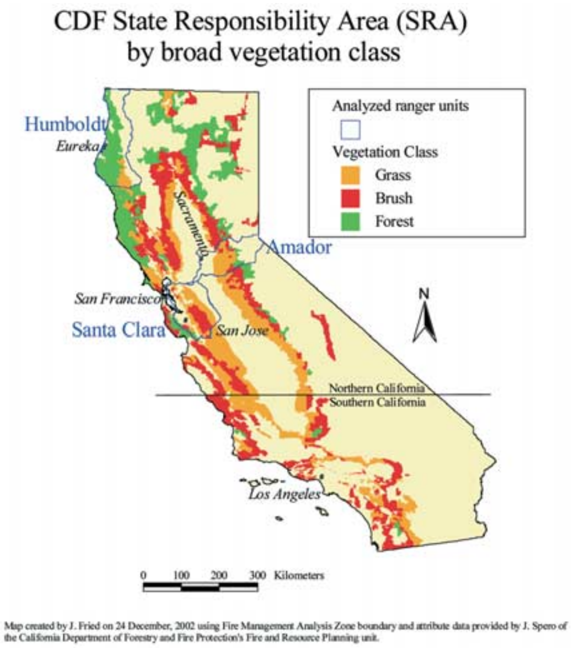

Figure 1. Broad vegetation fuel classes for State Responsibility Area for which the California Department of Forestry and Fire Protection has primary protection responsibility and boundaries of ranger units analyzed for this study.

chastic and planned disturbance agents such as fire, grazing, browse and timber management.

Our analysis region covered 10 million hectares of state responsibility area lands (non-federal, non-urban wildlands) in northern California (north of 35.8° N latitude) protected by the California Department of Forestry and Fire Protection (CDF). Three CDF ranger units (single or multi-county administrative areas covering 150 thousand to 9 million hectares) containing the range of vegetation fuel types, weather patterns, and fire suppression resources typical of northern California were selected for modeling: Santa Clara (southeast of San Francisco, covering 1 million hectares), Amador-El Dorado (hereafter 'Amador', in the Sierra foothills east of Sacramento, covering 0.9 million hectares), and Humboldt (on the northern coast, covering 1.3 million hectares; Figure 1). Two of these ranger units (Santa Clara and Amador) contain extensive areas of wildland-urban interface. CDF stratifies each ranger unit into Fire Management Analysis Zones (hereafter 'analysis zones') ranging from 300–400,000 ha each, judged to be reasonably homogeneous with respect to vegetation fuels, topography and human population density (an ordinal proxy for values-at-risk and ignition frequencies; U.S.D.A. Forest Service, 1985). Results for these three ranger units were interpolated, as described below, to generate predictions for all state responsibility areas in northern California.

2.3. CLIMATE SCENARIOS

Historical climate weather observations (2 pm and 24-h minimum and maximum) were obtained from the National Weather Data Library (Furman and Brink, 1975) for seven weather stations in the modeled ranger units. We used local weather stations within or nearby each Analysis Zone for the base (current) climate because weather varies over short distances in California's mountainous terrain. Climate change scenarios were created by multiplying the percent change between monthly, average $1 \times CO_2$ and $2 \times CO_2$ GCM output by the historical daily observations of temperature, humidity, precipitation and wind speed (Fried and Torn, 1990; Torn and Fried, 1992). This approach allowed us to bridge the coarse spatial (on the order of degrees of latitude and longitude) and temporal (90 minute output composited to monthly averages) resolution of readily available GCM output with the fine scale needed to directly model fire behavior at particular locations (Flannigan and Van Wagner, 1991; Fried and Torn, 1990).

Using a percentage change in climate variables presupposes that climatic change does not alter diurnal or daily variability in the weather variables, and that the proportional difference between the $1 \times CO_2$ and $2 \times CO_2$ simulations provides a good estimation of climate change effects on weather variables. It does not require the assumption that $1 \times CO_2$ GCM output provides an accurate representation of the present climate. Applying GCM predictions as absolute differences or percentage changes makes little difference in the number of escapes or the size distribution of contained fires (Fried and Torn, 1990). However, the percentage change approach produces smaller (more conservative) estimates of the increase in the frequency of fires with fast spread rates. The GISS GCM double-CO_2 climate output applied in this study predicts warmer, windier and somewhat drier conditions for Santa Clara and Amador (Table I) and warmer but less windy, more humid, and heavier precipitation conditions for Humboldt.

2.4. FIRE BEHAVIOR

CCFMS models potential fire behavior based on weather, fuel conditions, and slope, for the historical weather and the climate change scenario. Weather observations were processed with FBDMOD (CDF, 1992; Main et al., 1990) for all National Fire Danger Rating System fuel models (Deeming et al., 1977) designated by ranger unit staff as representative. It generates a database of fuel-specific fire behavior indices for each Analysis Zone. Each location- and time-indexed fire *occurrence* record was joined to the fire *behavior* record with the corresponding fuel model, date and weather station representing conditions most similar to the fire's location.

A fire behavior record containing estimates of *fireline intensity* and *rate of spread* was matched to each historical fire between 1980 and 1985 (1693 fires in Santa Clara, 2175 in Amador and 950 in Humboldt). The behavior records contained fire behavior indices based on one of six fuel models, four slope classes,

Table I

GISS GCM output for monthly average temperature, precipitation, relative humidity, and wind speed for area centered on Lat. 38° N, Lon. 120° W

Control	Month											
(present climate)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp (°C)	0.8	3.8	7.1	10.9	14.0	21.2	26.7	24.7	18.6	9.6	5.8	1.9
Precip (mm/day)	2.2	3.8	1.7	1.2	1.5	0.6	0.0	0.0	0.0	0.2	1.6	1.4
Rel. hum. (%)	101.5	106.9	94.2	78.9	91.6	65.0	52.6	58.1	68.0	78.8	93.3	102.4
Windspeed (m/s)	1.6	4.6	6.3	2.9	2.3	1.5	1.8	1.6	1.7	3.4	13.3	18.7
Double CO_2												
Temp (°C)	4.6	8.0	9.2	16.1	15.2	24.5	31.4	29.6	22.2	14.2	9.8	7.4
Precip (mm/day)	2.6	3.7	3.5	0.7	2.2	0.1	0.0	0.0	0.1	0.2	2.0	2.0
Rel. hum. (%)	105.6	106.5	99.5	74.2	99.6	61.7	52.5	60.2	68.4	76.2	91.1	100.2
Windspeed (m/s)	1.0	3.7	5.9	2.2	3.3	1.8	1.8	2.1	2.2	2.5	4.3	4.7

seven weather stations, and two climate scenarios (historical and climate change). Each fire was assigned a fire dispatch level (FDL) of low, medium, or high on the basis of its predicted fireline intensity. Fire behavior could not be directly modeled for ∼300 fires because they occurred during gaps in the historical weather record (some weather stations operate only during the 4-month peak fire season). These fires were apportioned to behavior classes according to the relative frequencies of low, medium and high dispatch fires in the modeled fires, so that predicted and historical numbers of fires match.

2.5. FIRE SUPPRESSION

For simulation of fire growth and suppression, the behavior of ∼4500 fires (under each climate scenario) was used to generate statistics that represent the distribution of fires: for each Analysis Zone, the 50th and 90th percentile spread rates within each FDL represented, respectively, 80% and 20% of the fire load at that FDL for representative fire locations (RFLs). There are typically between two and ten RFLs defined per Analysis Zone, depending on the degree of within-Analysis-Zone variability in firefighting conditions and travel times. Hence, the outcomes of six fires were modeled for each RFL – for 50th and 90th percentile spread rates at each of three FDLs, for each climate scenario. In total, suppression operations were simulated for 390 representative fires distributed over 65 RFLs. Fire suppression simulation for these representative fires was conducted using CFES (California Fire Economics Simulator version 1.43; Fried et al., 1987; Fried and Gilless, 1988a) to produce the two annual, expected value statistics: number of fires which escape initial attack and area burned by fires that are successfully contained. CFES is a strategic planning model of initial attack on wildfire used routinely over the past decade by the CDF to evaluate deployment and positioning of fire fighting equipment and personnel (Gilless and Fried, 1991; CDF, 1990; Spero, 1998a,b).

2.6. REGIONAL INTERPOLATION

Fire protection policy for the State of California (California State Board of Forestry, 1996), includes a mandate to provide ‘equal protection for areas of similar type’ (California Public Resources Code § 4130). Because CDF is currently in compliance with this mandate, statistics on area burned and escapes per acre protected can be calculated for the Analysis Zones in the three modeled ranger units and applied to ‘similar’ Analysis Zones in the other 17 ranger units in northern California.

For this strata-based, modified-Thiessen style interpolation, the Analysis Zone polygons in the 17 ranger units that were not directly simulated were assigned to the ‘closest’ matching modeled Analysis Zone, with the assistance of area and distance measurements computed on an Analysis Zone coverage in Arc/Info GIS (ESRI, 1998). The determination of closeness was based on an assessment of similarity in fuels, population density, climate characteristics, and geographic (Euclidean) distance. The escapes and area burned per hectare for the modeled

Analysis Zones were multiplied by the area represented by the comparable, interpolated Analysis Zones. For example, Analysis Zones in the Lassen-Modoc Ranger unit were represented by CCFMS results from Amador rather than the geographically closer Humboldt ranger unit because of climate and vegetation considerations. Coastal Analysis Zones as far south as San Mateo (south of San Francisco) were represented by Humboldt rather than the more proximal (but non-coastal) Santa Clara because of the dominating influence of fog on coastal northern California weather. In a few cases, subjective aggregation decisions were required because exactly equivalent Analysis Zones were not available. For example, some ranger units have only tall/hard chaparral and others have only low/soft chaparral; some interpolated Analysis Zones have population density/fuel combinations not found within the simulated areas.

3. Results

3.1. FIRE BEHAVIOR AND SUPPRESSION RESPONSE

For all three ranger units taken together, the climate change scenario increased the number of fast-burning fires and reduced the number of slow-burning fires (Figure 2a). Disaggregating results by ranger unit tells a different story (Figures 2b–d). Fire spread rates increased in Amador and Santa Clara, but in Humboldt spread rates did not change in forest fuels and decreased slightly in grass fuels. It appears that GCM predictions of slower winds and higher humidity in Humboldt offset the effects of higher temperatures. Considering impacts by vegetation type in Santa Clara and Amador, there were substantial increases in the frequency of fast-spreading fires in grass and moderate increases in brush (Figure 2e).

By influencing fuel moisture and wind speed, climatic change caused fires to burn with greater intensity in Amador and Santa Clara. Because intensity determines dispatch level, this triggered more intensive suppression efforts. Higher intensity fires are also more likely to overwhelm suppression efforts and to lead to greater damage to both natural resources and property.

The vast majority of fires under both present climate and double-CO_2 scenarios have moderate fireline intensity and rates of spread (Figures 2a–d), and are unlikely to become large, damaging fires. It is the few fires with extreme behavior (e.g., those that spread faster than 1800 m/h in Figure 2) that are most likely to become large and damaging. In Santa Clara and Amador, the number of such fires grows several-fold under climate change.

3.2. AREA BURNED AND ESCAPES

For two of the three ranger units analyzed, climatic change would result in substantial increases in escapes and area burned by contained fires in areas covered by grass and brush (Table II). In forests, and in the Humboldt ranger unit, fires move

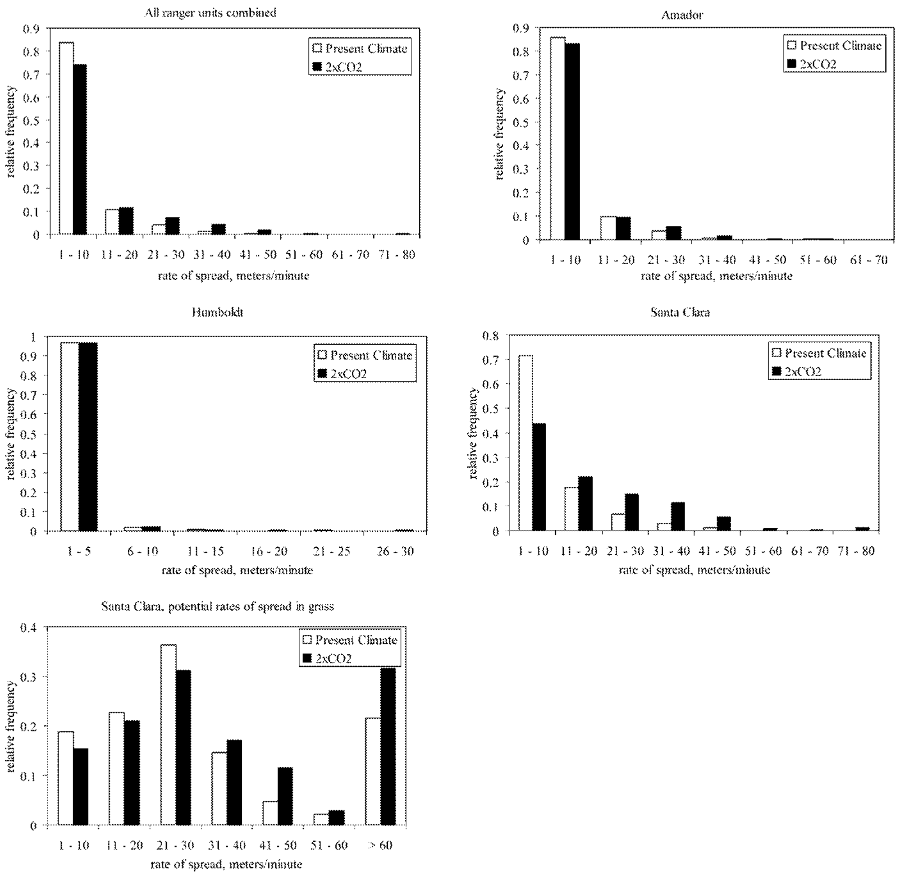

Figure 2. Frequency of predicted rates of spread (ROS) in m/min for 'historical' fires for Present Climate and $2{\times}CO_2$ climate change scenarios for (a) all three ranger units, (b) Amador ranger unit, (c) Humboldt ranger unit, (d) Santa Clara ranger unit, and (e) grass fuel Analysis Zones in the Santa Clara ranger unit.

much more slowly, and impacts would be slight. The greater impact of climate change in grass is not surprising given the greater influence of wind speed in rate-of-spread calculations for such fuels and the elevated wind speed predictions during fire season for the changed climate weather data (Torn and Fried, 1992). Response in chaparral and oak woodlands was intermediate between that in grass and forest.

The number of fires and area burned by size class for present and $2{\times}CO_2$ scenarios disaggregated by FDL, for each of the 16 Analysis Zones modeled, reveal some striking patterns (Table III). There was noticeable movement of fires into larger size classes, particularly in zones without escapes (e.g., some redwood forest Analysis Zones), and, some fires moved into higher dispatch categories.

In Santa Clara, contained fires in grass and brush burned 41% and 34% more area, respectively, under climate change than they did under the present climate.

Table II

Simulated annual escape frequency and area burned by contained fires under present and double-CO_2 climate scenarios by vegetation fuel type for three California Department of Forestry and Fire Protection ranger units

Ranger unit/ fuel	Number of fires	Number of escapes			Hectares in contained fires		
		Present climate	$2 \times CO_2$ climate	Percent change	Present climate	$2 \times CO_2$ climate	Percent change
Santa Clara							
Grass	168.1	4.5	6.9	53	938.0	1326.7	41
Brush	22.7	0.3	0.4	21	4.0	5.3	34
Tall brush	11.6	0.0	0.0	0	0.8	1.7	100
Redwood	23.0	0.0	0.0	0	0.8	0.9	7
Overall	225.4	4.8	7.3	51	943.6	1334.6	41
Amador							
Grass	58.5	1.2	2.8	143	691.6	885.8	28
Brush	62.9	5.0	11.1	121	89.6	187.1	109
Oak savanna	152.8	0.0	0.0	0	118.2	194.5	65
Mixed conifer	29.0	0.0	0.0	0	10.5	15.1	43
Overall	303.2	6.2	13.9	125	909.9	1282.5	41
Humboldt							
Grass	15.1	0.0	0.0	0	15.5	11.4	–27
Redwood	158.9	0.6	0.6	0	83.7	80.1	–4
Overall	174.0	0.6	0.6	0	99.3	91.5	–8

The number of escapes increased by 53% in grass and by 21% in brush. For the redwood forests in the coastal fog belt, there were enhanced fire-fighting efforts (triggered by the increase in fire intensity), higher suppression expenses, and a small change in area burned.

In Amador, the effect of climatic change was even more dramatic. The expected annual number of escapes rose 143% in grass and 121% in brush. The area burned by contained fires increased in all four vegetation fuel types: the area of brush burned more than doubled, and there was a 65% increase in the area of oak woodland burned (Table II).

Climate change had little impact in Humboldt due to comparatively slow fires, effective fire suppression, and GCM predictions of a wetter, less windy climate. Like the redwood forests of Santa Clara, those in Humboldt showed almost no change in escapes or area burned. The small area of grassland in Humboldt experienced a decrease in burned area and suppression efforts.

Table III

Simulated annual escape frequency, number of contained fires, area burned in contained fires, and number of contained fires by size class for present and double-CO_2 scenarios, by Fire Management Analysis Zone and Fire Dispatch Level, for the Amador (AEU), Humboldt (HUU) and Santa Clara (SCU) ranger units of the California Department of Forestry and Fire Protection

Analysis zone fuel population	FDL	Present climate								$2 \times CO_2$							
		Escapes	Number contained	Contained hectares	Number by size class					Escapes	Number contained	Contained hectares	Number by size class				
					1	2	3	4	5				1	2	3	4	5
AEUAH	L	0.0	6.1	1.2	2.4	3.7	0.0	0.0	0.0	0.0	5.8	1.0	4.6	1.2	0.0	0.0	0.0
Grass	M	0.0	6.8	28.3	0.0	2.7	3.4	0.0	0.7	0.0	6.5	29.9	0.0	2.6	3.3	0.0	0.7
High	H	1.2	4.6	62.8	0.0	0.0	2.3	0.0	2.3	1.3	5.2	127.6	0.0	0.0	0.0	2.6	2.6
AEUAL	L	0.0	13.0	11.1	0.0	10.4	2.6	0.0	0.0	0.0	11.5	14.8	0.0	9.2	2.3	0.0	0.0
Grass	M	0.0	13.9	111.7	0.0	0.0	12.5	1.4	0.0	0.0	13.0	121.5	0.0	0.0	10.4	2.6	0.0
Low	H	0.0	12.8	476.6	0.0	0.0	5.1	5.1	2.6	1.5	13.7	590.9	0.0	0.0	0.0	6.1	7.6
AEUBH	L	0.0	7.4	0.6	5.9	1.5	0.0	0.0	0.0	0.0	7.2	2.6	5.8	0.0	1.4	0.0	0.0
Brush	M	0.0	4.9	1.2	1.6	3.3	0.0	0.0	0.0	0.0	6.7	1.1	1.1	5.6	0.0	0.0	0.0
High	H	2.6	10.3	9.7	0.0	10.3	0.0	0.0	0.0	2.9	11.4	17.4	0.0	2.3	9.2	0.0	0.0
AEUBL	L	0.0	10.9	0.7	8.7	2.2	0.0	0.0	0.0	0.0	8.3	0.6	6.6	1.7	0.0	0.0	0.0
Brush	M	0.0	12.0	3.4	0.0	12.0	0.0	0.0	0.0	0.0	12.7	3.3	0.0	12.7	0.0	0.0	0.0
Low	H	2.4	9.6	74.0	0.0	0.0	4.8	4.8	0.0	8.2	5.5	162.0	0.0	0.0	0.0	0.0	5.5
AEUCH	L	0.0	27.1	1.1	25.3	1.8	0.0	0.0	0.0	0.0	23.5	1.0	21.9	1.6	0.0	0.0	0.0
Oak Savanna	M	0.0	32.5	12.3	0.0	32.5	0.0	0.0	0.0	0.0	31.0	12.7	0.0	31.0	0.0	0.0	0.0
High	H	0.0	31.3	74.3	0.0	8.3	20.9	2.1	0.0	0.0	36.5	126.9	0.0	9.6	24.4	2.5	0.0
AEUCL	L	0.0	21.6	1.0	18.7	2.9	0.0	0.0	0.0	0.0	19.0	1.0	15.2	3.8	0.0	0.0	0.0
Oak Savanna	M	0.0	20.3	3.8	5.4	14.9	0.0	0.0	0.0	0.0	19.9	4.2	5.3	14.7	0.0	0.0	0.0
Low	H	0.0	19.9	25.7	0.0	15.9	4.0	0.0	0.0	0.0	22.9	48.6	0.0	18.3	4.6	0.0	0.0
AEUUH	L	0.0	9.6	0.4	8.8	0.8	0.0	0.0	0.0	0.0	8.6	0.4	7.9	0.7	0.0	0.0	0.0
Mixed conifer	M	0.0	9.1	1.3	5.1	4.0	0.0	0.0	0.0	0.0	8.9	1.3	4.6	4.3	0.0	0.0	0.0
High	H	0.0	10.3	8.8	0.0	7.4	2.5	0.0	0.4	0.0	11.5	13.4	0.0	8.3	1.8	0.9	0.5
HUUAL	L	0.0	4.9	0.0	4.9	0.0	0.0	0.0	0.0	0.0	5.2	0.0	5.2	0.0	0.0	0.0	0.0
Grass	M	0.0	3.6	0.1	3.6	0.0	0.0	0.0	0.0	0.0	3.9	0.1	3.9	0.0	0.0	0.0	0.0
Low	H	0.0	6.6	15.4	0.0	5.3	1.2	0.1	0.0	0.0	6.0	11.2	0.0	4.8	1.2	0.0	0.0

Table III
(Continued)

Analysis zone fuel population	FDL	Present climate: Escapes	Present climate: Number contained	Present climate: Contained hectares	Present: Number by size class 1	2	3	4	5	$2 \times CO_2$: Escapes	$2 \times CO_2$: Number contained	$2 \times CO_2$: Contained hectares	$2 \times CO_2$: Number by size class 1	2	3	4	5
HUUGL	L	0.0	37.1	1.4	35.9	1.3	0.0	0.0	0.0	0.0	38.4	1.5	37.4	1.0	0.0	0.0	0.0
Redwood	M	0.0	28.1	4.4	9.3	18.2	0.6	0.0	0.0	0.0	28.1	4.5	9.3	18.8	0.0	0.0	0.0
Low	H	0.0	34.5	58.2	0.0	10.1	23.6	0.8	0.0	0.0	33.0	54.2	0.0	9.8	22.4	0.8	0.0
HUUGM	L	0.0	19.3	0.8	19.3	0.0	0.0	0.0	0.0	0.0	20.1	0.8	20.1	0.0	0.0	0.0	0.0
Redwood	M	0.6	15.6	14.6	10.4	2.6	1.9	0.7	0.0	0.6	15.6	15.0	10.4	2.6	1.9	0.7	0.0
Moderate	H	0.0	24.0	4.4	11.8	12.2	0.0	0.0	0.0	0.0	23.1	4.2	11.3	11.8	0.0	0.0	0.0
SCUAL	L	0.0	53.1	14.4	39.7	11.3	2.1	0.0	0.0	0.0	51.0	21.9	25.5	23.5	1.6	0.4	0.0
Grass	M	0.2	26.0	217.6	0.0	0.0	24.4	0.0	1.6	1.9	25.2	158.8	0.0	0.0	21.0	4.2	0.0
Low	H	2.4	4.4	174.1	0.0	0.0	0.0	3.7	0.7	2.8	5.1	344.2	0.0	0.0	0.0	0.0	5.1
SCUAM	L	0.0	53.8	24.8	13.8	34.8	5.3	0.0	0.0	0.0	48.8	29.7	12.5	31.5	4.8	0.0	0.0
Grass	M	0.0	24.5	317.2	0.0	5.7	14.8	2.1	2.0	0.2	28.1	516.5	0.0	6.6	13.1	5.3	3.2
Moderate	H	1.9	2.0	190.0	0.0	0.0	0.0	0.0	2.0	2.0	3.0	255.6	0.0	0.0	0.0	0.0	3.0
SCUBL	L	0.0	5.4	0.5	4.4	1.0	0.0	0.0	0.0	0.0	4.6	0.4	3.7	0.9	0.0	0.0	0.0
Brush	M	0.2	4.6	0.8	2.5	2.1	0.0	0.0	0.0	0.2	5.4	0.9	3.6	1.8	0.0	0.0	0.0
Low	H	0.2	0.7	0.2	0.3	0.3	0.1	0.0	0.0	0.2	0.7	1.1	0.0	0.5	0.1	0.0	0.0
SCUBM	L	0.0	8.1	0.3	7.6	0.5	0.0	0.0	0.0	0.0	7.6	0.3	7.1	0.5	0.0	0.0	0.0
Brush	M	0.0	2.8	0.3	1.9	0.9	0.0	0.0	0.0	0.0	3.4	0.5	1.9	1.5	0.0	0.0	0.0
Moderate	H	0.0	0.7	1.8	0.0	0.6	0.0	0.1	0.0	0.0	0.7	2.1	0.0	0.6	0.0	0.0	0.1
SCUFM	L	0.0	8.5	0.2	8.5	0.0	0.0	0.0	0.0	0.0	8.3	0.3	8.3	0.0	0.0	0.0	0.0
Tall brush	M	0.0	2.2	0.2	1.8	0.4	0.0	0.0	0.0	0.0	2.4	0.4	1.9	0.5	0.0	0.0	0.0
Moderate	H	0.0	0.9	0.4	0.0	0.9	0.0	0.0	0.0	0.0	0.9	1.0	0.0	0.7	0.2	0.0	0.0
SCUGM	L	0.0	17.3	0.4	17.3	0.0	0.0	0.0	0.0	0.0	16.3	0.4	16.3	0.0	0.0	0.0	0.0
Redwood	M	0.0	5.2	0.4	4.6	0.6	0.0	0.0	0.0	0.0	5.9	0.4	3.9	2.0	0.0	0.0	0.0
Moderate	H	0.0	0.6	0.1	0.2	0.4	0.0	0.0	0.0	0.0	0.8	0.1	0.5	0.4	0.0	0.0	0.0

Table IV

Simulated annual escape frequency and area burned by contained fires under present and double-CO_2 climate scenarios by vegetation fuel type and population density for fire management analysis zones that have escapes under the double-CO_2 climate scenarios, in the Santa Clara and Amador ranger units

Ranger unit fuel population	Number of fires of fires	Number of escapes Present climate	$2 \times CO_2$ climate	Percent change	Hectares in contained fires Present climate	$2 \times CO_2$ climate	Percent change
Santa Clara							
Grass							
Low	86.0	2.6	4.7	80	1003.43	1297.30	29
Moderate	82.1	1.9	2.2	16	1314.33	1981.13	51
Brush							
Low	11.0	0.3	0.4	9	3.71	5.80	56
Moderate	11.7	0.0	0.1	–	6.07	7.31	20
Amador							
Grass							
Low	39.7	0.0	1.5	–	1481.11	1797.10	21
High	18.8	1.2	1.3	12	227.95	391.74	72
Brush							
Low	34.7	2.4	8.2	242	192.94	410.02	113
High	28.2	2.6	2.9	11	28.39	52.33	84

Where climate change led to increased escape frequencies, most of the increase occurred in low population density Analysis Zones (Table IV). The dependence of suppression response on population density and fire dispatch level led to seemingly counter-intuitive results in some cases, and contributes to the difficulty of interpreting the more subtle outcomes represented by changes in the number of contained fires by size class (Table III). For example, in Amador's high population density, oak savanna Analysis Zone, the number of fires in the smallest and two largest size classes dropped, with no change in the number of escapes, for a variety of interacting and countervailing reasons, such as: (1) under climate change, fire severity increases in some months, but decreases in others; (2) more severe fire weather can move fires to higher dispatch levels (so that they are attacked more vigorously and contained at smaller sizes); and, (3) fire behavior may become more extreme, but not sufficiently so to increase dispatch level, so that final fire size increases.

The interpolation to all State responsibility area in northern California predicts that climate change will lead to an additional 114 escapes per year on average,

Table V

Simulated annual number of escapes and area burned by contained fires for CDF protected wildlands in northern California (north of Latitude 35.8° N) by broad vegetation fuel class and population density under present climate and double-CO_2 scenarios

Vegetation fuel	Population density	Number of escapes per year			Hectares in contained fires		
		Present climate	$2 \times CO_2$ climate	Percent change	Present climate	$2 \times CO_2$ climate	Percent change
Grass	Low	16.7	37.8	127	5830.72	7354.76	26
Brush	Low	38.3	125.0	226	1175.21	2491.25	112
Forest	Low	0.0	0.0	0	409.54	526.50	29
Grass	Medium	8.0	9.1	14	1678.23	2631.67	57
Brush	Medium	23.9	26.8	12	131.12	230.67	76
Forest	Medium	1.4	1.4	0	71.63	83.37	16
Grass	High	6.2	7.1	14	1239.55	1964.35	58
Brush	High	14.8	16.8	13	95.10	162.68	71
Forest	High	0.1	0.1	0	19.83	26.30	32
Total		109.5	224.2		10651.34	15471.55	

more than doubling the current 110 escapes per year under the present climate, and an additional 5,000 ha burned in contained fires (Table V). Because CCFMS predicts expected value conditions, these represent long-term averages. In reality, some years could be expected to have much less damage, and others much more than these predictions suggest (Fried and Gilless, 1993).

4. Discussion

The post-climate change statistics for northern California (15,300 hectares in contained fires and 224 escapes) may seem low when considered as a fraction of the area protected (9,700,000 hectares). Yet, applying the historical, regional mean escape size (1600 hectares, CDF, 1998) implies an annual burned area roughly equal to 4% of the region versus 2% for the present climate case, which is equivalent to a halving of fire return interval from 50 to 25 years. The limitations and conservatism of these estimates is discussed below in the modeling and suppression sections. We also discuss the potential ecological, social and economic implications of the estimated increases in fire severity.

4.1. MODELING: FEEDBACKS, CONSERVATISMS, AND CAVEATS

By using 'conservative' climate model projections and disregarding various feedbacks, the estimates reported represent a *minimum* expected change, or best-case forecast. Although fire behavior is controlled by both fuel moisture content and fuel structure (e.g., packing density, surface to volume ratio), we only addressed the direct effects of climate change on fuel moisture content. For example, we did not consider the indirect effects of climate change on rates of plant growth or vegetation distribution (Westman and Malanson, 1992) or the effects of increased lightning on ignitions (Price and Rind, 1994). It is possible that the predicted increase in winter precipitation will result in higher fuel loadings during the fire season. However, recent analysis of fire frequency in southern California did not find a correlation between large fires and fuel age or density (Keeley et al., 1999). In terms of shifts in plant type, exogenously generated vegetation scenarios could be used to re-parameterize the fuel models used in CCFMS to assess the effects of climate-induced changes in fuel structure.

In a feedback with potentially serious consequences, wildfires may create conditions that set the stage for subsequent wildfires. In much of California, increased fire frequency (shorter return interval) favors grass and shrub vegetation over longer-lived vegetation such as forests. These ecosystems show the greatest susceptibility to fire under current conditions, and fires in these ecosystems show the greatest increase in response to climate change. Consequently, the effect of climatic change on wildfire may be more severe than our model predicts due to fire-induced changes in vegetation distribution.

Although the results for changes in escape frequency and area burned by contained fires will be useful to more audiences than would changes in fire danger indices, they fall short of predicting specific damages like lives lost or homes destroyed. In part, this is because the skewed distribution of escapes limits the usefulness of mean escape size – the rare, very large, fire (that may happen only once every 20 or 50 years) drives that statistic.

CCFMS only models surface fire behavior, which may lead to an underestimate of fire severity in forests. In forest fuel types, surface fire behavior is rarely extreme enough to generate escapes. However, extreme weather can convert a surface fire into a crown fire (where fire spreads from crown to crown), at which point the surface fire spread rates grossly underestimate actual fire spread rates and our model would underestimate the frequency of escapes.

CCFMS was designed to assess the physical aspects of the wildland fire system; it was not designed to estimate the stochastic, contingent, and spatially heterogeneous economic and social impacts, notwithstanding their importance to those in the policy and management arena (Gilless and Fried, 1991). If 'production functions' for such impacts are constructed and linked to CCFMS outputs, mitigating actions such as fire protection enhancement could be represented, enabling parametric assessment of the costs of compensatory societal responses to climate change. In the interim, statistics (e.g., median, quartiles) can be calculated from historical data on damages, fatalities, and fire size frequency distributions and used to make qualitative statements about changes in damages based on predicted changes in fire size class distributions.

Another limitation to the current approach is the deterministic structure of the fire suppression model. Our results are based on the difference between expected-value fire years under present and future climate scenarios. A stochastic model would make it possible to characterize changes in the severity of unusual years (e.g., 1 out of 10 year worst case) – a statistic that might generate different reactions in a risk-averse manager or homeowner than the change in the expected value statistics (Fried and Gilless, 1988b, 1999).

Despite the caveats, by generating predictions of escape frequency and area burned that reflect the interaction of fire growth and suppression, our modeling approach addresses changes in fire outcomes of greatest interest to fire and resource managers. These statistics, along with optional model output such as the utilization frequency of firefighting resources, can be used to evaluate likely impacts on fire protection efficacy and efficiency, as well as ecosystems, smoke emissions, and economic losses.

4.2. ECOSYSTEM IMPACTS

Our predicted changes in fire intensity and fire return interval would have repercussions for California's vegetation dynamics, natural resources, and ecosystem services. The landscape-level effects of wildfire disturbance include landslides, flooding, erosion, and water-quality impairment. In California, where the majority of sediment entering streams does so after fires, shorter fire return intervals would affect stream habitats, degrade water quality, and increase dam siltation and potential flood severity (Keller et al., 1997; Florsheim et al., 1991).

Consequently, the distribution of plant species is expected to change in response to climatic change, but the rate of change is highly uncertain. In many places, wildfire will play a critical role in determining the rate and type of vegetation changes that occur. In a study of southern California coastal sage scrub, climate-induced changes in fire intensity had more effect on plant growth and survival than did the direct effects of changes in temperature and precipitation (Malanson and Westman, 1991). Another outcome is a likely shift in the competitive balance between currently co-existing species or communities. For example, *Artemisia californica* and *Salvia mellifera* are more sensitive to fire return interval than are *Eriogonum cinereum, Encelia californica*, and *Salvia leucophylla* (Malanson and Westman, 1991) and chamise chaparral, *Adenostoma fasciculatum*, is relatively fire insensitive (Minnich and Bahre, 1995).

Wildfire activity will accelerate the change in species' distributions because mortality from wildfire removes the existing vegetation and exposes the most climate-sensitive life stages (germination and sprouting) to the new climate (Ryan, 1991). A shorter fire return interval would slow invasion by emerging woody species that are killed by fire (Greenlee and Langenheim, 1990) and low-intensity ground fires can stem *Baccharis* invasion into grassland (McBride and Heady, 1966). As a result of these effects, increased fire severity will both amplify and accelerate the ecological impacts of climatic change.

4.3. ROLE OF FIRE SUPPRESSION

In our model results, increases in fire spread rate and intensity had much greater than expected impact on fire outcomes. Even modest shifts upward in the spread rate distribution translated to large increases in the number of escapes, because the initial attack system does not have the resources to handle much more than the current baseline. As a result, earlier climate change impact studies that report only changes in fire behavior may miss a non-linear response in fire outcomes, particularly in locations where fire suppression is practiced.

In our results, fire spread rates and intensity increased throughout most of analysis region, yet the resulting increase in area burned was concentrated in low-population-density areas, where all but 6% of the additional escapes and 40% of the additional area burned by contained fires occurred. This is because fewer fire suppression resources are typically dispatched to these predominantly rural areas. In these simulations, the greater suppression effort prevented big changes in fire outcomes in densely populated areas (Table IV). Nevertheless, the expected additional nine escapes per year in moderate- to high-population-density zones would almost certainly result in additional homes and lives lost. One approach to mitigating climate change impacts would be to reduce the number of large fires in low population areas via additional investment in fire protection infrastructure. A policy response of increasing suppression infrastructure could be quite costly; California currently spends more than $250 million per year on initial attack fire protection (CDF, 1996).

Long run damages and area burned may be insensitive to suppression intensity. First, over the long-term, suppression can lead to a buildup of fuel that exacerbates fire danger. By the same principle, in suppression-free areas, the reduction in fuel loading from increased fire frequency can have a self-limiting effect on area burned. Second, fires can escape and burn large areas, even with high suppression intensity. For example, a landscape analysis of fire-interval and area-burned statistics in southern California and Baja found little sensitivity to suppression intensity because areas without suppression had a patchy and heterogeneous distribution of vegetation age classes resulting from prior, unsuppressed fires, which tended to limit fire size (Minnich and Chou, 1997; Chou et al., 1993). It has been proposed that fuel management oriented towards creating a mosaic of vegetation types and age classes may have the potential to limit the size of escapes (Salazar and Gonzalez-Caban, 1987). CCFMS does not have the spatial specificity to effectively address these issues.

4.4. SOCIAL AND ECONOMIC IMPACTS

The social and economic effects of wildfire manifest through property loss (e.g., buildings, personal property, timber), firefighting costs, injuries, and loss of life. Wildfires are a pervasive risk in the United States, burning an average of 2 million hectares per year and occurring in every state in some years (ISO, 1997; Mills, 1998; Peara and Mills, 1999). Between 1985 and 1994, wildfires destroyed more than 9,000 homes in the U.S. at an average insured cost of about $300 million per year, nearly an order of magnitude greater than during the three decades prior to 1985. While the acceleration in housing development in areas with fire-prone vegetation is an important driver of the upward trend, the Intergovernmental Panel on Climate Change recognizes that observed increases in disaster losses tend to be caused by a combination of climate change and demographic factors (Watson et al., 2001).

In California, as in much of the world, patterns of development are superimposed on patterns of vegetation in ways that may amplify the consequences of wildfire. In the Sierra Nevada, for example, population growth and density are often much greater in the fast-burning grass, chaparral, and oak woodlands common at low elevations than at higher, forested elevations.

Given that California's population density is increasing in high-risk areas, additional infrastructure investment may fail to offset the increased danger. For example, firefighting resources are already diverted to protecting structures in high-population-density zones at the expense of the capacity to control the growth in fire perimeter, resulting in larger fires. If present development trends continue, the economic impact of 114 additional escapes per year could well be substantial. Even with no augmentation of firefighting forces, firefighting costs will increase as climate change accelerates the development of fires to higher dispatch levels where more expensive resources (e.g., air tankers and bulldozers) are routinely utilized.

The Oakland/Berkeley Tunnel Fire of 1991 demonstrates the enormous damage potential of even a single fire in the wildland-urban interface. The third costliest fire in U.S. history, it resulted in $2 billion in insured losses (at 1997 prices), including the destruction of 3,400 buildings and 2,000 cars (ISO, 1997). For reference, this compares with the losses resulting from a major hurricane. Added to this were extensive losses of urban infrastructure (e.g., telecommunication, water, and transportation systems); the costs of which are borne largely by local government. The insured losses from this single fire were twice the cumulative losses experienced nationwide during the previous thirty years. Swiss Reinsurance company (1992) cited global climate change as a possible factor influencing the extent of damages caused by this and future wildfires.

5. Conclusions

Climatic change results in more frequent and more intense fires in northern California, where escape frequencies increased by more than 100%, based on relatively conservative GCM output and despite more extensive utilization of available firefighting forces. The greatest increases in fire spread rates and area burned occur in landscapes dominated by grass and brush. Only 9 of the 114 additional escapes occur in high population areas due to the greater depth of fire suppression resources available.

Because predicted climate change is heterogeneous, some areas will likely experience a negligible change in fire severity while others will experience a large increase. Ultimately, the effect of climate change on wildfire severity will depend on pre-suppression activities, fire suppression strategies, human settlement patterns, the degree of climate change, and how these affect vegetation type and fuel loading.

Policymakers, risk managers, and the disaster preparedness/recovery community often find limited utility in traditional climate change model outputs, given their coarse spatial scales and lack of impacts analysis. This study illustrates the potential role of coupled climate and impacts models in better serving these communities.

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