Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest

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[1] The diverse vegetation types and carbon pools of the U.S. Pacific Northwest (PNW) are tightly coupled to fire regimes that depend on climate and fire suppression. To realistically assess the effects of twenty-first-century climate change on PNW fire and carbon dynamics, we developed a new fire suppression rule for the MC1 dynamic general vegetation model that we ran under three climate change scenarios. Climate projections from the CSIRO Mk3, MIROC 3.2 medres, and Hadley CM3 general circulation models, forced by the A2 CO_2 emissions scenario, were downscaled to a 30 arc-second (~0.6 km^2) grid. Future climates amplify the already strong seasonality of temperature and precipitation across the domain. Simulations displayed large increases in area burned (76%–310%) and burn severities (29%–41%) by the end of the twenty-first century. The relatively dry ecosystems east of the Cascades gain carbon in the future despite projections of more intense wildfires, while the mesic maritime forests lose up to 1.2 Pg C from increased burning. Simulated fire suppression causes overall carbon gains yet leaves ecosystems vulnerable to large future fires. Overall, our simulations suggest the Pacific Northwest has the potential to sequester ~1 Pg C over the next century unless summer droughts severely intensify fire regimes.

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1. Introduction

[2] Changes in twenty-first-century climate are projected to cause an increase in wildfires in many ecosystems [*Flannigan et al.*, 2009], which may adversely affect the terrestrial carbon sink [*Kasischke et al.*, 1995; *Williams et al.*, 2004; *Mouillot and Field*, 2005]. The U.S. Pacific Northwest (PNW) contains a wide variety of tightly coupled biomes and fire regimes, which have been sensitive to past climatic shifts during the Holocene and medieval warm period [*Whitlock et al.*, 2003] and may be vulnerable to future changes. This sensitivity stems in part from the PNW's strong seasonality of cool wet winters and warm-hot dry summers, which becomes amplified in most climate projections [*Mote and Salathé*, 2010]. On a per area basis, the PNW contains some of the world's highest biomass forests with a tremendous potential for carbon storage [*Hudiburg et al.*, 2009; *Smithwick et al.*, 2002]. Future increases in growing season length and atmospheric CO_2 concentration may enhance ecosystem productivity and carbon sequestration that may or may not mitigate the impacts of summer drought and wildfires [*Cubasch et al.*, 2001], although progressive nitrogen limitation may attenuate the CO_2 fertilization effect [*Thornton et al.*, 2009, 2007].

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[3] Historic fire return intervals are estimated at 200–500 years in the mesic forests in the western third of the PNW and they were usually large, stand-replacing fires that occurred in rare conditions of high winds and drought. In contrast, the drier mixed conifer forests in the eastern PNW were adapted to shorter fire return intervals on the order of 10–50 years [*Agee*, 1996]. Anthropogenic fire suppression has substantially altered natural fire regimes and vegetation compositions in many of these eastern (semi)arid ecosystems. Fire suppression is estimated to have decreased burned area by an order of magnitude since the mid-twentieth century [*Pacala et al.*, 2001], promoting woody encroachment [*Hessburg et al.*, 2000] and denser forests with higher abundances of small trees and ladder fuels that increase vulnerability to large fires [*Stephens et al.*, 2009]. Although certain agencies are starting to selectively let some fires burn, for the most part similar fire suppression efforts are expected to continue into the future [*Berry*, 2007] and thus represent an essential control on U.S. fire regimes.

[4] A number of studies have predicted substantial increases in annual burn area for the PNW; however, these studies

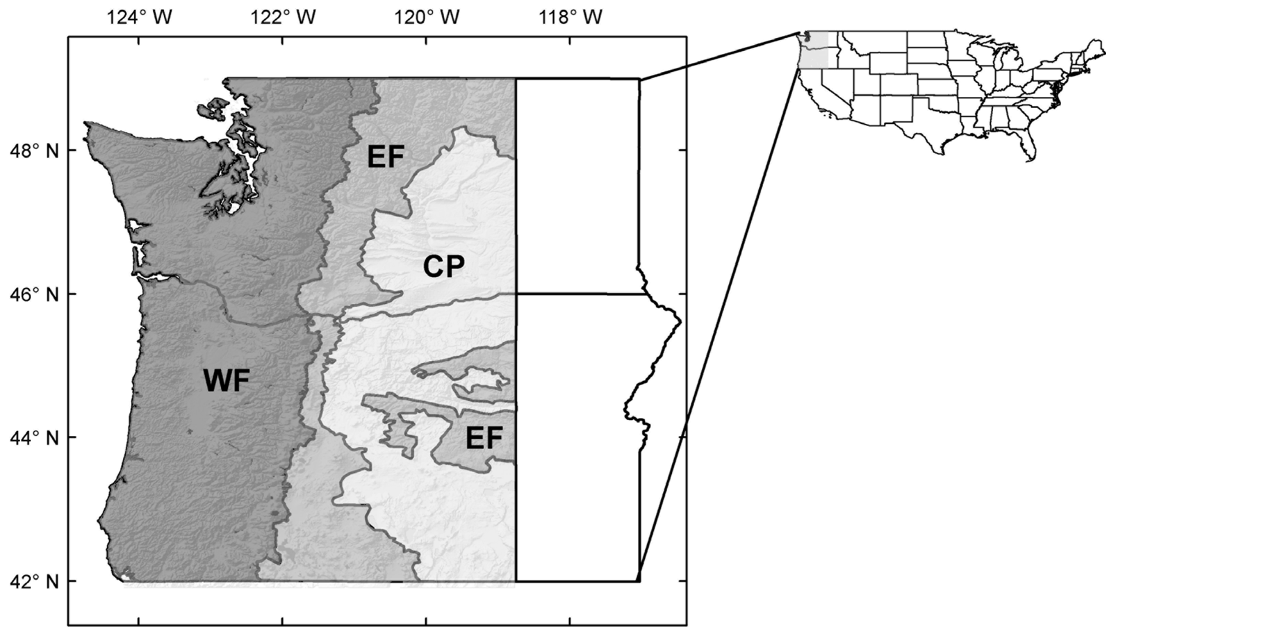

Figure 1. U.S. Pacific Northwest study domain: WF = Western Forests, EF = Eastern Forests, CP = Columbia Plateau.

either simulate much larger domains [e.g., *Bachelet et al.*, 2004] or use statistical fire models [e.g., *McKenzie et al.*, 2004; *Littell et al.*, 2010]. Statistical models provide a straightforward and species-specific approach, yet they depend upon the choice of explanatory variable, may be extrapolated beyond the scope of their historical climates used for fitting, are unable to account for CO_2 fertilization effects and biotic feedbacks, do not couple fire regimes to carbon stocks, and are difficult to construct for the PNW's mesic maritime forests because of low annual burn area [*Littell et al.*, 2010]. Instead, it has been suggested that mechanistic ecosystem models that include fire, such as dynamic general vegetation models (DGVMs), be used on regional domains to understand the future role of fire in the PNW [*Gavin et al.*, 2007; *Littell et al.*, 2010]. However, because of the estimated decrease in burn area due to fire suppression, DGVMs without explicit suppression rules are expected to overestimate burned area by an order of magnitude across the U.S.

[5] The twenty-first-century carbon budget of the PNW will likely be a balance between competing processes, such as increased spring precipitation and CO_2 fertilization versus summer drought and intensified fire regimes. Because of the region's high diversity, different ecoregions within the PNW may respond in contrasting ways to these interacting factors. Based on paleoclimate data and other modeling efforts, fire will likely play a crucial role, although anthropogenic suppression exerts a dominant control on burned area. In order to assess which processes may dominate the PNW's carbon budget and fire regimes over the coming century and where, we used a DGVM, the MAPSS-CENTURY 1 model (MC1) [*Bachelet et al.*, 2001], that is able to capture the interactions and feedbacks between major ecosystem processes. We developed a new fire suppression rule for MC1 based on metrics of modeled fire intensity that directly relate to firefighting capabilities. We then ran MC1 over the PNW on a fine-scale grid (30 arc-seconds) under historical and three projected future climates and conducted sensitivity analyses to highlight the potential changes and most important drivers.

2. Data and Methods

2.1. Study Domain

[6] Our study domain covers roughly the western three-quarters of Oregon and Washington (Figure 1). For analysis purposes, level III ecoregions [*Bailey*, 1995] that displayed similar historical climates and vegetation types, and reacted in comparable ways in the future, were aggregated into three regions: Western Forests, Eastern Forests, and the Columbia Plateau. Western Forests experience a maritime climate with high rainfall, averaging 2003 mm of mean annual precipitation (MAP) between 1971 and 2000, and are comprised of high-biomass conifer forests characterized by long fire return intervals (~200–500 years). Eastern Forests are considerably drier (717 mm MAP) and burn more frequently (~50 years). The Columbia Plateau is the driest of the regions (295 mm MAP), and is dominated by grasslands, shrublands, and woodlands.

2.2. Input Data

[7] The MC1 DGVM requires inputs of soil (depth, texture, and bulk density), monthly climate, and yearly ambient CO_2. Soils data were modified from *Kern* [1995]. Historical climate data (1895–2006) were obtained from the PRISM [*Daly et al.*, 2008] model at 30-arc-second resolution (~0.6 km^2). Future climate projections were obtained from three general circulation models (GCMs), chosen for their representative range of temperature changes, forced by the IPCC SRES A2 emissions scenario [*Nakićenović et al.*, 2000]: CSIRO Mk3 [*Gordon*, 2002], MIROC 3.2 medres [*Hasumi and Emori*, 2004], and Hadley CM3 [*Johns et al.*, 2003] (hereafter CSIRO, MIROC, and Hadley).

[8] GCM climate fields were downscaled to our 0.6 km^2 grid using the delta, or perturbation, method [*Fowler et al.*, 2007]. For each climate variable (monthly vapor pressure, precipitation, mean temperature, and mean daily maximum and minimum temperatures) and each future month, anomalies between future and mean monthly historical (1971–2000) GCM-simulated values were calculated. Difference anomalies were used for temperature and ratio anomalies were used for vapor pressure and precipitation (capped at a maximum of five). To reduce GCM biases in temperature ranges, maximum and minimum temperature difference anomalies were calculated with respect to mean temperatures, normalized against 1971–2000 observations, and applied to future mean temperatures. Anomalies were downscaled to our fine resolution grid using binomial interpolation and then applied to the mean high-resolution historical climatology from the PRISM model. More sophisticated downscaling techniques are available, such as higher-order statistical methods and regional climate models. However, the more complex statistical techniques add little skill over the delta method in producing monthly climatologies [*Diaz-Nieto and Wilby*, 2005; *Maurer and Hidalgo*, 2008]. Regional climate models capture the effects of local climate feedbacks, topography, and meteorology, yet they retain the large-scale biases in upper air patterns inherited from the GCMs and remain somewhat impractical for deriving century-long data sets of multiple scenarios because of computing resource demands [*Fowler et al.*, 2007; *Salathe et al.*, 2007]. Domain-averaged interannual precipitation variability was measured in two ways: the standard deviation of annual precipitation calculated relative to (1) a scenario's linear trend, and (2) a scenario's previous year's precipitation.

2.3. Model Description

[9] MC1 originated from a coupling between the MAPSS biogeography model [*Neilson*, 1995], the CENTURY biogeochemistry model [*Parton et al.*, 1987], and MCFIRE, a mechanistic fire model [*Lenihan et al.*, 1998]. The biogeochemistry module simulates water and nutrient cycling, plant productivity and mortality, and organic matter decomposition. Competition between woody and herbaceous life forms is constrained by temperature and available soil water, nutrients, and light. The biogeography module assigns vegetation types based on woody versus herbaceous biomass stocks and climatic indices. MCFIRE simulates the occurrence, intensity, and effects of fire. Its complexity lies somewhere between the detailed local- to regional-scale empirical and cellular automata models [e.g., *Finney and Ryan*, 1995; *Hargrove et al.*, 2000; *Yang et al.*, 2004; *Yassemi et al.*, 2008] and the simpler fire modules of global scale GCMs [e.g., *Thonicke et al.*, 2001; *Kloster et al.*, 2010]. MCFIRE is thus able resolve multiple fuel classes, moisture contents, and fire intensities without requiring detailed landscape data inputs, therefore making it suitable for regional-scale studies using GCM-derived input fields. Additional details on MCFIRE are given by *Lenihan et al.* [1998]. MC1 is routinely implemented on time scales of months to centuries and on spatial scales from 30 arc-seconds (~800 m) to 0.5° (~50 km). Additional information on general model formulation is provided by *Bachelet et al.* [2001].

[10] A new fire suppression rule based on metrics of fire intensity was implemented to better represent actual suppression tactics and limitations, historical burned area, and effects on ecosystem composition. Fireline intensity, or flame length, and rate of spread at the fire front, both of which are simulated by the model using Rothermel ground fire algorithms [*Rothermel*, 1972], are two main metrics that determine the feasibility and strategy of suppression [*NWCG*, 1996]. Based on these observations, simulated fires were allowed to burn naturally if thresholds for fireline intensity (3.1 MW m^{-1}) or rate of spread (0.51 m s^{-1}) were exceeded. Below these thresholds, burned area was capped at 0.06% of the grid cell per fire.

2.4. Calibration and Validation

[11] MC1 historical output was compared to a wide variety of observations in the PNW for calibration and validation purposes. Model fire suppression thresholds were obtained by optimizing the comparison in our study domain between MC1 historical burn area and (1) gridded 1° × 1° data from *Westerling et al.* [2003], and (2) the 95% rule, which states that that approximately 95% of historical fires in the western U.S. have been suppressed since the mid-twentieth century, and the remaining 2%–5% escaped fires burn approximately 95% of the area [*Graham et al.*, 1999]. The resulting model thresholds are similar to values at which fire fighting becomes ineffective. When fireline intensities reach between 1.7 MW m^{-1} and 3.5 MW m^{-1}, torching, crowning, and spotting may occur and control efforts at the fire front will probably be ineffective [*Agee*, 1996]. Similarly, spread rates over 0.5 m s^{-1} (1.1 mph) may thwart suppression efforts, in part because of the difficulty in continually walking this speed in complex terrains. The previous fire suppression rule reduced all fires' burn areas by 87.5%. While the implementation of this rule leads to favorable comparisons with observations across the continental U.S., it cannot discriminate between fire intensities, which greatly affect the success of suppression efforts, and thus results in distinctly different projected ecosystem impacts.

[12] Vegetation types simulated with full fire for the period 1971–2000 were compared to the potential vegetation map devised by *Kuchler* [1975], in which vegetation types were aggregated into 35 classes as part of the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP) [*Kittel et al.*, 1995]. Biogeography thresholds were calibrated so that modeled vegetation better matched Kuchler's map. Simulated combustion factors (fraction of biomass combusted by fire) for different carbon pools from the 2002 Biscuit Fire in southwestern Oregon were compared to data compiled and analyzed by *Campbell et al.* [2007].

[13] Simulated carbon fluxes and pools were compared to four data sets. An aggregated database of periodic Forest Inventory and Analysis (FIA) plots in Oregon described by *Hudiburg et al.* [2009] was used to calibrate net primary production (NPP), mortality, and live and dead aboveground and belowground carbon pools. MC1 was run under varying conditions, including full fire, fire suppression, and no fire, to emulate plots classified by ecoregion and disturbance history. A gridded map of aboveground forest biomass developed by *Blackard et al.* [2008], who interpolated FIA plots using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, was used to validate ecoregion-specific aboveground forest carbon over the entire domain. A separate comparison was carried out using data on old-

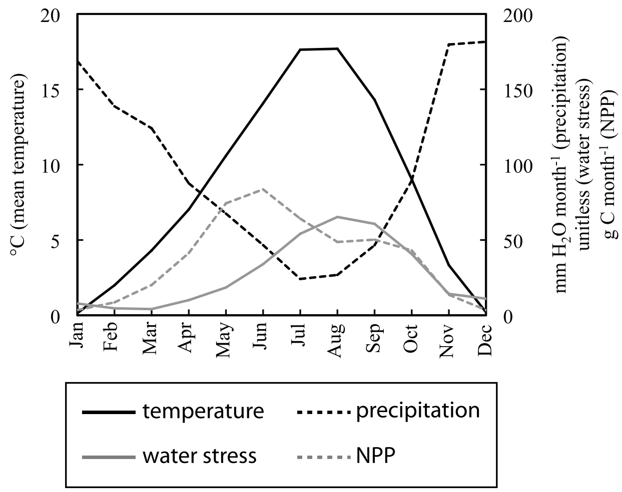

Figure 2. Mean monthly historical (1971–2000) temperature, precipitation, water stress, and net primary production (NPP). Water stress is defined as 100*(1 – w_s/PET), where w_s = mean monthly available soil water and PET = potential evapotranspiration.

growth forests in the Western Forests region from three data sets: *Smithwick et al.* [2002], the periodic FIA plots used by *Hudiburg et al.* [2009], and the Environmental Protection Agency (EPA) plots used in the ORCA regional carbon study [*Hudiburg et al.*, 2009; *Sun et al.*, 2004]. To ensure simulated grid-cells were undisturbed, fire was turned off in MC1. Old-growth forests are defined as those older than 180 years, measured by the Spies and Franklin, or Van Tuyl, method [*Spies and Franklin*, 1991; *Van Tuyl et al.*, 2005]. The majority of all plot data were collected between 1991 and 2001, with a few observations post-2001. Simulated annual averages of the model variables from 1991 to 2001 were therefore used for data-model comparisons. The seasonality of NPP in MC1 was also compared to the MODIS Aqua satellite product [*Running et al.*, 2004] and eddy covariance data from the Metolius Intermediate Pine site [*Law et al.*, 2003], the only AmeriFlux site within the domain that resolved NPP. In all plot-based comparisons, MC1 results were extracted from the grid-cell containing the location of a given observational plot. Model parameters for woody and herbaceous mortality, productivity, evaporation, and transpiration were augmented during calibration to the measured carbon flux and stock data. When interpreting these comparisons, it should be noted that AmeriFlux tower data and models of satellite spectral data undoubtedly incorporate a land-use history or spectral calibration that could bias the calibration. Additionally, comparisons with plot data must take into account disturbance history and the method of plot selection, which may differ between data sets and misrepresent the domain as a whole.

2.5. Simulation Protocols

[14] MC1 was first run with a mean 1895–2006 climate for up to 3000 years to establish initial carbon pools, and second spun up with a de-trended and looped 1895–2006 time series for an additional 3000 years to establish stable fire dynamics and vegetation responses. Historical simulations began in 1895, and future scenarios in 2007. Fire suppression was initiated in 1940, as this decade marks the beginning of widespread successful fire suppression [*Pyne*, 1982].

[15] Two Monte Carlo sensitivity analyses were conducted to test the dependencies of model output on the choice of input parameters and climate scenario. In each analysis, 100 randomly selected points were run through the entire time series (historical and three future GCMs) for the same 100 different choices of parameters, which were selected randomly from a Latin hypercube of ±20%. The first sensitivity analysis changed 30 parameters that controlled key elements of productivity, mortality, decomposition, CO_2 fertilization, evapotranspiration, and thresholds for fire suppression (see Table S1 in the auxiliary material).[1] Nitrogen was either chosen to be limiting or not, and future climates were selected from the three GCMs run through either the B1, A1B, or A2 CO_2 emissions scenario [*Nakićenović et al.*, 2000]. Only the fire suppression thresholds (rate of spread and fireline intensity) were changed for the second analysis.

3. Results and Discussion

3.1. Historical Comparisons

[16] During the historical period (hereafter 1971–2000 means), the study domain averaged 8.4°C and 1182 mm mean annual precipitation (MAP), with a clear distinction between cool wet winters and warm-hot dry summers. Simulated NPP peaks in June, decreases mid-summer due to water stress, and again in the fall due to temperature limitations (Figure 2).

[17] MC1 results compared favorably with observations during the historical period, although there are a few sources of disagreement. First, MC1 vegetation distribution fails to capture the mixed open forests of the Willamette Valley and the pattern of grasslands and shrublands on the exterior edges of the Columbia Plateau (Figure 3). However, Native Americans and European settlers greatly modified the fire regime in the Willamette Valley [*Whitlock and Knox*, 2002], thus allowing the establishment and maintenance of mixed oak forests and woodlands. Additionally, the Columbia Plateau is particularly vulnerable to both grass [*Keane et al.*, 2008] and woodland [*Belsky*, 1996] encroachment, promoted by late-twentieth-century climate trends, fire suppression, and early-twentieth-century grazing. These issues complicate the assignment of potential vegetation communities in the two regions.

[18] Second, while MC1 captures the broad spatial patterns of burn areas (Table 1), it often misses the magnitude and timing of individual fire years (Figure 4). Although climate exerts a dominant control on fires at large spatial and temporal scales [*Flannigan et al.*, 2000], fine-scale patterns of ignition, weather, and suppression render temporal patterns of burn area more difficult to match on an annual basis. Simulated large (un-suppressed) fires account for 95.2% of the overall simulated burned area.

[19] Third, MC1 overestimates combustion factors (fraction of biomass combusted by fire) in the Biscuit Fire and may therefore overestimate carbon losses from fires throughout the domain and time series. High severity fires typically

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011JG001695.

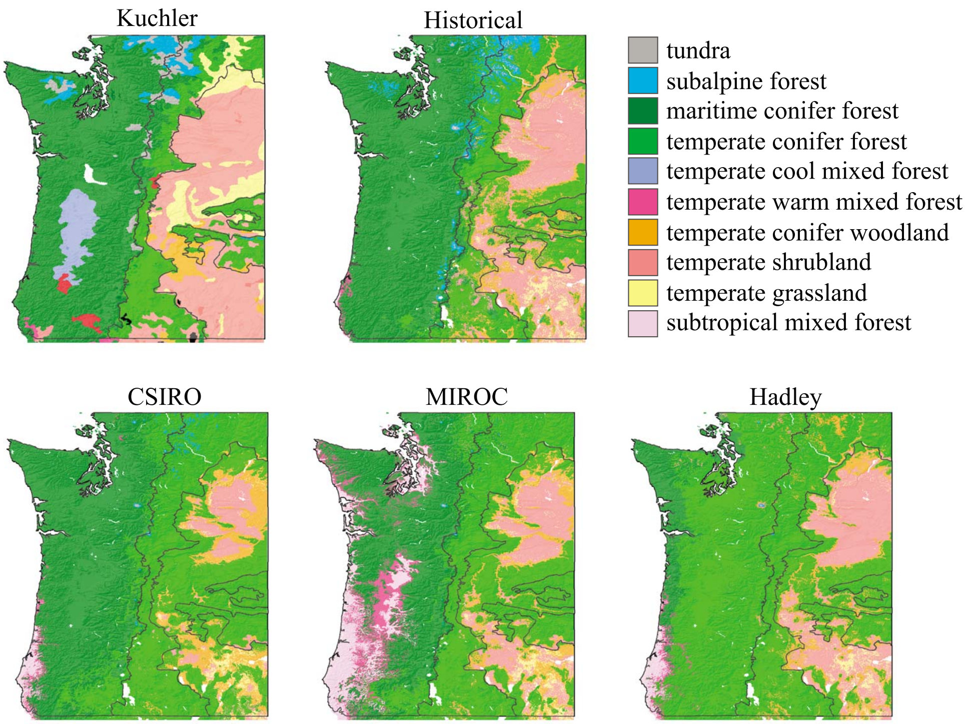

Figure 3. Simulated most common vegetation types with full fire for the historical (1971–2000) and future (2070–2099) periods under the three climate projections: The CSIRO Mk3 [*Gordon*, 2002], MIROC 3.2 medres [*Hasumi and Emori*, 2004], and Hadley CM3 [*Johns et al.*, 2003] models run through the A2 CO_2 emissions scenario [*Nakićenović et al.*, 2000]. Also shown is the aggregated potential vegetation map from *Kuchler* [1975].

account for ~20% of burned area in the PNW (G. Meigs, manuscript in review), and observations made by *Campbell et al.* [2007], disaggregated by carbon pools to match MC1's structure, show low, medium, and high severity combustion factors from the Biscuit Fire to be 0.14, 0.17, and 0.23, respectively. MC1 simulates a mean of 0.26.

[20] Finally, MC1 overestimates carbon stocks in Western Forests (Figure 5b). However, many areas within Western Forests, particularly the Coast Range, the Willamette Valley, and to some extent the western Cascades, were subject to heavy human influence during the twentieth century, including land conversion, logging, and urbanization. These activities all acted to decrease total ecosystem carbon [*Smithwick et al.*, 2002]. Comparisons with old-growth forests yielded mixed results depending on the data source (Figure 5c), which may in part result from differing methods of plot selection.

3.2. Future Projections

[21] Future climate projections (2070–2099 means) display both similarities and differences in the seasonality and magnitudes of changes. Temperatures rise ubiquitously (Figure 6a) with larger increases in summer than winter (Figure 6c). Consistent with the findings of *Mote and Salathé* [2010], increased precipitation generally occurs in winter and decreased precipitation occurs in summer months (Figure 6d). Comparatively speaking, the CSIRO climate projection is cool and wet (+2.6°C and +176 mm MAP), MIROC is hot and wet (+4.2°C and +82 mm MAP), and Hadley is hot and dry (+4.2°C and −78 mm MAP). Calculating the interannual variability of precipitation relative to a scenario's linear trend, the future CRISO projection displayed more (167 mm yr^{-1}), MIROC displayed similar (149 mm yr^{-1}), and Hadley displayed less (124 mm yr^{-1}) variability than the historical time series (149 mm yr^{-1}). Results were similar when variability was calculated relative to a scenario's previous year's precipitation (CSIRO = 184 mm yr^{-1}, MICOC = 149 mm yr^{-1}, Hadley = 125 mm yr^{-1}, and Historical = 151 mm yr^{-1}).

[22] *Mote and Salathé* [2010] compared 21 GCMs used in the IPCC AR4 [*Alley et al.*, 2007] to CRU version 2.02 climate data [*Mitchell et al.*, 2004] over the PNW and found that each of our three selected GCMs showed its own strengths and weaknesses. Notably, Hadley produced one of the lowest precipitation biases (both annually and seasonally), yet was relatively poor in representing the spatial distribution of meteorological fields and had a near-zero twentieth-century temporal temperature trend. MIROC displayed one of the lowest temperature biases, yet one of the highest precipitation biases. CSIRO ranked highest of all

Table 1. Historical Burn Areas From *Westerling et al.* [2003] and MC1 Simulated With Fire Suppression

Region	Observations (1980–2004) (% area yr^{-1})	MC1 (1980–2004) (% area yr^{-1})
All Domain	0.321	0.326
Western Forests	0.164	0.143
Eastern Forests	0.498	0.638
Columbia Plateau	0.416	0.362

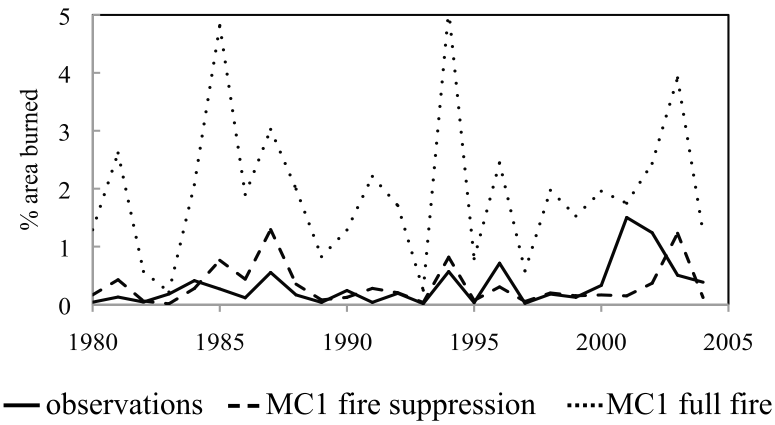

Figure 4. Comparison of domain-wide burned area between *Westerling et al.* [2003] and MC1. Time series are shown for MC1 simulations with full fire and fire suppression.

models for its twentieth-century temperature trend, yet had the highest positive temperature bias. Otherwise, the three GCMs selected here performed close to average for all other metrics considered.

[23] With MIROC and Hadley, climate projections lengthen the growing season and amplify the already strong simulated seasonal climatic cycles, thereby increasing NPP during the rainy season and decreasing summer NPP by exacerbating summer drought. Under CSIRO's milder conditions, NPP increases and water stress decreases year-round (Figures 6e and 6f). As a general trend, the relative seasonal amplitude of simulated plant functions and stresses are amplified by future climate projections, thereby increasing summer drought stress and susceptibility to fires, but also increasing productivity during the rest of the year. These ecosystem responses have been observed in the tree ring record [*Villalba et al.*, 1994] and predicted under projected future climates for lodgepole pines in other parts of the American West [*Smithwick et al.*, 2009]. It should be noted that MC1 does not contain a radiation constraint on NPP. The model may therefore overestimate increased productivity due to warmer temperatures in non-summer months, causing the build-up of fuel loads and depletion of soil water, and hence overestimate responses to summer drought and susceptibility to fire.

[24] Simulated fires increase under all climate projections across the domain (Table 2). Although these increases appear late in the twenty-first century under CSIRO and MIROC, Hadley's hot and dry conditions cause large fires early to mid-twenty-first century (Figure 7), primarily in Western Forests. Because of woody encroachment in the Columbia Plateau and larger and more frequent fires in Western and Eastern Forests under all three scenarios, burn severities (kg C m^{-2} burned) steadily increase across the domain throughout the twenty-first century (Figure 7) and result in large increases in biomass consumption (Table 2). More frequent forest fires also generally decrease the interannual variability in burn severities. These intensifications of PNW fire regimes are caused by three main factors in the model: (1) increased frequency and intensity of droughts in mesic regions, (2) elevated fuel loads in xeric regions, and (3) higher interannual variability of precipitation, particularly in CSIRO. When a three-year running average filter was applied to CSIRO precipitation by month, which preserves seasonality and long-term means but dampens variability, burn area decreased by 88% compared to historical. It should be noted that while precipitation variability is important for the dynamic fire model, overall drying trends can be the most important factor in some cases, such as under the Hadley scenario, where interannual precipitation variability decreases but burn area increases dramatically due to more frequent summer droughts in Western Forests.

[25] The simulated twenty-first-century PNW carbon budget is a balance between biomass losses from intensified summer drought and fire, and biomass gains from higher rainy season NPP due to increased precipitation, longer growing seasons, and/or CO_2 fertilization. The domain gains 1.1 Pg C under CSIRO and 0.9 Pg C under MIROC. Thresholds of summer drought are surpassed such that 1.2 Pg C are lost under Hadley due to large and frequent fires in Western Forests. To put this in context, 1 Pg C is approximately $\frac{1}{8}$ of our current global annual fossil fuel emissions [*Le Quéré et al.*, 2009] and 23 times the size of Oregon and Washington's current combined annual emissions [*Oregon Department of Energy*, 2010; *Waterman-Hoey and Nothstein*, 2006].

[26] Domain-wide impacts have distinct regional differences. Western Forests, typically considered stable with long fire return intervals, proved to be the most vulnerable of the three regions in MC1. These mesic maritime forests are largely unable to benefit from increased winter precipitation because, as has been observed [e.g., *Harr*, 1977], soils are already saturated in winter. Instead, the region suffers from more intense summer droughts and incurs the greatest relative increases in fires (Table 2). Large fires are simulated in years with summer droughts substantially worse than those during the historical period. These droughts occur more often under CSIRO and MIROC after 2070 and are mainly limited to the southwest part of the domain, but they occur much more frequently under Hadley throughout the twenty-first century and cause fires throughout most of the Western Forests region. Under this latter projection, burn area and biomass consumption increase by an order of magnitude and the region loses nearly a quarter of its large ecosystem carbon stocks. Western Forests are also subject to relatively large-scale forest type conversions, with expansions of subtropical mixed forests under MIROC and temperate coniferous forests under Hadley, and losses of subalpine forests under all three projections (Figure 3). Taken

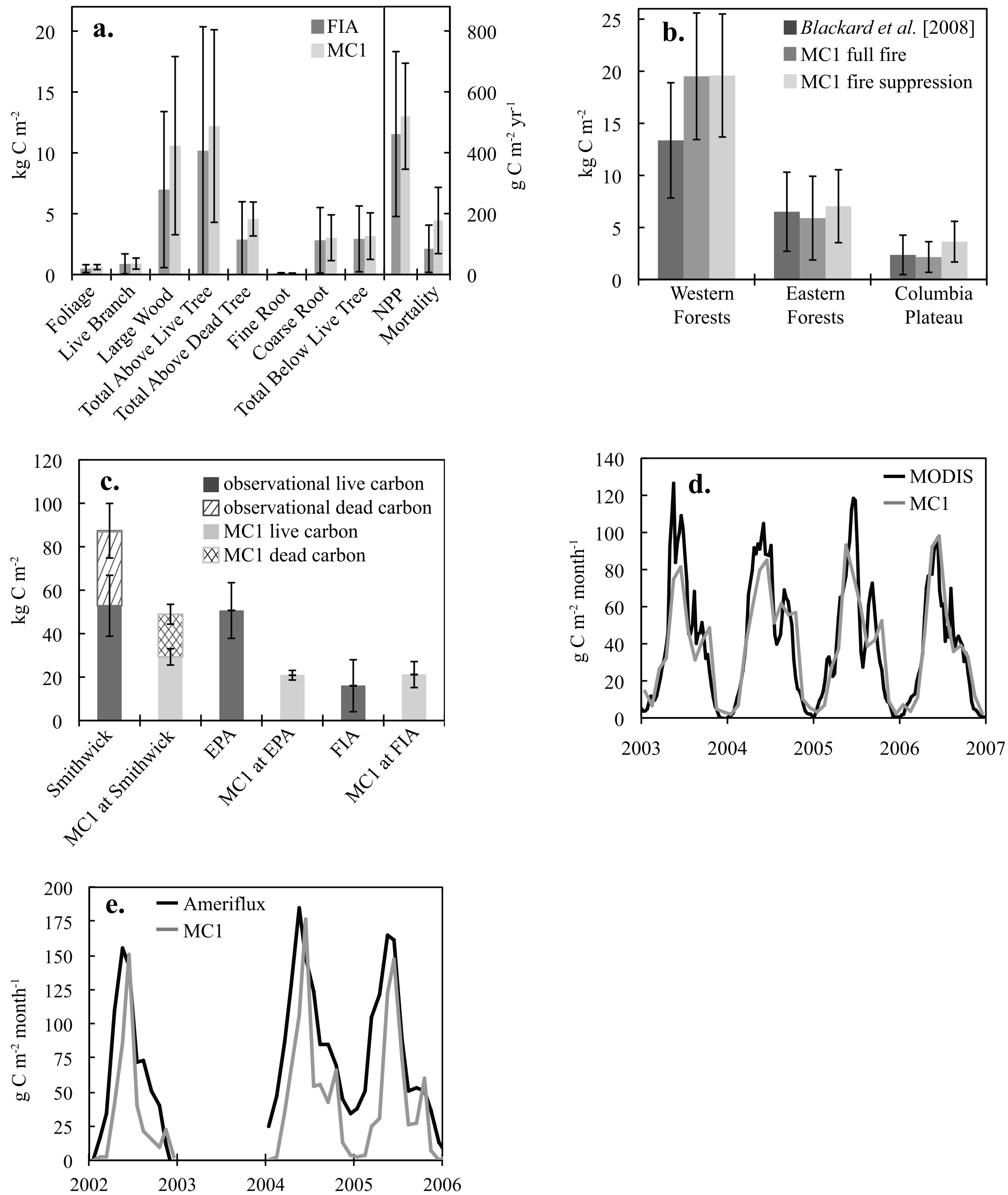

Figure 5. Comparisons of carbon pools and fluxes between MC1 and observations: (a) FIA plots across Oregon from *Hudiburg et al.* [2009] (5,093 plots, 90.4% on public lands, with stand ages of 212 ± 134 years), (b) aboveground live forest carbon from *Blackard et al.* [2008], (c) old-growth plots and MC1 run without fire (Smithwick data [*Smithwick et al.*, 2002] contain 37 plots on public lands with stand ages of 429 ± 257 years; EPA data [*Hudiburg et al.*, 2009] contain 8 plots on public lands with stand ages of 417 ± 215 years; and FIA data [*Hudiburg et al.*, 2009] contain 1,607 plots, 98.2% on public lands, with stand ages of 332 ± 123 years), (d) domain-wide monthly net primary production (NPP) from the MODIS Aqua product [*Running et al.*, 2004] (with a 24-day moving average filter), and (e) NPP derived from flux measurements at the Metolius Intermediate Pine site tower [*Law et al.*, 2003] (44.4523° lat, −121.5574° lon).

together, simulations of Western Forests under Hadley conditions resemble the climate, vegetation, and fire regimes of the late Holocene Thermal Maximum [*Whitlock et al.*, 2003]. In comparison, both the Columbia Plateau and Eastern Forests gain carbon in all three scenarios despite intensified fire regimes because of longer growing seasons, greater synchrony between spring growth and precipitation, and woody encroachment in the case of the Columbia Plateau

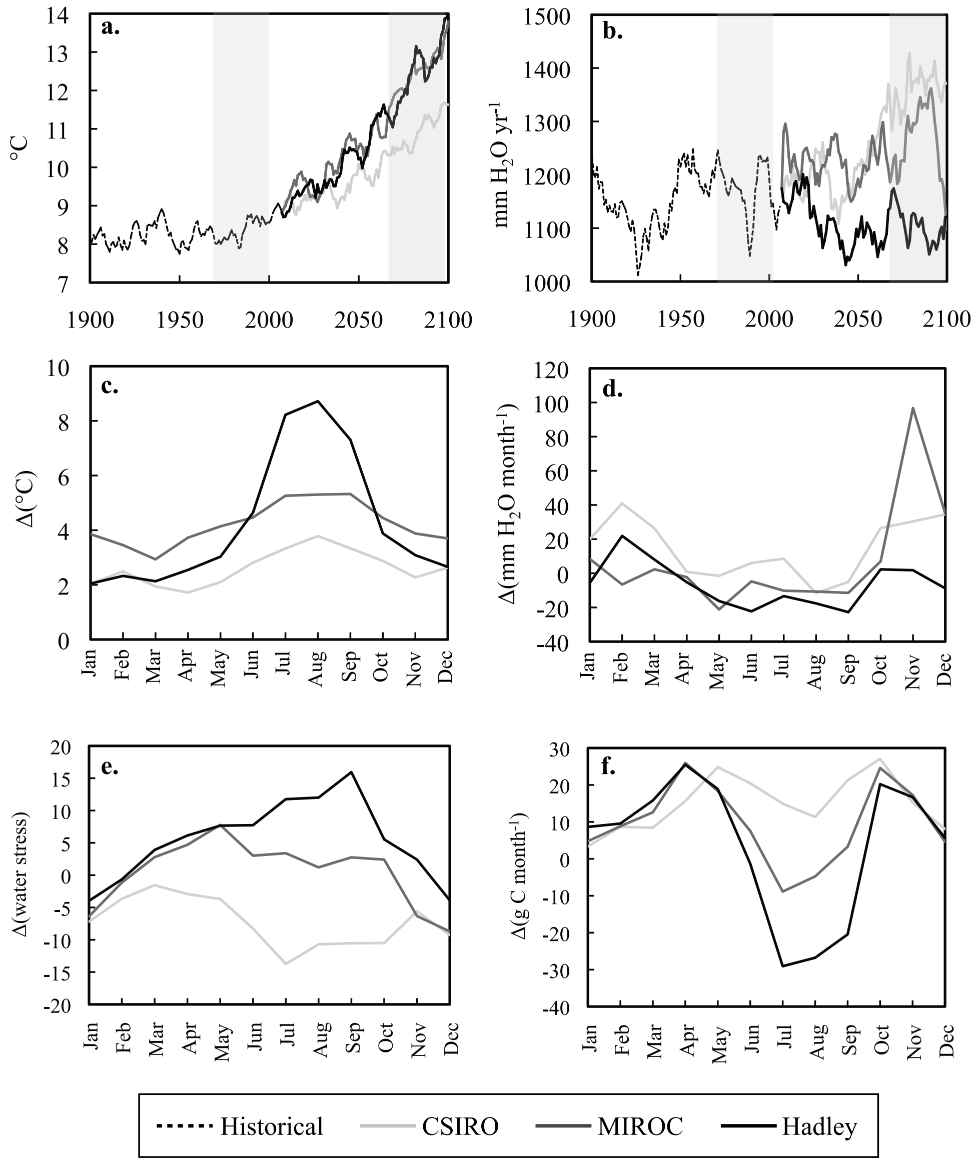

Figure 6. Projected annual (a) temperature and (b) precipitation, and monthly changes in (c) temperature, (d) precipitation, (e) water stress, and (f) net primary production (NPP). Shaded areas in (a) and (b) indicate the time periods used for analysis in (c)–(f) (1971–2000 and 2070–2099).

(Table 2, Figure 8). The highest spatial agreements between projections occur in the cases of increased fires and ecosystem carbon in the eastern domain, and vegetation shifts in Western Forests (Figure 8).

3.3. Sensitivity Analyses

[27] A number of full-domain fire sensitivity analyses were conducted in order to assess the influence of fire and fire suppression on the carbon balance. MC1 was first run with fire suppression turned off (full fire) and second with all fires turned off (no fire). As expected, fire suppression always produces less burn area and biomass consumption than full fire. However, when compared to results for historical periods with the same fire rules, fire suppression results in greater relative and absolute increases in burn area and biomass consumption than does full fire, under all scenarios (Table 3). This suggests an intensification of future PNW fire regimes due to suppression because (1) simulated (and observed) historical fire suppression is causing elevated fuel loads in semi-arid ecosystems and (2) current fire suppression (as assumed in the model) will not be as effective against intense future fires. Paradoxically, because absolute biomass consumption is less and ecosystems continue to gain carbon after the initiation of simulated fire suppression, suppression results in greater carbon gains (or smaller losses) than full fire simulations (Figure 7). Nonetheless, suppression is unable to curtail the large carbon losses under Hadley's hot and dry climate. Because the domain is a carbon sink under Hadley when fire is turned off, carbon losses are due entirely to large conflagrations in high-biomass forests. A third sensitivity analysis was conducted wherein the suppression thresholds of fireline intensity and rate of spread were raised until future burn area matched historical levels. To reach that goal, fire suppression needed to be effective on fires that

Table 2. Historical (1971–2000 Means) and Future (2070–2099 Means) Changes to Fire Regimes and Carbon Stocks by Ecoregion

Region	Variable	Historical	Percent Changes		
			CSIRO	MIROC	Hadley
All Domain	Burn area[a]	0.326	+76.3	+95.0	+310.1
	Biomass consumed[b]	8.95	+127.9	+165.3	+477.6
	Ecosystem carbon[c]	29.4	+12.2	+9.9	−13.4
Western Forests	Burn area	0.143	+161.5	+159.6	+1177.4
	Biomass consumed	5.74	+153.2	+182.1	+1313.4
	Ecosystem carbon	44.4	+2.5	+1.7	−23.9
Eastern Forests	Burn area	0.638	+110.6	+141.0	+133.4
	Biomass consumed	21.9	+116.3	+163.0	+116.6
	Ecosystem carbon	22.5	+24.7	+22.1	−1.7
Columbia Plateau	Burn area	0.362	−28.5	−11.2	+28.4
	Biomass consumed	3.79	+101.6	+126.1	+171.0
	Ecosystem carbon	12.2	+47.5	+37.4	+26.0

[a]Percent area burned per year.
[b]Unit of measure is g C m^{-2} yr^{-1}.
[c]Unit of measure is kg C m^{-2}.

were 30% more intense under CSIRO, 41% more intense under MIROC, and 287% more intense under Hadley climate projections. Finally, MC1 was run with the previous fire suppression rule that reduced all burn areas by 87.5%. While historical burn area is similar to those simulated with the new rule (both rules were calibrated to historical data in the U.S.), this simple reduction in burn area results in distinctly different impacts under climate change: ecosystem carbon increases under all scenarios (7%–15%) and burn area changes only slightly (±25%).

[28] These fire sensitivity analyses suggest that fire will exert a dominant control over future PNW biomass stocks and that the simulation of fire impacts is strongly influenced by how fire suppression is modeled. More importantly in terms of management, the model suggests that current suppression efforts may become less effective against more intense future fires.

[29] Two Monte Carlo parameter sensitivity analyses were also conducted. The first, in which 100 points were run through 100 random selections of parameters related to fundamental model processes, revealed that our model

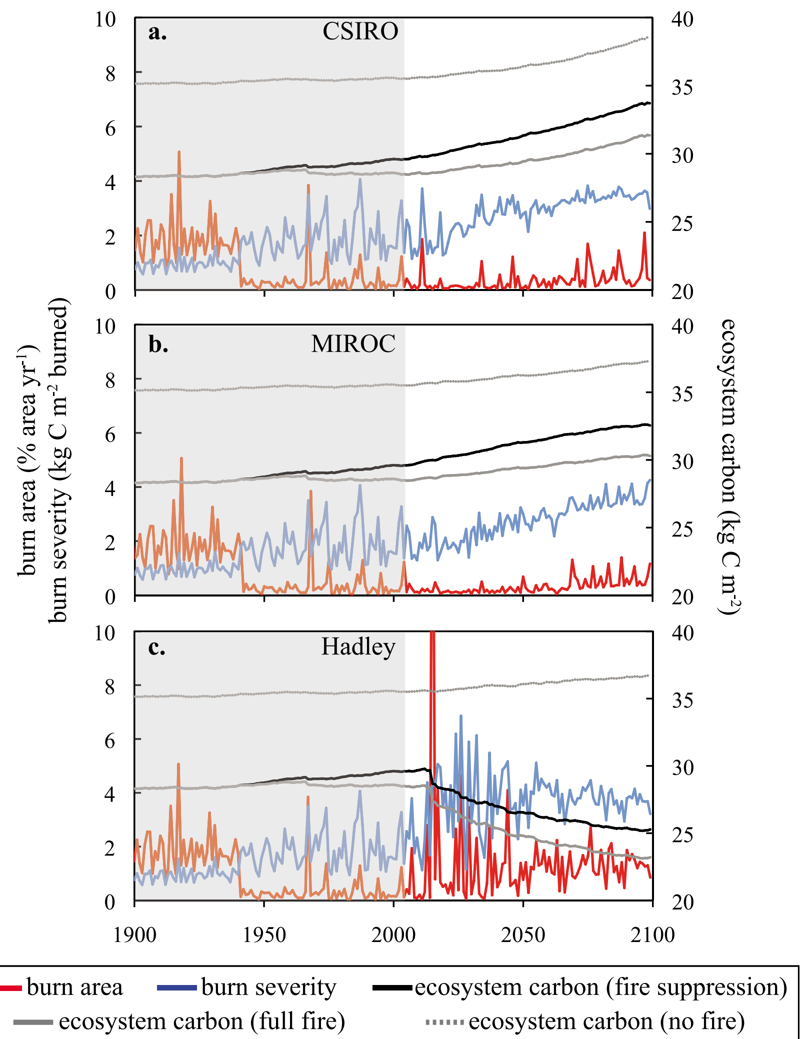

Figure 7. Changes in burn area, burn severity, and ecosystem carbon with fire suppression, as well as ecosystem carbon with full fire and no fire. Shaded areas cover the historical period. Fire suppression was initiated in 1940.

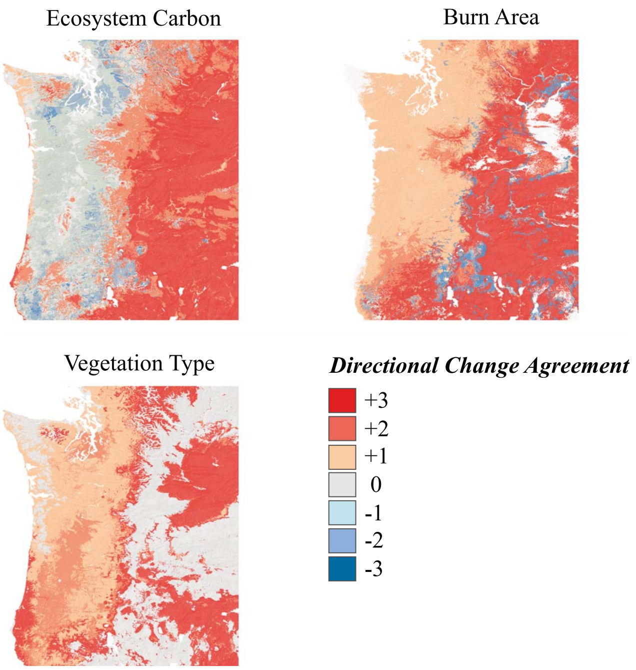

Figure 8. Number of future scenarios that agree on a change from the historical baseline. Changes in the positive and negative direction are given by positive and negative numbers for carbon and burn area. Changes of less than 5% (carbon) and 10% (burn area) from historical on a grid-cell basis were deemed insignificant.

conclusions are relatively conservative (Figure 9). Because the number of augmented parameters was high (30), the output spread is considerable. However, when the 100 points were aggregated together to represent a sample of the full domain, the median historical ecosystem carbon and burn area values were close to those from the original run. Additionally, in almost every case, the future Monte Carlo simulations result in less ecosystem carbon and more future burn area than our original run. The exception is MIROC burn area, where the median change is slightly less than value from the original run (+78% versus +95%). This suggests that uncertainty in our input parameters leads to more unfavorable projections for the PNW (i.e., more fires and less carbon sequestration).

[30] A second parameter sensitivity analysis was conducted by varying only thresholds for fire suppression. With the exception of simulations using the CSIRO climate, results from this analysis are much more tightly constrained than those from the previous (see above). Compared to the original full domain run, slightly less area burns during the historical period (mean of 0.26% versus 0.33%) while slightly more area burns in the future (+350% versus +310% changes under Hadley and +127% versus +95% changes under MIROC). The effects on ecosystem carbon are negligible: changes are within 1% of the original run. Under CSIRO, however, much more area burns than does in the original run (+352% versus +76.3%) and the domain gains substantially less carbon (+8.4% versus +12.2%). This again suggests that uncertainty in our fire suppression thresholds results in exacerbated future projections.

3.4. Uncertainties

[31] These results come with numerous sources of uncertainty, some of which may be quantified using Monte Carlo sensitivity analyses such as those above, and others that are more overreaching. The primary control on twenty-first-century climate change will be the trajectory of anthropogenic CO_2 emissions, which depends on political and social decisions and are thus highly unpredictable. Additionally, as seen in this study, individual GCMs display their own biases and unique projections for the PNW. Our downscaling method cannot correct for these GCM-simulated biases in annual means and seasonal, interannual, and/or interdecadal climate variability. The method can also not account for local biosphere-atmosphere feedbacks such as increased warming over regions that lose snowpack. Moreover, the monthly time step in MC1 may miss physiologically important daily changes such as differential warming between day and night. This version of MC1 assumes no nitrogen limitation and may therefore miss carbon-nitrogen feedbacks associated with warming and changing fire regimes. Because MC1 does not take radiation effects on NPP into account, it may overestimate future increases in productivity and vulnerability to fire by overestimating growth responses to temperature and related water use. MC1 does not include inter-cell communication, which at smaller scales is important for hydrology, erosion and sedimentation, and fire spread. While some vegetation changes are driven by competition and incorporate biogeochemical processes, others rely strictly on physiologically based climatic indices. The rates of vegetation change, and influences of adaptation, may therefore not be accurately captured.

[32] MC1 does not account for many direct impacts on the landscape. Changes to agriculture area, farming practices, harvested land, and/or rotation ages may affect carbon stocks in ways unaccounted for in this study. Our fire suppression rule is based on physical metrics of fire intensity, but it includes no information on human population densities, forest fragmentation, fire fighting policies and budgets, or ignition sources. While lightning is the primary ignition source in the PNW [*Rorig and Ferguson*, 1999], changing storm patterns, arson rates, or population expansion could influence future fires. MC1 does not simulate insects and pathogens, yet mortality from pest outbreaks has been increasing [*van Mantgem et al.*, 2009] and tends to increase fire vulnerability in low elevation dry forests. Finally, the model does not account for herbivory, which could greatly reduce post-fire forest regeneration.

Table 3. Burn Area and Biomass Consumed Simulated With Full Fire and Fire Suppression[a]

Scenario	Burn Area (% area yr^{-1})		Biomass Consumed (g C m^{-2} yr^{-1})	
	full fire	*fire suppression*	*full fire*	*fire suppression*
Historical[b]	1.94	0.33	24.2	08.9
CSIRO[c]	1.92 (−1.1)	0.57 (+76.3)	31.5 (+30.1)	20.4 (+127.9)
MIROC[c]	2.01 (+3.9)	0.63 (+95.0)	33.7 (+39.5)	23.7 (+165.3)
Hadley[c]	2.75 (+41.6)	1.34 (+310.1)	61.5 (+154.3)	51.7 (+477.6)

[a]Values in parentheses denote percent changes from historical.
[b]Mean 1971–2000.
[c]Mean 2070–2099.

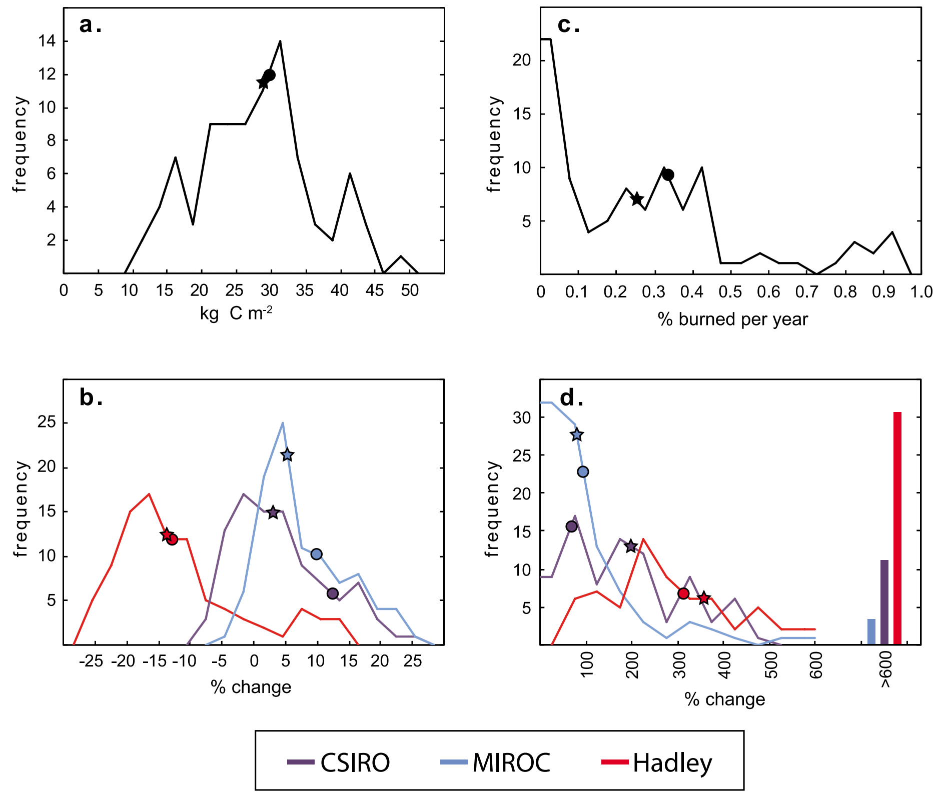

Figure 9. Probability density functions of (a) historical and (b) future changes to ecosystem carbon, and (c) historical and (d) future changes to burn area from a Monte Carlo sensitivity analysis. One hundred points were simulated with 100 different choices of 30 parameters, chosen from a ±20% Latin hypercube. Points were aggregated to a single value for each of the 100 runs. Stars represent median values from the Monte Carlo runs, and dots represent values from the original full domain run.

Many of these issues suggest model results should be considered relatively conservative.

4. Conclusions

[33] A growing body of research suggests that we can expect a significant amplification of fire regimes across North America during the twenty-first century. Our simulated increases in area burned for the Pacific Northwest (76%–310%) under future climate conditions lie in general agreement with previously published studies for the northwestern U.S. [*Littell et al.*, 2010; *McKenzie et al.*, 2004] as well as larger forested regions of North America [e.g., *Westerling and Bryant*, 2008; *Balshi et al.*, 2009; *Spracklen et al.*, 2009]. The MC1 model suggests ubiquitous increases in fire intensities (energy released) and severities (biomass burned), exacerbated by the legacy of fire suppression. The (semi)arid biomes east of the Cascades appear capable of future biomass gains despite intensification of fire regimes because of increased productivity in non-summer months. The maritime forests west of the Cascades, however, appear vulnerable to increases in summer drought and fire occurrence, and could possibly lose up to 1.2 Pg C by the end of the twenty-first century. Simulated fire suppression was unable to curtail this large fire-induced carbon source. This suggests a risk to the future sustainability of carbon sequestration and forest harvesting efforts in these high biomass forests, although we caution there are large model uncertainties, including those inherited from GCM-projected climates. If future wildfires increase only moderately, either through effective suppression or relatively benign climate changes, the study domain may sequester more than 1 Pg C during the twenty-first century. Possible mitigation options, both for the PNW and other temperate forests, could include funding long-term fuels reduction in low-elevation semi-arid forests, gaining a larger acceptance for the role of fire prescription and letting certain fires burn naturally in restoring a more natural fire regime, establishing longer rotation periods to maximize carbon storage and allow for large trees in uneven aged stands that are more resistant to disturbance, identifying and monitoring ecosystem stressors that can trigger large fires and cause vegetation shifts, and protect grasslands and open savannas that can sequester carbon belowground and are therefore less vulnerable to fire losses.

[34] It is increasingly recognized that fires exert critical controls on terrestrial carbon stocks, species distributions, forest age classes, and surface energy budgets. This study underscores that importance and the influence that anthropogenic fire suppression has on burn area in the U.S. Pacific Northwest, a result that likely applies to modeling fire in many other industrialized countries. Elsewhere, particularly the sub-tropics and tropics, anthropogenic ignition and deforestation may be equally or more important. Further studies that couple land surface processes to regional cli-

mate, include socio-economic and demographic influences on fire suppression and ignition, and account for agriculture, forestry, and urbanization are needed to further understand and predict future ecosystem responses in the PNW. This region is particularly important because of its sensitivity to climate changes, its vast array of biomes and fire regimes, and its large biomass stocks and their suggested relationship to fire. Further refinement of climate and ecosystem models, as well as studies that validate and provide metrics of accuracy across model ensembles, will help narrow the uncertainty in assessing terrestrial responses to climate change.

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