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Climate, Fire and Carbon: Tipping Points and Landscape Vulnerability in the Greater Yellowstone Ecosystem

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Project Title:

***Climate, Fire and Carbon:
Tipping Points and Landscape
Vulnerability in the Greater Yellowstone
Ecosystem***

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ABSTRACT

More frequent fires under climate warming are likely to alter terrestrial carbon (C) stocks by reducing the amount of C stored in biomass and soil. However, the thresholds of fire frequency that could shift landscapes from C sinks to C sources under future climates and whether these are likely to be exceeded during the coming century are not known. We used the Greater Yellowstone Ecosystem (GYE) as a case study to explore the conditions under which future climate and fire regimes would result in tipping points of C source/sink dynamics. We asked: (1) *How great a change in climate and fire regime would be required to shift each of the dominant vegetation communities in the GYE from a net C sink to a net C source?* (2) *Do current projections indicate that changes of this magnitude are likely to occur in the next century, and if so, where in the GYE do they occur?* and (3) *What are the integrated effects of changing climate, vegetation, and fire on spatial patterns of C flux across the GYE landscape as a whole?* To answer these questions, we developed downscaled climate projections for the GYE for three general circulation models and used these projections in dynamic and statistical modeling approaches.

Using the CENTURY ecosystem model, we simulated C storage for individual forest stands under three fire-event pathways (fires at 90, 60 or every 30 years) to year 2100 compared to a reference simulation (no fire, representing the historical fire interval) under both future and current climate scenarios. Our results show that fire intervals would need to be less than 90 years for lodgepole pine (*Pinus contorta* var. *latifolia*) forest stands to shift from a net C sink to a net C source because the time between fires would be less than the time required to recover 85% of the C lost to fire (Question 1).

We also developed new statistical models to relate monthly climate data to the occurrence of large fires (> 200 ha) and area burned, evaluated these for the 1972-1999 time period, and then used these relationships to predict fire occurrence and area burned in the GYE through 2100 given the downscaled climate projections. Results showed that anticipated climate changes are likely to increase fire frequency and annual area burned over the next century compared to the observational record. However, the timing of these changes and the probability of future large-scale 1988-type fires depended on the type of climate-fire model that was used, the accuracy of the simulated future climates, and to a small degree, the specific climate simulation. The climate-fire frequency and climate-fire size models are extremely sensitive to temperature differences between the projected future climate and the 1961-1990 base period because the two large fire years that occurred in the 1972-1999 climate-fire model calibration period had relatively small temperature anomalies (0.5 to 1 °C) and the small sample size of the large fire years in the time series makes model building a challenge. Between now and 2050, where we have the most confidence in the model, all climate scenarios and both fire-climate model formulations projected at least two 1988 sized fires (range 2-6, fires projected to be > 300,000 ha). After 2050, climatic conditions are sufficiently outside the historic range of variability used to estimate statistical fire models that those models cannot be used to characterize the magnitude of extreme fire years. However, extreme fire years from 2050-2100 will almost certainly become more common than projected for 2010-2050, because temperature is projected to continue to increase while precipitation is projected to remain at historical levels. We note, however, that projected

changes in temperature by the climate scenarios only reach the historical differences in temperature between a subalpine forest (with an historical fire return interval of > 100 years) and a montane forest (with an historical fire return interval of < 30 years) by the end of this century (5-6 °C).

In the northern Rocky Mountains, large fire years have been driven historically by extreme climate conditions. Our results imply that fuel availability would become increasingly important for fire as weather conditions conducive to large fires become common. The capacity for fast post-fire regeneration of lodgepole pine from an aerial seedbank (serotinous cones) and the projected increase in lodgepole pine productivity under warmer climate conditions are unlikely to counter the anticipated reductions in fire-return interval. In all future climate scenarios, decreases in fire-return interval are likely to reduce the potential of the GYE landscape to store C (Question 3). The magnitude of this shift will depend on the future distribution of forest and non-forest ecosystems across the landscape, other constraints on fire patterns not considered here (fuels, ignition factors, and landscape management), and the accuracy of the fire-climate model as future climate diverges increasingly from the past. If past climate-fire relationships can predict the future, soon after 2050 climate conditions projected by all three general circulation models would likely result in more fire than the current conifer forest ecosystem in the GYE could sustain. Forest managers should be considering the potential for qualitative shifts in forest distribution and regional C storage to occur before 2100.

BACKGROUND AND PURPOSE

Forest managers in the western US are facing more wildfires than ever before, and it is increasingly important for scientists and managers to anticipate the consequences of this trend. In subalpine forests of the northern Rocky Mountains, the number of large fires has increased in the past 25 years in association with warmer temperatures, earlier snowmelt, and longer fire seasons (Westerling et al. 2006; Running et al. 2006). This trend is expected to continue with global warming (Tymstra et al. 2007; Littell et al. 2010). Yet, the consequences of increased fire frequency and climate warming for western forests remain uncertain. Increased fire occurrence is a prime concern of residents and land managers from state and federal agencies because of direct effects of fire on life, property, and resources (GAO 2007). More frequent fire may also trigger important ecological changes, and carbon (C) source-sink dynamics may be particularly vulnerable to altered fire regimes (e.g., Kurz et al. 2008, Balshi et al. 2009).

Our previous work, based on intensive field measurements in a chronosequence of 77 lodgepole pine (*Pinus contorta* var. *latifolia*) stands (Smithwick et al. 2009a; Kashian et al., in prep) and simulation models (Smithwick et al. 2009b), has shown that C and nitrogen (N) losses following stand-replacing fire are recovered within 70-100 years, well within the relatively long, average historical fire intervals (135 to 310 years) in lodgepole pine forests of the GYE (Schoennagel et al. 2004; Schoennagel et al. 2003). When simulating C balance in lodgepole pine forests under projected future climates, our results also suggested the potential for an increase in net C storage (Smithwick et al. 2009b) because lodgepole pine productivity in the GYE may be limited, in part, by temperature and/or length of the growing season. Because C losses to fire are relatively low and C stocks recover within the observed fire-return intervals (FRIs), we surmised that

forests in the GYE would need to burn much more frequently than has occurred throughout most of the Holocene (fire intervals generally >100 years, Whitlock et al. 2003) for C storage to be substantially altered (Kashian et al. 2006). However, how climate change and fire regime may potentially interact and whether fire frequency is likely to change that much during the coming century have not been explored previously.

Our goal in this project was to advance scientific understanding of landscape-scale vulnerabilities of key western forest types to climate change. Our overall questions were (1) *How great a change in climate and fire regime would be required to shift each of the dominant vegetation communities in the GYE from a net C sink to a net C source?* (2) *Do current projections indicate that changes of this magnitude are likely to occur in the next century, and if so, where in the GYE do they occur?* and (3) *What are the integrated effects of changing climate, vegetation, and fire on spatial patterns of C flux across the GYE landscape as a whole?* We aimed to identify when, where, and under what range of conditions, conifer forests become net sources of C to the atmosphere (i.e., lower C storage in the future than current conditions). Previous results have suggested that a large portion of the Rockies and Cascades are likely to experience similar moisture deficits as the GYE, and therefore we aimed to provide results that could be generalized to other western subalpine forests.

STUDY DESCRIPTION AND LOCATION

Study area. The GYE encompasses nearly 80,000 km² in northwestern Wyoming (**Figure 1**), Montana, and Idaho and includes two major national parks, notably Yellowstone National Park, which was established in 1872 as America's first national park and remains an icon for broad-scale conservation. The GYE is ideal for this study because its fire regime and vegetation dynamics are reasonably well understood (e.g., Romme and Despain 1989, Whitlock et al. 2003, Turner et al. 2003). In 1988, the extensive Yellowstone Fires inaugurated a new era of major wildfires in the western U.S., and 20 years of intensive post-fire research have provided many new insights into the consequences of large, severe wildfires in the Yellowstone ecosystem (Turner et al. 2003; Kashian et al. 2006; Schoennagel et al. 2008). Lodgepole pine, the dominant tree species in Yellowstone National Park, can regenerate rapidly and abundantly after fire due to its serotinous cones (Turner et al. 1997), and the abundance of serotinous cones covaries spatially with elevation and historical fire frequency (Schoennagel et al. 2003). Although canopy fires consume fine litter, branches, and foliage, and kill live trees, relatively little of the C pools in tree boles, downed wood, and soil are combusted (Tinker and Knight 2000, Campbell et al. 2007).

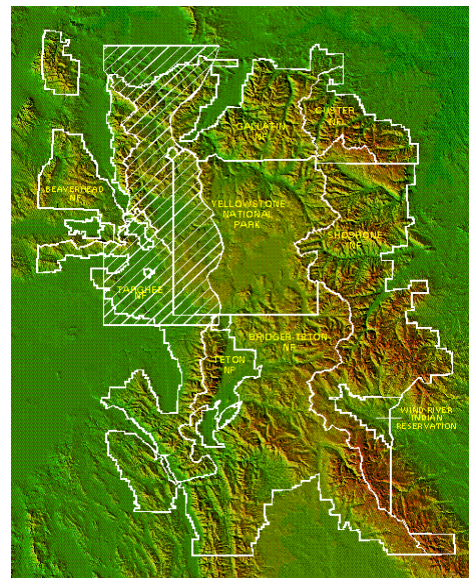


Figure 1. Map of the Greater Yellowstone Ecosystem including National Park and National Forest boundaries (source: <http://biology.usgs.gov/>)

Study description. Our approach combined a dynamic ecosystem model to project future carbon stocks under different climate scenarios and fire regimes (Question 1) with probabilistic statistical modeling of the relationship between historical climate and fire, which was then used to project expected fire occurrence and area burned under alternative climate scenarios (Question 2). We present the detailed methods below for each of these approaches. Because the results of our study (described in detail below) suggest qualitative changes could occur under future climate, a simple landscape sum of net C balance (Question 3) would be misleading. However, we have made substantial progress on developing new methods to address these challenges and describe those briefly below.

APPROACH AND KEY FINDINGS

Question 1: How great a change in climate and fire regime would be required to shift each of the dominant vegetation communities in the GYE from a net C sink to a net C source?

To identify how great a change in climate and fire regime would be required to shift vegetation from C source to C sink, we proposed to run the ecosystem model CENTURY version 4.5 (Parton et al. 1987; Smithwick et al. 2009b) aspatially for the dominant vegetation communities in the GYE given a large fire event in 1988, and a range of estimated fire-return intervals and current/future climate conditions. Based on our previous work (Kashian et al. 2006; Kashian et al., in prep.), we identified general patterns of fire regime and forest regeneration pathways across the region. Our goal was to focus on critical drivers that would be likely to result in observable and representative change across the landscape. We concluded that changes in C stocks would be most significant for transitions of forest to non-forest (rather than forest to forest only). Other studies have shown substantial differences in C stocks with stand age up to about 100 yrs, but less difference among different conifer forest types (Bradford et al. 2008). Thus, our current modeling was focused on lodgepole pine, a representative forest type in the region. The model has to-date been additionally parameterized for warm-dry conifer (primarily Douglas-fir (*Pseudotsuga menziesii*) forests in the GYE) and grasslands in the Lamar Valley; as validation data of C stocks in this ecosystem (Donato, Turner et al., in prep) become available, we will incorporate these vegetation types into our approach. However, to capture variation in recovery pathways in lodgepole pine, we modeled two recovery pathways: fast (high pre-fire serotiny, more prevalent at elevations < 2400 m) and slow (low pre-fire serotiny, characteristic of elevations > 2400 m; Schoennagel et al. 2003). We expect that the slow recovery pathway will be representative of other vegetation types that lack serotinous cones and are likely to regenerate more slowly, e.g., Douglas-fir or spruce-fir forests. All fires were prescribed to be high-severity, stand-replacing fire events.

Climate scenarios. To estimate current and future climate conditions, we used historical climate data and general circulation model (GCM) runs downscaled to the North American Land Data Assimilation system 1/8-degree latitude/longitude grid (12 x 12 km resolution). We used three AR4 GCMs (CCSM 3.0, CNRM CM3.0, and GFDL CM 2.1) forced with the Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report: Special Report on Emissions

Scenarios (SRES) A2 emissions pathway to generate a set of plausible climate futures for the western USA. The three GCMs used here are among a larger group that were assessed to adequately represent important aspects of Western North American climate, including seasonality of temperature and precipitation, and multi-year variability in sea surface temperatures (Daniel Cayan et al., unpublished). This particular subset of models was chosen because daily values for important variables such as temperature and precipitation were available for each GCM run, which were required to force the hydrologic simulations used here. The A2 emissions scenarios have been a frequent focus for impact assessment work because they were thought to represent a plausible high-end emissions scenario. However, for much of the past decade, emissions and atmospheric concentrations of greenhouse gases have exceeded the range of commonly used IPCC emissions scenarios, including far exceeding SRES A2. Consequently, given current and past emissions, the long lead times necessary to reduce future emissions, and the long atmospheric residence times of many greenhouse gases, climate projections using the SRES A2 CO₂ trajectory can no longer be considered a plausible representation of the future, nor representative of a ‘high’ emissions scenario, but were used here given their availability. Because current atmospheric concentrations exceed those represented in the SRES A2 scenarios, the climate scenarios used to derive our results will be conservative. GCM temperature and precipitation fields were downscaled using the Constructed Analogs method with bias correction (Maurer and Hidalgo 2008). Gridded historical climate data (temperature, precipitation, radiation, and wind speed) were obtained from Dr. Lettenmaier at the University of Washington and Dr. Maurer at the University of Santa Clara (see Maurer et al. 2002; Hamlet and Lettenmaier 2005). A full suite of hydrologic variables was simulated using the Variable Infiltration Capacity hydrologic model (Liang et al. 1994; Hamlet and Lettenmaier 2005) driven with historical and downscaled GCM climate data and climatological wind speeds. Because downscaled wind products are not yet available for Global Climate Model runs, we generated historic hydrologic simulations using climatological winds (i.e. average wind speed for time of year) to provide data consistent with the climate change scenarios. For the simulations of lodgepole pine forest, we used climate data from the grid centered on the Yellowstone Lake climate station, which is centrally located in the GYE and surrounded by lodgepole pine forest. To model non-forest vegetation communities, we used the climate grid cell centered on the Lamar climate station, which is surrounded by extensive sagebrush-grasslands.

Carbon modeling. Productivity, mortality, and post-fire recovery were parameterized in CENTURY for lodgepole pine and warm-dry-conifer trees based on empirical data (Tinker and Knight 2000; Pearson et al. 1987; Ryan et al. 1992; Stump and Binkley 1993; Smithwick et al. 2009a; Kashian et al., in prep) and previous modeling efforts (Kashian et al. 2006; Smithwick et al. 2009b). The model was running ‘savanna’ mode, allowing for grass and tree competition for water and nutrients. For all simulations, we assumed a C3 grass parameterization available in CENTURY. Grass represented a small proportion of C stocks in mature stands, but was a large and transient component of total C stocks for several years following fire. Because the statistical modeling (described below) was not capable of capturing these large, transient pulses, and because belowground grass C stocks were likely overestimated, future model efforts will be increasingly focused on grass dynamics in early post-fire years.

The fire-return intervals used in the CENTURY and landscape C modeling are based on understanding of the canopy seed bank and its influence on post-fire regeneration. Specifically,

Turner et al. (2007) demonstrated that lodgepole pine saplings are producing cones (including a few serotinous cones) by age 15 years. Cone production begins at about the same age or even later in the other conifer species of the GYE, and recent fires that have burned young conifer forests (<30 yr) show minimal tree regeneration (Romme and Turner, personal observations). To encapsulate this rapid but variable trend in development of a canopy seed bank, we used a 30-year fire interval as a conservative estimate of the minimum FRI that would be followed by a very high likelihood of reforestation. If fire recurs at < 60 year intervals, seeds are present but in moderate quantities. By stand age of > 90 yrs, lodgepole pine trees are generally producing substantial numbers of cones. Although stands are likely to regenerate at different rates following stand-replacing fire due to patterns in fire severity and pre-fire levels of serotiny (Turner et al. 2004), cone production is not limiting by age 90 yr and even initially sparse stands experience infilling (personal observations; Kashian et al. 2005, 2006). Empirical work along chronosequences of >77 stands in the GYE (largely in Yellowstone NP) indicated that most differences in nitrogen and C stocks occur at stand ages < 100 (Smithwick et al. 2009a; Kashian et al., in prep).

Using these parameterizations for vegetation, climate, and fire, we performed a model experiment using a 4x4x2 factorial design to answer Question 1 in which we considered four climate scenarios (historical plus the three GCMs), four fire-event pathways (no fires after 1988, a fire 90 years after 1988 event, a fire 60 years after 1988 event, and fires every 30 years after 1988 event), and two recovery pathways (fast/slow).

Model output included live and dead pools (large wood, branches, leaves, coarse roots, fine roots), as well as active, slow, and passive pools in surface and soil, and relevant ecosystem processes such as respiration and decomposition. The time needed for forest C recovery following fire under both current and future climate scenarios was determined by comparing the time to recovery of pre-1988 C stocks (average of 1950-1987) of mature forest stands to that of both future periods (1970-2099) or averaged across the post-1988 simulation period (1989-2100). Total ecosystem C stocks varied little (<10%) among future climate scenarios for a given fire-event pathway and were therefore averaged for the purposes of demonstrating the large differences in C stocks forecast among fire scenarios. Similarly, fast versus slow regeneration had a much smaller effect on total ecosystem C stocks than the timing of individual fire events. For simplicity, only fast recovery pathways from the CENTURY model are shown here.

Results. Using the CENTURY model simulations, average C storage between years 1950 and 1987 was 17,900 g C m⁻² (**Figure 2**). Simulation of the large fire in 1988 resulted in a 12% reduction in total C stocks from pre-fire levels, largely due to the limited amount of biomass in the consumable pools (litter, foliage, fine branches) that was available to burn. Live pools were killed and converted to dead pools but not consumed (**Figure 2a,b**). In the absence of subsequent fire (assuming historical fire-return intervals and therefore no fire in the post-1988 period), prefire C stocks were recovered by mid-century and, on average across the climate scenarios, continued to increase slowly through the end of the simulation (**Figure 2d, hist**). Under future climates and in the absence of subsequent fire, total C stocks were between 17 and 30% higher than historical C stocks. Increases in total ecosystem C under the future climates were stimulated by higher rates of net primary production of lodgepole pine with warmer temperature compared to the control simulation, although relative increases in productivity were less for the GFDL

scenario (data not shown). For simulations assuming one fire event (90 year FRI), live and total C stocks were recovered following the 1988 fire before the 90-year fire event. However, for scenarios with FRIs at 60 or 30 years, live, dead, soil, and total C stocks were not recovered prior to the next fire event, and total ecosystem C storage declined progressively through the future simulation period due to the lack of time for C recovery (**Figure 2**).

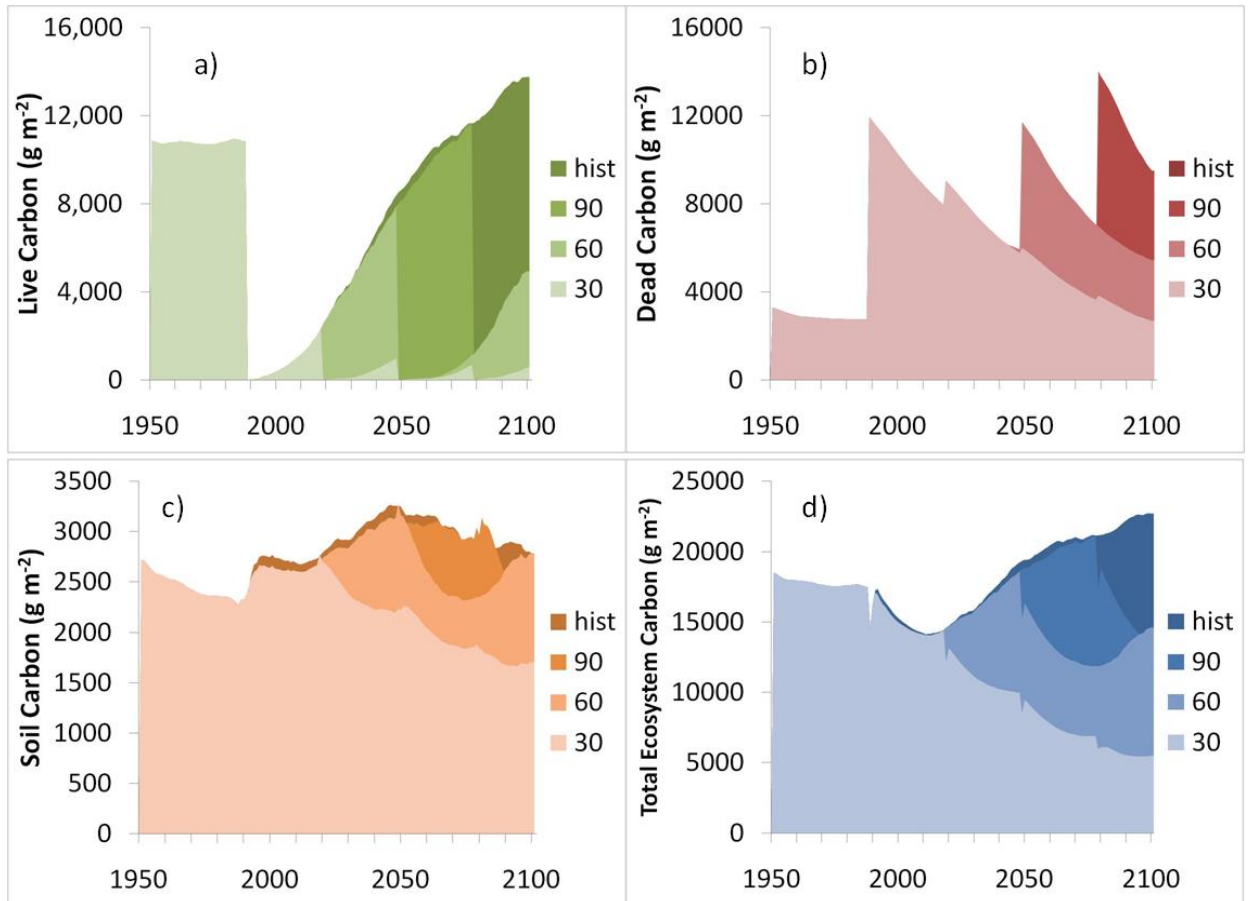


Figure 2. Results from the CENTURY v.4.5 model simulations showing C stocks (a) live, (b) dead, (c) soil, and (d) total, g C m^{-2} for 30-, 60-, 90-, or historical (>200 year) fire-return intervals averaged across 3 different climate scenarios (CCSM, CNRM, GFDL), fast recovery.

Averaged across the three future climate scenarios for the post-1988 fire period (1989-2099) and assuming fast recovery, total ecosystem C stocks at the end of the simulation period were 28% lower than historical stocks for the 60-year fire event and 66% lower than historical C stocks for the 30-year fire event scenario (**Figure 3**). In contrast, C stocks were within 5% of the pre-fire C stocks in the future period for the 90-year fire-event scenario. These three fire scenarios suggest that fire events would need to be separated by 90 years or longer for recovery of C stocks, whereas more frequent fire events would lead to C losses relative to the historical average for mature forest stands. However, these simulations represent singular pathways of one or more fire events spaced exactly at 90-, 60-, or 30- years. In reality, fire sequences at any given location on the landscape will be best represented by a probabilistic distribution of fire events centered on an average fire-return interval.

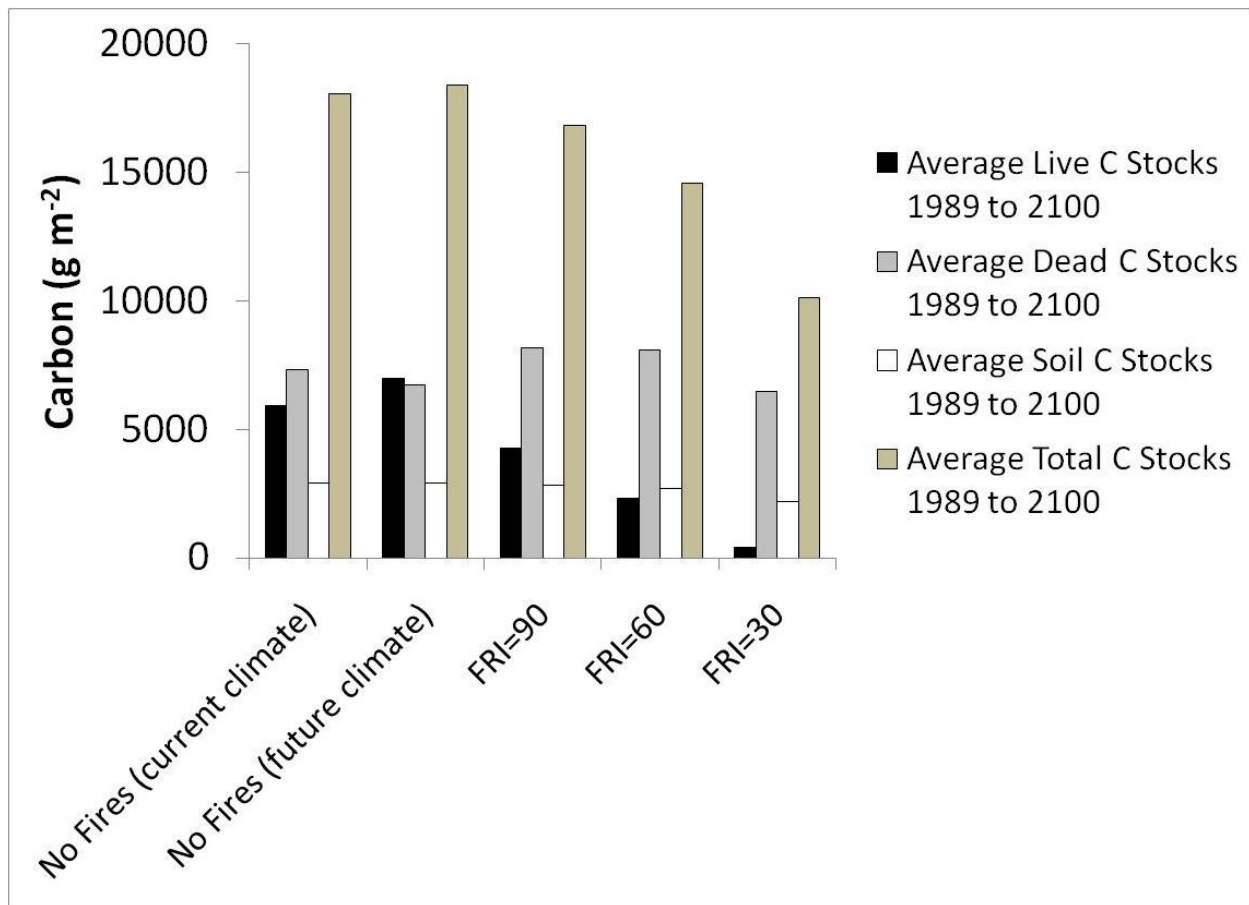


Figure 3. Carbon stocks for live, dead, soil, and total forest pools for historical (no fires), 90-, 60-, or 30-year fire

Question 2: Do current projections indicate that changes of this magnitude are likely to occur in the next century, and if so, where in the GYE do they occur?

Current fire incidence and area are sensitive to small changes in spring-summer temperature.

Modeling large fire occurrence and burned area in the Northern Rockies, and especially the GYE, from historical fire and climate data is especially challenging. This is so because the fire regime is extremely sensitive to temperature (**Figures 4-5**). Years with high fire activity (especially for naturally ignited fires, but also for human-caused fires) all occur when spring and summer temperatures are above average. However, there is great variability in fire activity within the subset of warm years, so additional information is needed to characterize fuel conditions coming into a fire season (such as cumulative water year moisture deficit), and sources of moisture during the fire season (such as monthly precipitation). Ideally, these variables will constrain a model so that it will burn realistically given the climatic conditions and topography.

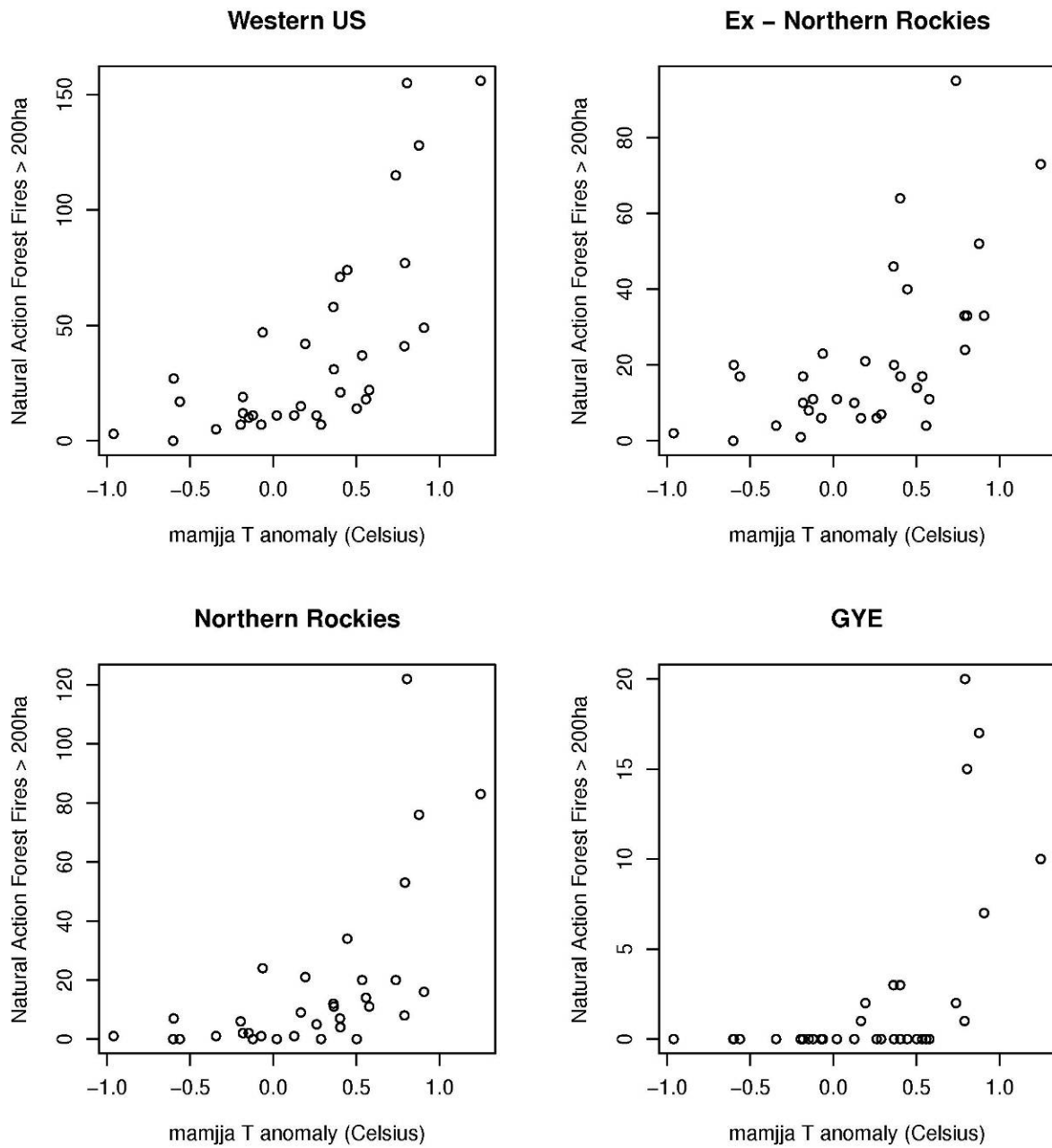


Figure 4. Annual fire frequency for naturally ignited forest fires on which suppression action was taken, reported by BIA, NPS, USFS 1972 - 2005, aggregated over the Western US, the Western US exclusive of the Northern Rockies, the Northern Rockies (including GYE), and the GYE. Spring + Summer temperature anomalies (1961-90 base period) from Climate Research Unit, averaged over interior North America (Jones and Moberg, 2003). Horizontal axis is temperature anomaly for spring-summer (March through August).

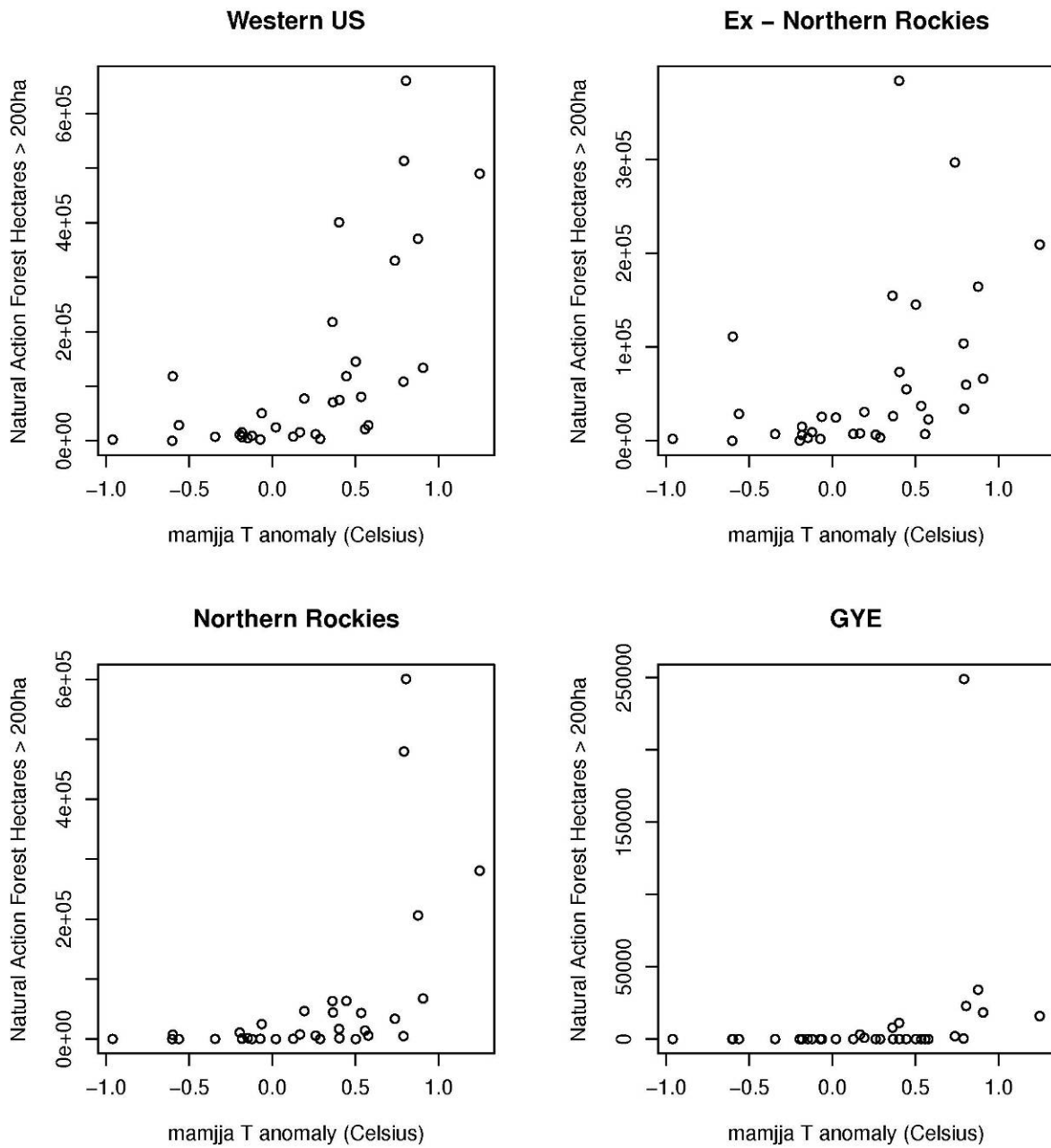


Figure 5. Annual burned area for naturally ignited forest fires on which suppression action was taken, reported by BIA, NPS, USFS 1972 - 2005, aggregated over the Western US, the Western US exclusive of the Northern Rockies, the Northern Rockies (including GYE), and the GYE. Spring + Summer temperature anomalies (1961-90 base period) from Climate Research Unit, averaged over interior North America (Jones and Moberg, 2003). Horizontal axis is temperature anomaly for spring-summer (March through August).

Some difficulty arises because of the extreme nonlinearity of the variables we wish to describe, and the need to fit those extremes very well if we are to have any hope of projecting how future changes in climate may affect fire. For example, during the model estimation period of 1972-1999, 95% of the cumulative GYE burned area occurred in just 1988. The case for fire occurrence is less extreme but still challenging from a modeling perspective: 33% of Northern Rocky Mountains large fires and 62% of GYE large fires occurred in two years, 1988 and 1994. A model that significantly under-predicts climatically driven extremes of this magnitude will probably drastically under-predict future climate change impacts as well, as the impact of climate change during this century is likely to be an increase in the frequency of these extreme events. On the other hand, accurately fitting extremely nonlinear climate-fire relationships in the historical record implies that small changes in model specifications can potentially produce very large differences in projections of future fire under a changing climate regime. Note that a shift in Spring and Summer temperature of just over half a degree Celsius above the 1961-90 average (**Figures 4-5** above) marks the difference between extreme fire years and all other fire years in the Northern Rockies, whereas the projected increase in average Spring and Summer temperatures in the region for the three GCM climate scenarios explored here is on the order of 4 to 6 degrees Celsius by end of century (**Figure 6**).

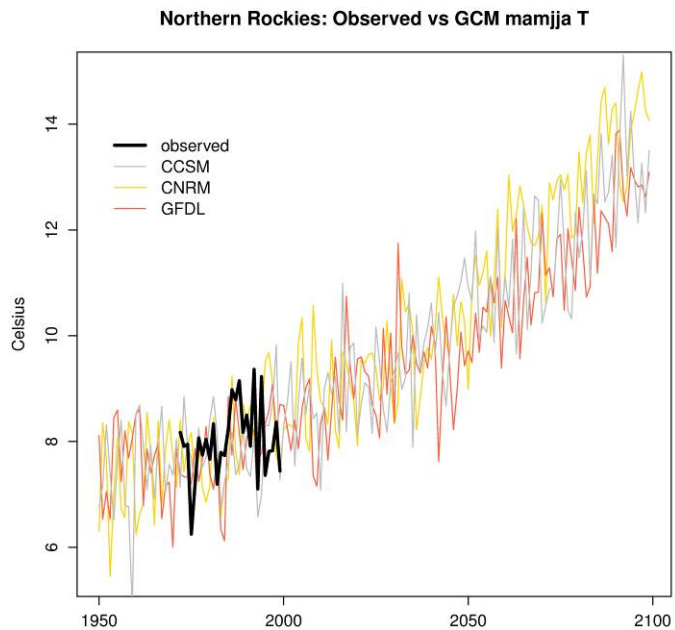


Figure 6. Northern Rockies average Spring and Summer temperature from three GCM runs and historical data.

The approaches used here all apply statistical models estimated on recent decades' experience to describe the response of fire regimes in current ecosystems to climatic variability. Models of this kind can be used to project how the ecosystem and fire regime present today could respond if immediately confronted with any particular climate. This approach assumes that the fundamental relationships between the climate conditions conducive to large fires and fire occurrence will not change, but the frequency and location of these climate conditions vary across the landscape (and may change in the future.) This assumption will at some point be violated if climate shifts beyond the conditions necessary to sustain the current ecosystem. Therefore, this approach is most useful for determining the response to climate change in the near future, and for helping to identify thresholds at which current ecosystems cannot be sustained.

These kinds of models might also be used to try to characterize how new, future ecosystems in a stable state might respond to the climate of that future. For example, a warmer climate accompanied by much shorter fire return intervals could be associated with ponderosa pine forests replacing current GYE forest types. The time period covered by this study (through

2099) is probably not, however, long enough to allow for the establishment of new successor ecosystems other than grass and shrub systems. And, in any event, the climate scenarios used here do not project stable climate states by end of the 21st Century, but rather accelerating change.

Thus, we are likely to be able to identify at coarse temporal resolution the onset of transitions away from current ecosystems and fire regimes, marked by changes in disturbance regimes and the onset of conditions (climate and/or disturbance frequency) not conducive to regeneration of currently dominant species. However, we will not be able to use our statistical models to describe the transitions themselves with much confidence once they are underway, because the ecosystems represented by these models will no longer exist in their current form, and so their future fire regime responses to climate will diverge from what we can model based on past responses. In addition, the functional form of statistical models that can adequately represent current nonlinear responses of fire regimes to historic climate variability is not likely to perform robustly under climatic conditions that exceed the historic range by some extent that may be difficult to ascertain.

Relating historical fire occurrence, number and area burned to climate. To determine which fire-return intervals are expected in the GYE given current climate projections (**Question 2**), we first developed three probabilistic statistical models to relate observed fires to climatic conditions. Logistic regression was used to predict the probability of the occurrence of large fires (defined as >200 ha), then a conditional Poisson lognormal model was estimated to predict the number (1 or greater) of large fires (given that a fire occurred), with a covariate derived from the logistic regression. Finally, the area burned in each fire was predicted using a Generalized Pareto Distribution (GPD) fit to our Northern Rockies fire history, using climatic covariates. The logistic regression and GPD models were rigorously cross-validated. The Poisson lognormal model, as we will discuss, was driven with output from the cross-validated logistic regression models. These models were then used to predict annual fire occurrence and area burned for each of the four climate scenarios (Table 1). The approach is summarized in the following formula:

$$\text{Expected Area Burned} = \mathbf{P}(\theta) * \hat{\mathbf{C}}(\theta|\text{fire}>0) * \hat{\mathbf{A}}(\mathbf{X}|\text{fire}=1)$$

where θ is the linear estimator from the logistic regression, \mathbf{P} is the probability of fire where

$$\mathbf{P} = \exp(\theta) / (1 + \exp(\theta)),$$

$\hat{\mathbf{C}}(\theta|\text{fire})$ is the expected number of fires given that fire occurs (1 or greater) estimated by a set of Poisson Lognormal models conditioned on θ , and $\hat{\mathbf{A}}$ is the expected burned area per fire estimated by a GPD model as a function of variates \mathbf{X} . For simplicity we will refer to this collection of models as Model 1.

Subsequently, we estimated an additional set of predicted fire occurrence and burned area for each climate scenario using a variation on the above models and the same predictor data sets. In this variant an unconditional Poisson lognormal model was used to estimate the number of fires (0 or greater) as a function of the linear output from the logistic regression. The effect of this model specification is to cap the maximum probability of a large fire occurring at the maximum

estimated for any location in the historic period (1972-1999). We will refer to this collection of models as Model 1B. The Model 1B approach is summarized in the following formula:

$$\text{Expected Area Burned} = \hat{C}_b(\theta) * \hat{A}(X|\text{fire}=1)$$

where \hat{C}_b is the expected fire count (0 or greater) estimated by another set of Poisson Lognormal models conditioned on θ , and \hat{A} is as before. Each step is described in more detail below.

Additionally, we estimated results for a Model 1C, where the GPD fire size distribution was also truncated at twice the historic maximum fire size:

$$\text{Expected Area Burned} = \hat{C}_b(\theta) * \hat{A}_c(X|\text{fire}=1, \text{area}<346152)$$

where \hat{C}_b is as above in Model 1B, and \hat{A}_c is the expected burned area per fire estimated by a truncated GPD model as a function of variates X .

Data

The spatial domain for this analysis is a 1/8-degree lat/lon grid for the Northern Rocky Mountains ($n = 2309$ grid cells, approximately 12 km x 12 km cell size; **Figure 7**); this area has a similar fire-climate relationship as the GYE and the larger area provides a stronger data base for model development. The spatial domain includes lands managed by the US Forest Service, National Park Service and Bureau of Indian Affairs. Models were estimated for the entire Northern Rockies domain, and then applied to a subsample ($n = 578$ cells) comprising the GYE study area. The temporal domain included monthly data from January 1972 to December 1999. We fit our models for 775,824 data points (12 months x 28 years x 2309 grid cells).

Federal fire histories for the National Park Service and Bureau of Indian Affairs were obtained from the Department of Interior (2008 Fire CDROM), and for the Forest Service from Department of Agriculture (downloaded using an account on the KCFast data center <http://fam.nwccg.gov/fam-web/kcfast/mnmenu.htm>). The common time period covered by these data was 1972-2008.

Topographic information on a 1/8 degree grid were accessed online from the North American Land Data Assimilation System (LDAS) (<http://ldas.gsfc.nasa.gov/>).

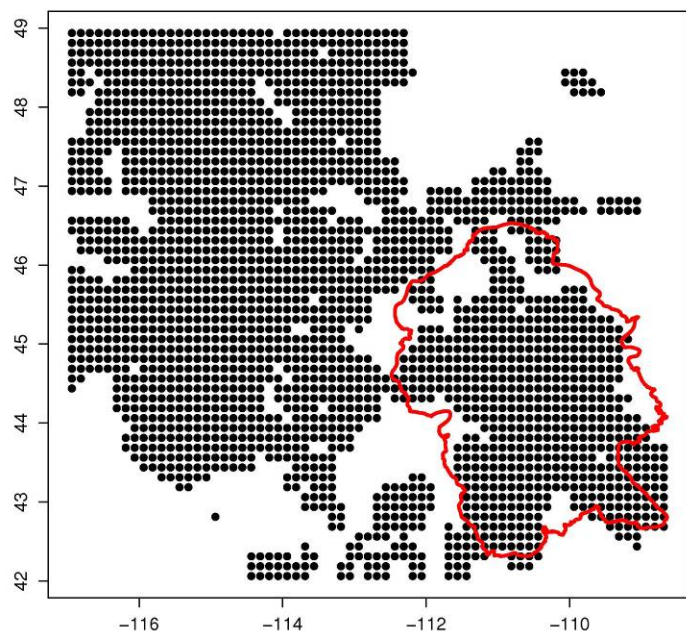


Figure 7. Grid cells used for modeling fire occurrence and area burned in the northern Rocky Mountains and the boundary of the Greater Yellowstone Ecosystem.

Vegetation data were accessed online from the LANDFIRE project (<http://www.landfire.gov/>). These data were scaled up from 30- and 120-meter polygons to the 1/8 degree lat/lon grid used by LDAS to provide summary statistics for each grid cell.

Using the climate data described earlier, we created a monthly record for each grid cell of number of fires, fire presence (i.e., 1 if number of fires > 0, 0 otherwise) and area burned, along with historic temperature, precipitation and simulated hydrologic values including evapotranspiration, relative humidity, soil moisture, snow water equivalent, etc., and topographic variables such as mean and standard deviation of elevation, slope, and aspect. Potential evapotranspiration was calculated using the Penman Monteith equation (Penman 1948; Monteith 1965) and used to estimate cumulative moisture deficits.

Methods

The monthly **presence/absence of large fires** (> 200 ha) was estimated on a 1/8-degree grid for the Northern Rockies grid as a function of land surface characteristics and climate using *logistic regression* (see Preisler and Westerling 2007).

Our predictand (response variable) is the probability that a fire exceeds an arbitrary size threshold:

$$P_{i,j,t} = \text{Prob}[A_{i,j,t} > 200\text{ha} \mid X_{i,j,t}, e]$$

where $P_{i,j,t}$ is the probability that the point in space and time denoted by longitude = i , latitude = j , time = t contains at least one fire greater than 200 hectares given a vector of predictor variables $X_{i,j,t}$.

The precise model specification used for our analysis is:

$$\begin{aligned} \text{Logit}(P) &= \log(P / (1-P)) \\ &= \beta * [1 + \text{elevsd} + \text{mmonth} + \text{precn} + \text{tavg} + (\text{precn} \times \text{tavg}) + \\ &\quad \text{tmamjjaZ} + (U \times \text{md0n}) + \text{md00n}] \end{aligned}$$

where:

elevsd is the standard deviation of elevation within a 1/8 degree grid cell, derived from GTOPO30 Global 30 Arc Second (~1km) Elevation Data Set, distributed by the North American Land Data Assimilation System (<http://ldas.gsfc.nasa.gov/>),

mmonth is a smoothed curve fit to average monthly fire occurrence,

precn is the normalized monthly cumulative precipitation (using 1972 - 1999 base) in each grid cell,

tavg is the monthly mean bias corrected temperature in each grid cell,

tmamjjaZ is the regionally (Northern Rockies) averaged March through August temperature,

md0n is the normalized (1972-1999 base) monthly moisture deficit (calculated using evapotranspiration from the VIC model and potential evapotranspiration from the Penman-Monteith equation) for each grid cell,

md00n is the normalized (1972-1999 base) water-year moisture deficit for each grid cell,

U is a matrix describing a thin plate spline describing the interaction between long-term (1961-90) average cumulative water-year moisture deficit and long term (1961-90) average cumulative water-year actual evapotranspiration (for methods see Preisler and Westerling 2007, Preisler et al. 2008; the required modules for fitting thin-plate splines within R were downloaded from the Internet (Geophysical Statistical Project; information available online at <http://www.cgd.ucar.edu/stats/Software/Fields>),

and **β** is a vector of parameters to be estimated. The linear estimator for the logit(**P**) is **θ** (**Figure 8**). To estimate **θ** for the regression described above, we used the glm() function in the stats package in the R statistical computing and graphics environment (<http://www.r-project.org>) to estimate a generalized linear model with binomial error terms, where the response variable was 1 when a fire was observed and 0 otherwise. Model specifications were tested by sequentially removing candidate predictors and comparing the Akaike Information Criterion (AIC) statistics calculated by the glm() function. The AIC measures the goodness of fit of statistical models while accounting for differences in model complexity. (Burnham and Anderson 2002). The model coefficients and summary statistics for the uncross-validated model are provided (**Table 1**).

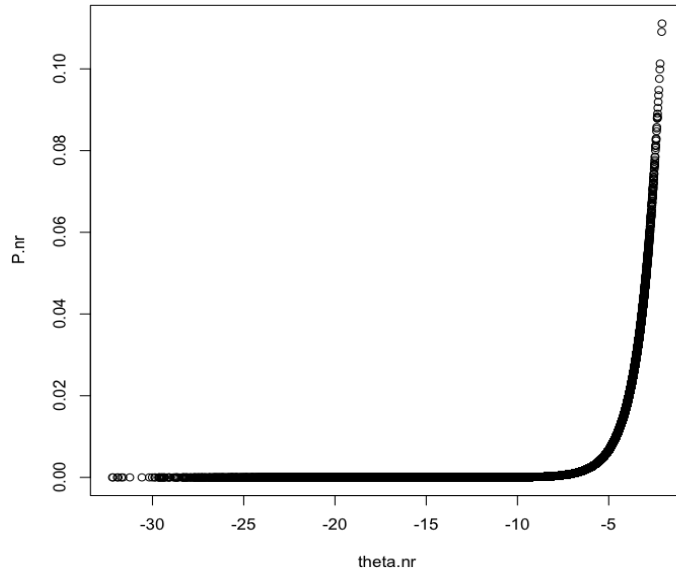


Figure 8. P vs θ from logistic regression of Northern Rockies fire occurrence on climate and topography.

Table 1. Model coefficients and summary statistics.

```
Call:
glm(formula = burn ~ md00n + U1:md0n + precn * tavg + elevsd +
     mmonth + tmamjjaZ, family = binomial, x = TRUE, y = TRUE)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.485340 -0.025639 -0.010600 -0.003962  4.867203

Coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept) -16.343666   0.738602  -22.128 < 2e-16 ***
md00n        0.296263   0.050287   5.891 3.83e-09 ***
precn       -1.839727   0.288724  -6.372 1.87e-10 ***
tavg         0.175611   0.021231   8.272 < 2e-16 ***
elevsd       0.003385   0.000490   6.908 4.92e-12 ***
mmonth       0.394684   0.044318   8.906 < 2e-16 ***
tmamjjaZ    0.646729   0.080948   7.989 1.36e-15 ***
U11:md0n    -0.095086   0.064578  -1.472 0.14091
U12:md0n     0.189709   0.046017   4.123 3.75e-05 ***
U13:md0n     0.129630   0.053888   2.406 0.01615 *
U14:md0n    -0.241810   0.059973  -4.032 5.53e-05 ***
precn:tavg   0.054009   0.019643   2.749 0.00597 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 8669  on 775823  degrees of freedom
Residual deviance: 6772  on 775812  degrees of freedom
AIC: 6796

Number of Fisher Scoring iterations: 14
```

The selection of predictor variables was motivated by recent work by Westerling and colleagues. Westerling et al. 2006 demonstrated the sensitivity of Northern Rockies fire occurrence to regional spring and summer temperature. Temperature and interactions between temperature and precipitation are key variables influencing fire occurrence in the region. Westerling et al. 2006, Westerling et al. 2009, and Westerling 2009 also demonstrated the importance of variables like current year moisture deficit that integrate the effects of temperature and precipitation on moisture available for the wetting of fuels in forest wildfire regimes.

Interestingly, the best models tested here were those that included both local monthly average temperature (**tavg**) and a regional spring and summer temperature index (**tmamjjaZ**). In particular, models without some form of the latter variable uniformly proved incapable of capturing the extremes of observed fire occurrence, both the high values in 1988 and '94, and the lowest values. Since most of the area burned occurs during those historically rare extreme events, it was crucial for this analysis to derive a model that could predict the most extreme fire seasons. Correlation between local monthly average temperature and regional spring and summer temperature, while extremely significant ($p < 2.2e-16$), was very low ($\rho < 0.05$). Even accounting for seasonal variations, correlation between the regional index and local monthly temperatures ranged from 0.01 (July) to 0.36 (April). We posit that the regional index may be both a good indicator of the timing of spring and the length and intensity of the overall Northern Rockies fire season, and thus may consequently also indicate when fire suppression resources are constrained.

The logistic regression model specification was tested using leave-one-out cross-validation. That is, for each of the 28 years in our fire history, we estimated a separate set of model parameters, using the other 27 years to train a model that would then be used to predict the 28th year. In this way we seek to avoid over-fitting our model, because the model being used to predict events in any given year was derived without using any data contemporaneous to the events it is intended to predict. Thus the cross-validated model skill is indicative of expected out of sample performance. None of the 28 models deviated significantly from the un-cross-validated model estimated using all of the data. To assess how well our logistic regression model captures seasonal and interannual variability in fire in the Northern Rockies, we estimated the expected number of grid cells with fire monthly and annually for the region by summing the probabilities predicted by our logistic regression for large fire presence across all 2309 grid cells by month and/or year. **Figure 9** shows the cross-validated and un-cross-validated model fits and observed fire presence.

The cross-validated logistic regression results aggregated over the region explain just over 82% of interannual variability in the presence of large fires. The results for the monthly values are similar (~78%), probably because so much of the area burned in the Northern Rockies (~75%) occurs in just July and August, and the allocation of fire starts across those two months probably has more to do with short term meteorology than with climate variables that are strongly correlated across the two months.

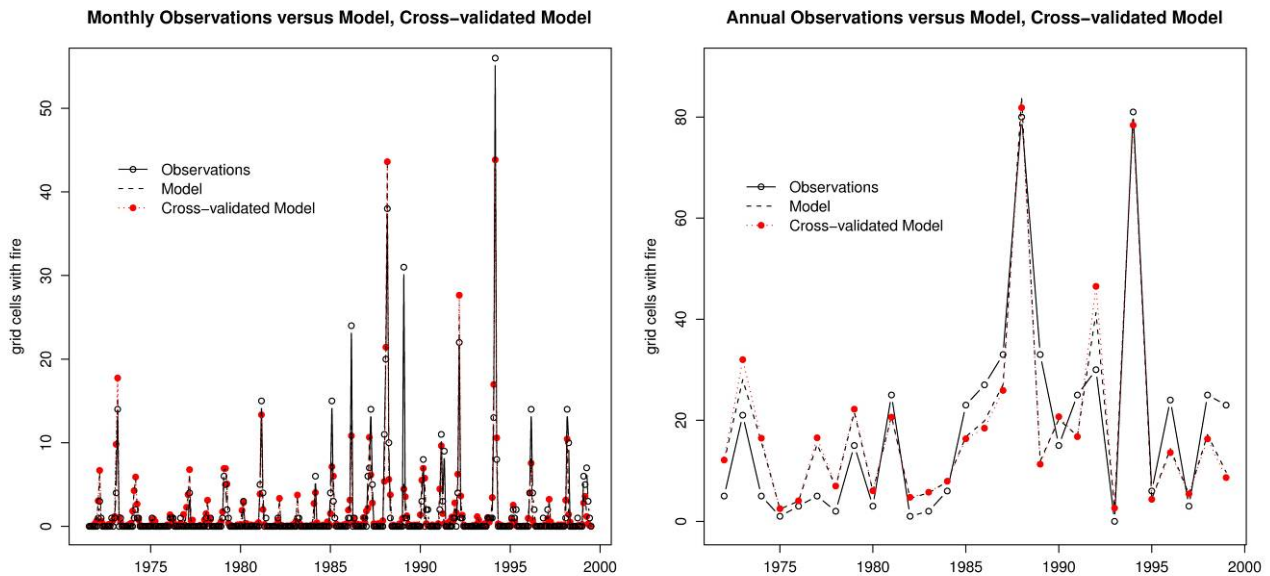


Figure 9. Logistic regression model results versus observations, aggregated by month and by year over the Northern Rockies.

To determine the **number of large fires** (> 200 ha) occurring in the $1/8$ degree grid cells given fire occurrence, we then fit the number of fires per grid cell and month to Poisson lognormal distributions. Two Poisson lognormal distributions were fit using a breakpoint (-6.68) in θ , the logit estimated by the logistic regression above (**Figure 10**). This value was selected as a good predictor of the probability of observing more than one large fire because we never observed more than one fire below this value. A Poisson lognormal distribution was fit to the observed fire data for all the months and locations where the logit was estimated to be less than -6.68 , and another for where the logit was estimated to be greater than -6.68 . The expected value of the first model was 1 with variance 0, while the expected value of the second was 1.12 with variance 0.18 (estimated over 100,000 simulations). We tested using multiple breakpoints, but the difference was negligible and, because of the sample size for larger fire numbers, the differences between categories above the -6.68 breakpoint did not vary smoothly.

In order to determine **fire size** for fires exceeding the 200-ha threshold, we used a Generalized Pareto Distribution (GPD) fit to the logarithm of fire size. The GPD is a “points over thresholds” model that allows us to simulate fire size distributions, in our case for fires > 200 ha. We fit a GPD to our observed large fire burned area data for the Northern Rockies using the ismev library in R, with normalized water-year cumulative moisture deficit as a covariate. As when estimating

our logistic regression, we used the AIC to compare model specifications for both the scale and shape parameters of the GPD. We compared the results sequentially adding and sequentially subtracting candidate variables (temperature, precipitation, moisture deficit, θ , topography). A parsimonious model with cumulative water year moisture deficit as a predictor for the scale parameter and a stationarity assumption for the shape parameter was best. For each fire in the

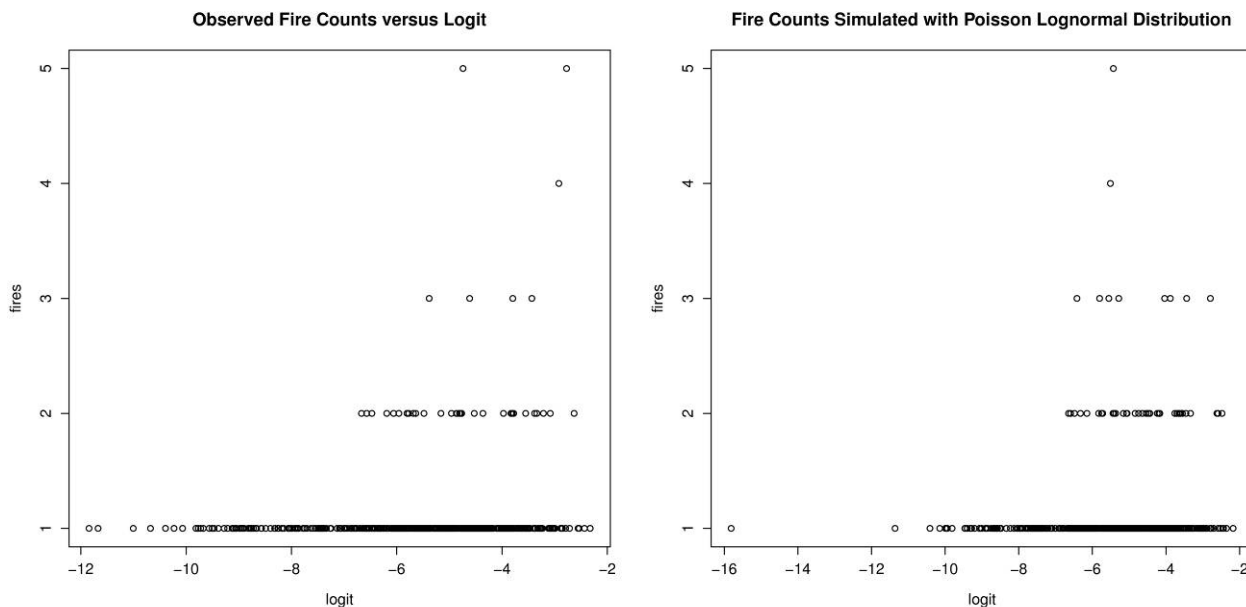
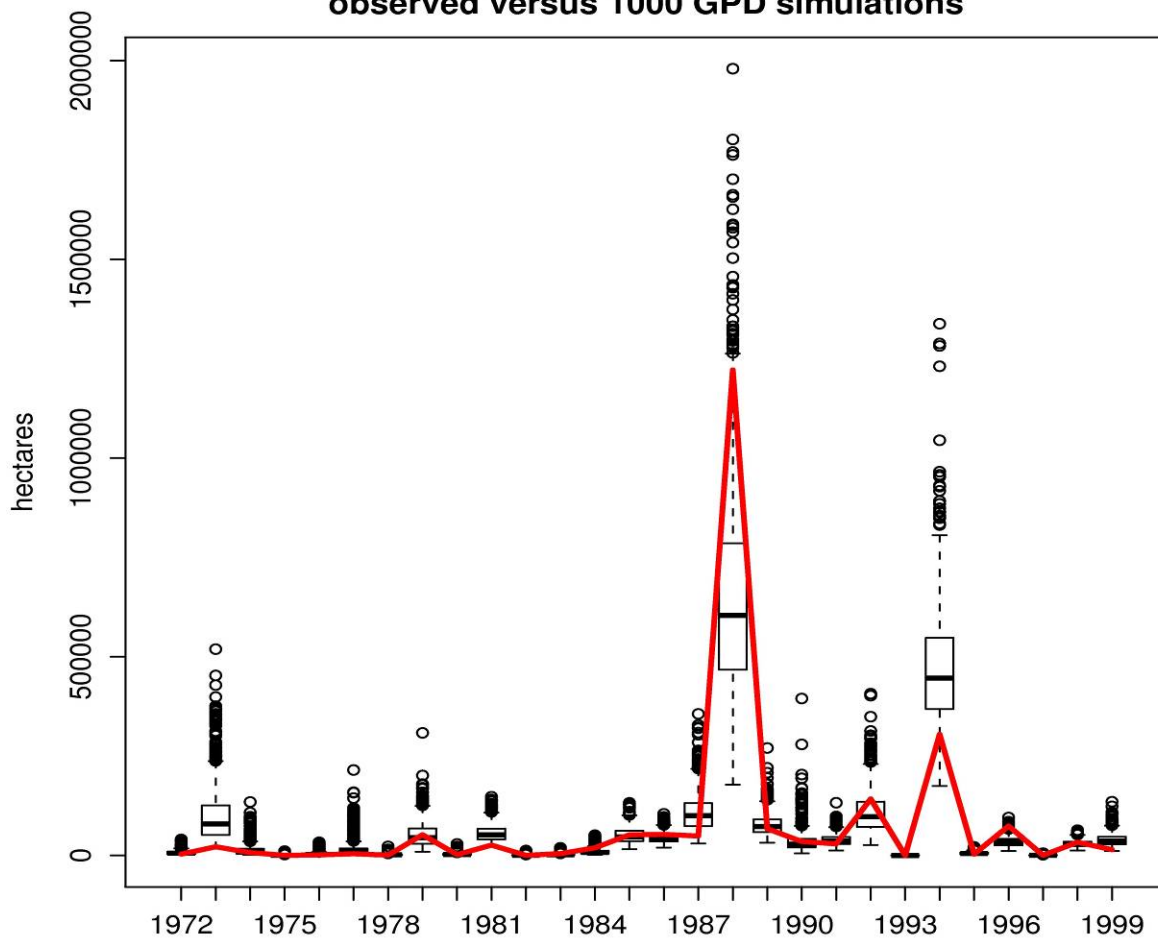


Figure 10. (left) Observed fire counts for grid cells with fire plotted versus the linear predictor from the logistic regression for fire presence/absence. Number of fires, given that fire occurred, is correlated with the θ , the predictor for the probability that fire occurred. (right) Fire counts simulated with Poisson Lognormal Distributions as a function of the linear predictor from the logistic regression. During the historic period, there were 522 grid cell-months with fire. For each of these, we used the corresponding value of θ from the logistic regression to choose which Poisson Lognormal Distribution to draw from, and then generated one random integer.

observed historical fire history, we estimated 1000 random draws from the GPD as a function of the cumulative water year moisture deficit and compared the distribution of simulated annual area burned for the Northern Rockies to the observed values. The area burned in 1988 was much higher than our median simulation, but well within the range of values from our simulation (**Figure 11**).

Finally, we used these probabilistic statistical models to simulate fire histories from 1951 to 2099 for each climate scenario using historic climate and the downscaled hydroclimate for each GCM run, to estimate expected values of numbers of fires and area burned, and to examine the ability of the models to predict observed fire over the historical record. The models are probabilistic, and thus many replicates are required to generate the expected mean frequency of fire and area burned for any given cell; i.e., the actual historical record is only one outcome of a probabilistic process, and thus the models will not reproduce the historical record exactly. However, the observed fires should be within the range of outcomes represented by the model. The ability to generate an arbitrary number of simulations will allow us to estimate changes in extremes as well as mean fire activity, to estimate confidence intervals, and to examine the effects of variations in the timing of fire events on subsequent carbon trajectories in the GYE.

Northern Rockies Annual area burned: observed versus 1000 GPD simulations



location = log(200ha), shape = -0.3761716 , scale \sim cumulative water year deficit

Figure 11. Annual box plots of aggregated area burned from 1000 GPD simulations for every historical fire. The horizontal bars show the median value, the boxes show the interquartile range (middle 50%), the whiskers the most extreme values within 1.5 x interquartile range, points extremes outside 1.5 x the interquartile range. The red line is the historical data.

Upon examining the results of applying these models to the GCM runs, we observed very large increases in expected area burned by end of century in all scenarios. Because fire occurrence in the Northern Rockies, and especially in the GYE, is a very nonlinear function of temperature, any model fit to historical data will be very sensitive to modest changes in temperature, especially spring and summer temperatures. Westerling et al. (2006) showed this result for western US federal forest areas (including the Northern Rockies), and similar sensitivity to temperature is apparent in data broken out for large areas outside the Northern Rockies as well (**Figures 4-5**). The consequence of this nonlinearity is that alternative model specifications with little apparent difference in fit during the model estimation period can result in enormous differences by the end of the climate projections in 2099.

Model 1

The Model 1 specification includes a regional spring and summer temperature term, ($tmamjjaZ$, the average temperature from March through August) that accounts for much of its success in fitting extremes in interannual variability in fire occurrence. This spring and summer temperature term, $tmamjjaZ$, is a linear term in the logistic regression (i.e., it is linear in θ); however, because the probability P is an exponential function of θ , $tmamjjaZ$ is nonlinear in the probabilities (**Figure 12**). Over the range of historic variability in $tmamjjaZ$, the effect of this nonlinearity is negligible. However, it implies a certain assumption about the relationships between fire activity and temperature in the Northern Rockies and GYE depicted in **Figures 4-5**. Namely, that the steep slope describing the relationship between fire and temperature for the highest historic temperature anomalies will continue to increase at a high rate for temperatures above the historic range of variability. We can use the logistic model we have already estimated to demonstrate that alternative specifications that use the same predictors and data sets, but embody very different assumptions, are possible. This is the motivation for Model 1B.

Model 1B

As we mentioned before, the historic fire counts data are strongly correlated with θ , the linear output from the logistic regression. Instead of estimating our Poisson lognormal distributions for fire number conditional on 1 or more fires occurring, we can estimate Poisson lognormal distributions for fire counts of zero and greater, conditioned only on θ . Since our temperature terms are linear in θ , the effects of temperature on our fire predictions can be more tightly constrained for temperatures above the historic range, while only sacrificing negligible cross-validated model skill in the model estimation period (e.g., 80% of interannual variability is explained by Model 1B instead of the 82% by Model 1).

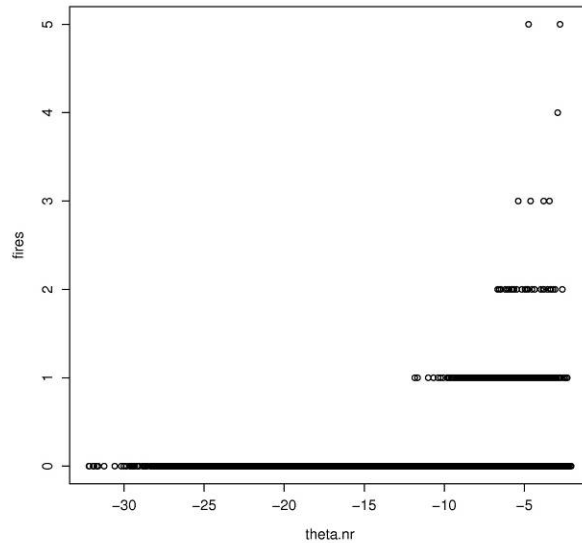


Figure 12. Observed fire counts for grid cells with fire plotted versus the linear predictor θ from the logistic regression for fire presence/absence.

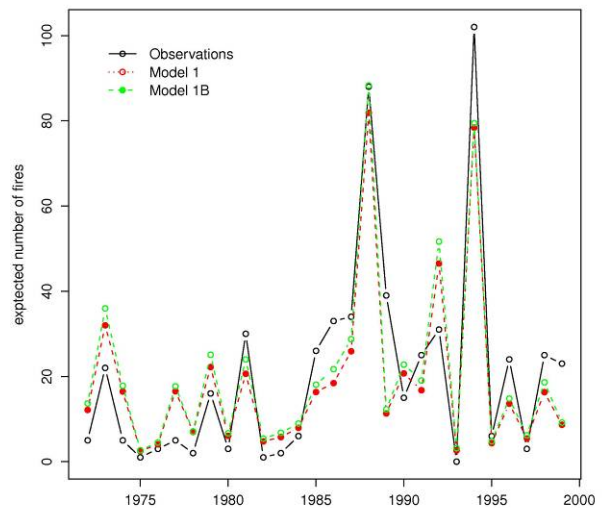


Figure 13. Model 1, Model 1B, and Observed Northern Rockies fire counts per year.

Similar to Model 1, we estimated multiple Poisson lognormal distributions for data between arbitrary breakpoints in θ . We fit six Poisson lognormal distributions to the observed data, with breakpoints in θ at -11.8, -9.3, -6.7, -5.4, and -4.7. All but the second of these were limiting values for observing higher incrementally higher numbers of fires. The second interval defined a region where two fires were sometimes observed, but relatively rarely so. The aggregated annual expected number of fires is plotted in **Figure 13**. Models 1 and 1B are essentially the same, although Model 1B has a slight positive bias compared to Model 1.

To characterize the differences in model sensitivity to temperature, we pooled the predicted annual GYE area burned and regional temperatures estimated for all three GCM climate scenarios using Model 1, and plotted smoothed area burned versus spring and summer temperature. Likewise, we did the same for Model 1B (**Figure 13**). The results are displayed in **Figure 14** in both linear and log scale. It is readily apparent that in the historic regional mean March - August temperature range (shaded gray), the models are quite close, as expected. They diverge significantly before 2050, and then quite dramatically after temperatures have increased about 3 °C over the historic range for the model estimation period. From Figure 14, it is clear that the Model 1 and 1B specifications are not robust after average spring and summer temperatures have increased by about 3°C. For Model 1, this is because probabilities of fire occurrence increase dramatically for temperatures above 3°C. Model 1B imposes a conservative assumption: that the probability of fire can never be greater than the maximum estimated for the historical period. It still produces an extreme response in burned area when Spring and Summer temperatures increase by about 3°C, because of increases in the expected size of fires generated by the GPD distribution. We can impose further constraints as in Model 1C, assuming a truncated fire size distribution. The historic simulation for Model 1C produces the same result as Model 1B, but even more tightly constrains future area burned for the GCM projections. Model specifications that make little difference within the historic range of variability are a significant source of uncertainty in predicting the effects of climate change projections. The constraints imposed to produce a realistic modeling scenario here are arbitrary.

Note that there is nothing inherently superior about any of the models from the standpoint of the historical record used to estimate them. Projecting larger or smaller fire frequency and burned

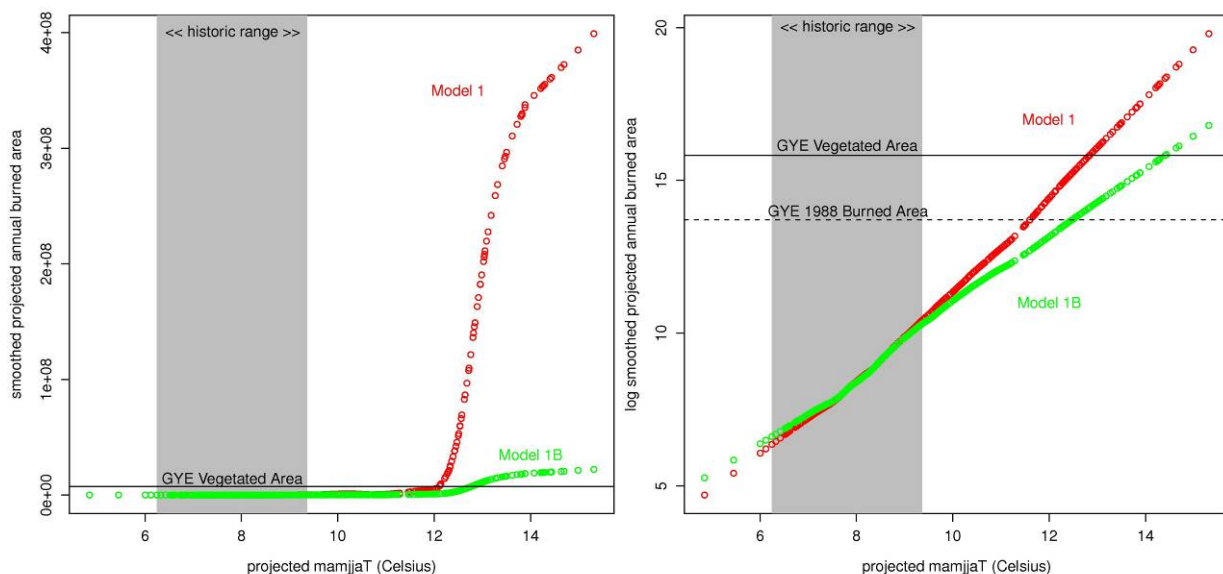


Figure 14. Models 1 and 1B sensitivity to regional spring and summer temperature.

area at a future date is not an objective basis for preferring one model to the other. The historic data used here do not provide any guidance as to which model has the correct implicit or explicit assumptions about the relationship between temperatures outside the historic range and fire activity in the GYE, *if any does*. Alternative model specifications with explicit assumptions about this could be used. For example, one could impose a model that assumed a particular historical event (the Yellowstone fires of 1988, the fires of 1910, etc) were an example of the upper limit possible for ignitions, large fires, or total area burned. One could attempt to relate number of fires to number of lightning strikes and potential human ignitions, and impose a range of scenarios for those causes. Reconstructions of paleo-fire events might provide some guidance for constraining climate-fire relationships outside the historic range of variability.

Predicting fire occurrence and area burned under projected future climates. When the statistical models developed above were employed in conjunction with the downscaled GCM model predictions for future climate in the GYE, fire frequency increased (shorter fire-return intervals) and expected burned area increased substantially during the coming century (**Figures 15-19**). However, the timing of these changes and the probability of future large-scale 1988-type fires depends on the type of climate-fire model used, the accuracy of the simulated future climates, and to a small degree, the specific climate simulation. The climate-fire frequency and climate-fire size models are extremely sensitive to temperature differences between the projected future climate and the 1961-1990 base period because the two large fire years that occurred in the 1972-1999 climate-fire model calibration period had relatively small temperature anomalies (0.5- 1 °C) and the small sample size of the large fire years in the time series makes model building a challenge. Between now and 2050, where we have the most confidence in the model, all climate scenarios and both fire-climate model formulations projected at least two 1988 sized fires (**Figures 15 and 16**, range 2-6, fires projected to be > 300,000 ha, noting that expected area burned for the model results using historic climate data (the black lines in **Figures 15 and 16**) also substantially under-predict the observed 1988 burned area).

Beyond 2050, Models 1 and 1B both predict that fires may burn areas as large as the GYE (**Figures 17 and 18**). Model 1C arbitrarily limits individual fires to a maximum twice the size of the largest fire observed in the recent historical record, and still suggests 1988-sized fire events would become a regular occurrence by end of century in all three future climate scenarios (**Figure 19**). After 2050, climatic conditions are sufficiently outside the historic range of variability used to estimate statistical fire models that those models cannot be used to characterize the magnitude of extreme fire years. However, extreme fire years from 2050-2100 will almost certainly become more common than projected for 2010-2050, because temperature is projected to continue to increase while precipitation is projected to remain at historical levels.

The fact that Models 1 and 1B eventually result in burned areas greater than the vegetated area in the GYE also does not in itself automatically disqualify this modeling approach. The GPD is calculated for data observed during an era when the number and size of fires burning at the same time or in the very recent past is not as limiting a factor on the potential size of any one fire as it would be under a more frequent fire regime. As we stated at the start of this section, the ability of these models to describe transient future fire regimes declines as changes in climate and disturbance regimes cross thresholds that begin to qualitatively change the underlying ecosystems and their responses to fire that are represented by the models. We could, for example,

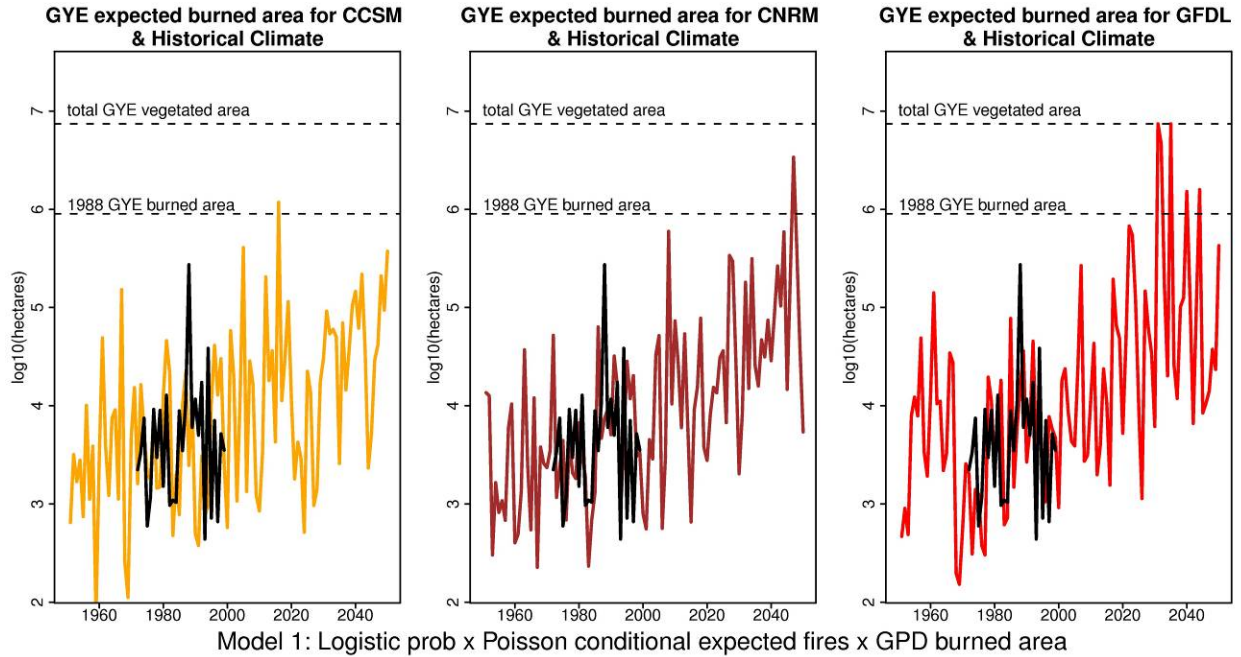


Figure 15. Model 1 expected area burned simulated for historic and projected climates through 2050. Note that we have not yet estimated distributions around the expected outcomes. So, for example, while the largest expected burned area years in the first decades of the 21st century are below the actual 1988 burned area (dashed line), they are above the mean historical model projection for the 1988 event (tallest black spike). Future work to calculate a large number of simulations for each projection will allow us to quantify, for these models, the probability of exceeding that threshold in any year of a scenario.

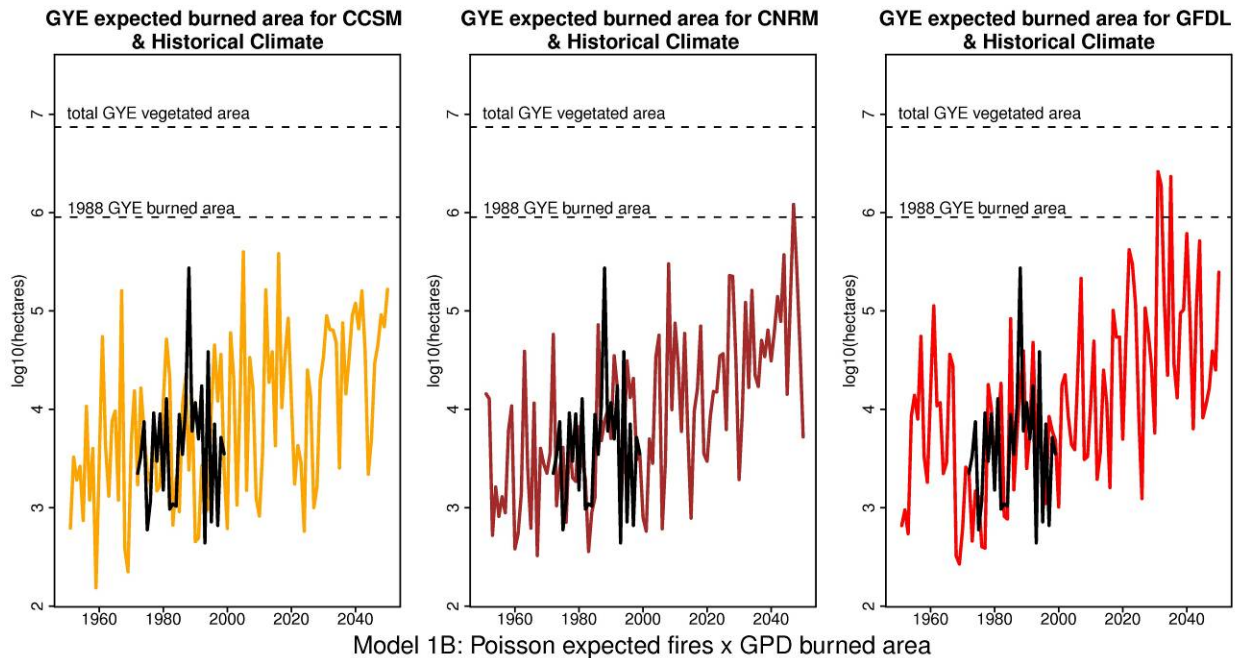


Figure 16. Model 1B expected area burned simulated for historic and projected climates.

locate random fire perimeters within the GYE when simulating fire histories probabilistically, and use information about recent and neighboring fires and topography to constrain them. For our figures showing the results for Models 1 and 1B here we simply limited total area burned to the available area in the GYE when the scenarios became extreme. Model 1C did not require

any addition limitation—truncating the GPD itself insured that projected burned areas remained below the vegetated area. Frequency of large fires in every scenario is high enough to begin to alter ecosystems beyond the capacity of these models to represent, well before the GYE burnable area becomes a binding constraint. The practical difference between the models would be differences in the date by which, if their projections are to be believed, they project regimes that could not be sustained by the current ecosystem.

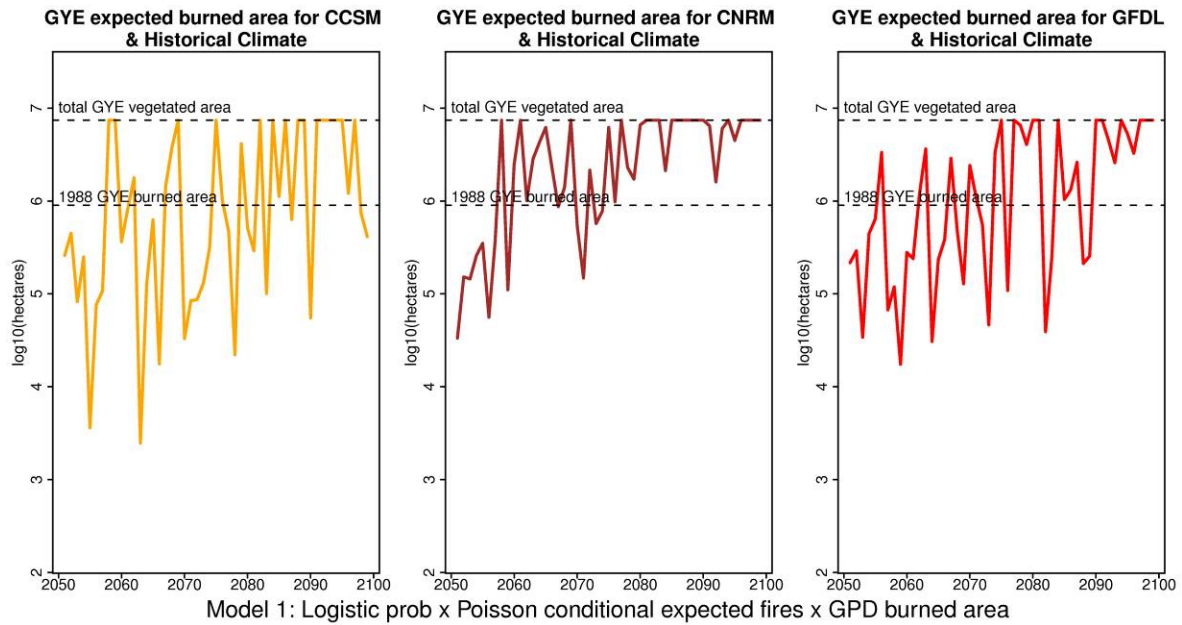


Figure 17. Model 1 expected area burned simulated for historic and projected climates from 2050 through 2100.

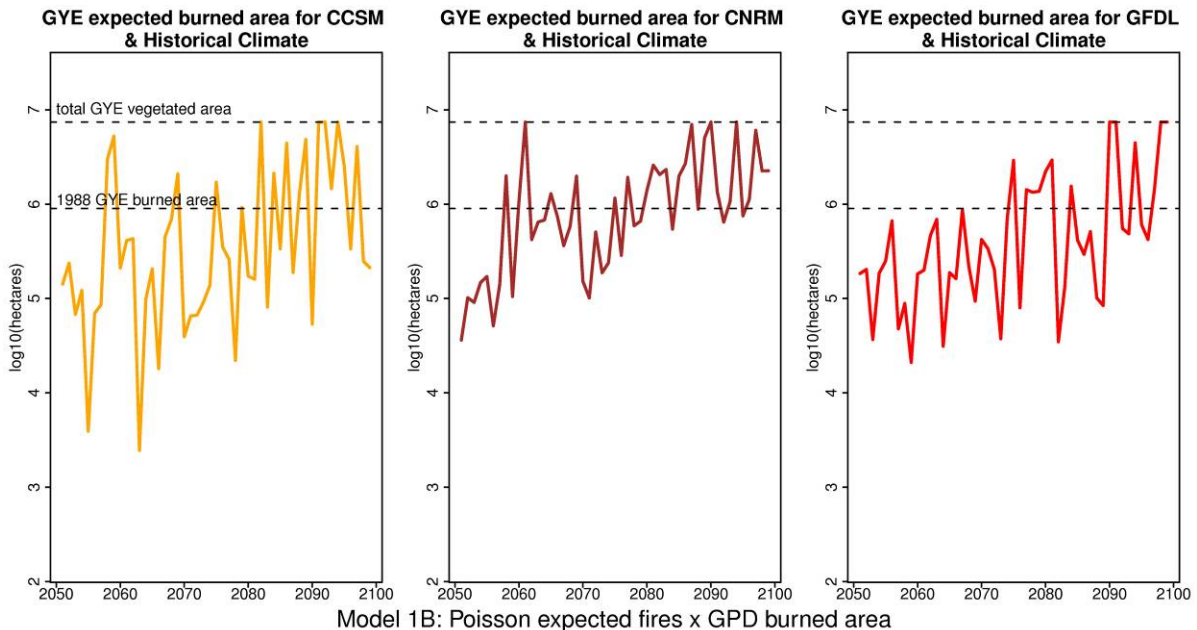


Figure 18. Model 1B expected area burned simulated for historic and projected climates from 2050 through 2100.

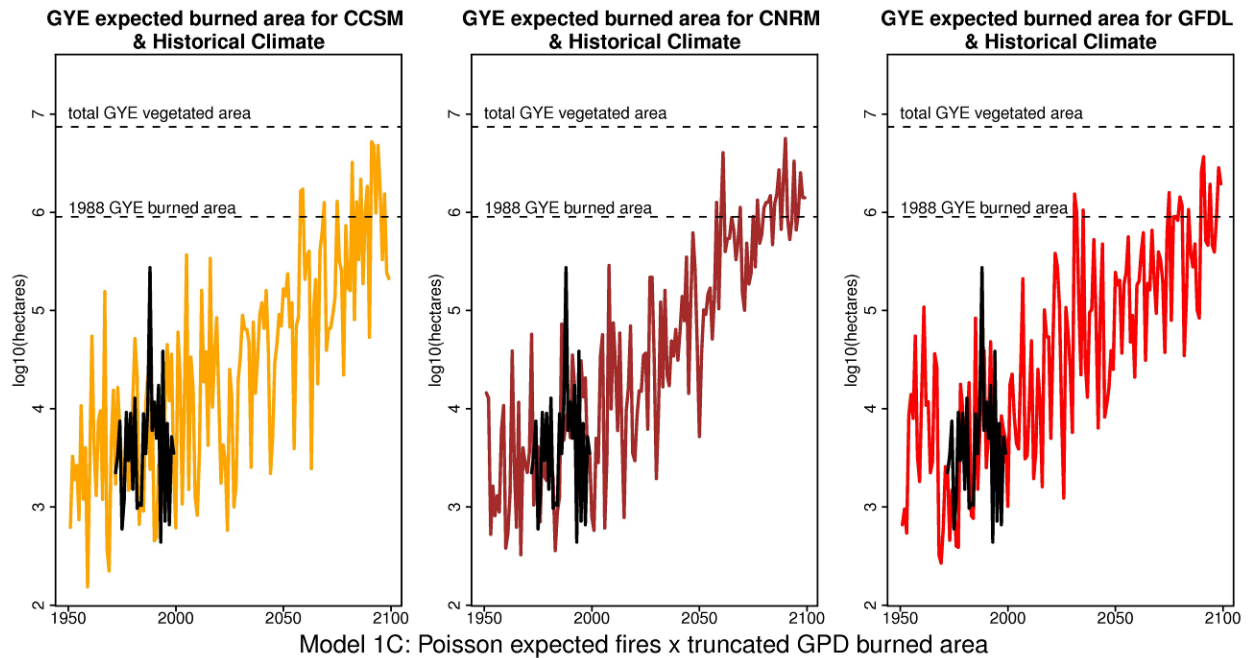


Figure 19. Model 1C expected area burned simulated for historic and projected climates from 1950 through 2100.

The more important issue is that model specifications that produce realistic looking scenarios require expert judgment and explicit assumptions about constraints on the response of current GYE forest ecosystems to climates outside the historic range of variability. Robustly characterizing future fire and carbon dynamics in these ecosystems requires exploring the effects of diverse assumptions on the range of outcomes. However, the fact that the range of model results reported here is very broad after 2050 does not mean we can say nothing about the later half of the century. The average climatic conditions by that point are such that, based on observed GYE fire regime responses to climate in recent decades, we do not expect climate to pose a limitation on the ability of GYE forests to burn (**Figures 17, 18, 19**). The assumptions in Model 1C, the most conservative by far, still produce changes in fire regime that would result in substantial changes to GYE ecosystems.

Historically, climate was the major driver of the fire regime in the GYE, with large fires occurring only in the (relatively infrequent) years of moderate to severe drought (Renkin and Despain 1992, Schoennagel et al. 2004). However, we expect that as temperatures increase, climate will no longer be a limiting factor for extreme fire years in the GYE landscape at some point in the later half of the century. Rather, across all three GCMs, by 2070 future climate conditions appear to be able to support large wildfires in most years if the current sensitivity of GYE fire regimes to temperature and moisture deficit persists (**Figures 17, 18, 19**). Therefore, it is important to recognize that other factors (notably fuels) would likely begin to constrain fire during the simulation period, more so than climate. At the same time, it is important to note that by 2050 climatic conditions are sufficiently outside the historic range of variability that the statistical models presented here cannot be used to estimate the expected magnitude of extreme fire years without acknowledging that they embody strong assumptions. This is probably true to some extent for any statistical model given the lack of recent historical analogues and the highly nonlinear relationship currently between climate and fire in the study area.

The predictions for the extent of fire in the 21st Century must be interpreted with care because changes in vegetation are not considered, and because the climate of the climate-fire models diverges substantially from the climate under which they were developed. In the statistical models, predicted fire occurrence and area burned is based on fires burning in conifer forests, and these statistical models do not incorporate the rate (or failure) of tree regeneration and successional trajectories, but are rather based on the relationship between current vegetation and climate. Thus, if fire return intervals become short enough to preclude tree regeneration, the vegetation may no longer support large forest fires. Rather, the fire regime of the GYE is predicted to move into uncharted territory, with fire frequency and size exceeding what has been observed in the historical record. As a further caveat, we note that projected changes in temperature by the climate scenarios only reach the historical differences in temperature between a subalpine forest (with an historical fire return interval of > 100 years) and a montane forest (with an historical fire return interval of < 30 years) by the end of this century (5-6 °C).

Can the climate-fire models accurately predict fire occurrence under projected future warmer climates? The climate-fire model development shows that the two large fire years (1988 and 1994 in the time series used to develop the model occurred under only slightly warmer conditions than average. So, the models are very sensitive to increases in temperature, and all of the climate scenarios predict a warmer climate, with longer warm and dry periods occurring more frequently. So, confidence in the predictions will reflect confidence in the predictor variables in the models, how representative the 1988 and 1994 fire years would be of conditions that would have large fires, and the ability of the statistical methods to robustly model fire under climate conditions outside the historic range. However, under a projected climate with the same precipitation (what is projected), higher fire incidence and more, larger fires are a reasonable outcome (**Figures 15-19**). For comparison, based on charcoal in lake core sediment, the most frequent fires in the Holocene occurred around 9900 years before present (15 fires/1000 years), under conditions that were likely warmer and drier than those of the 20th century (Millspaugh et al. 2000).

If the climate-fire models can accurately predict fire occurrence under projected future warmer climates, the predicted fire regime by the end of the 21st century appears similar to that of a more open montane forest with ponderosa pine or even non-forest vegetation types. As a result, we might expect an eventual shift to fire-climate-vegetation relationships that are novel for the GYE landscape. How soon or rapidly such a shift might occur, and whether such future environments would have analogues in other current systems (e.g., dry conifer or woodland/savanna systems) is uncertain at this time. It is clear, however, that changes in the fire regime of the magnitude projected here would lead to massive re-organization of the vegetation types within the region; anticipating those successional trajectories is beyond the scope of this study but is an important priority for scientists and regional land managers in planning for the future.

Question 3: What are the integrated effects of changing climate, vegetation, and fire on spatial patterns of C flux across the GYE landscape as a whole?

The results obtained for Questions 1 and 2 indicate that decreases in fire-return interval are likely to reduce the potential of the GYE landscape to store C in all future climate scenarios. The

capacity for fast post-fire regeneration of lodgepole pine from an aerial seedbank (serotinous cones) and the projected increase in lodgepole pine productivity under warmer climate conditions are unlikely to counter the anticipated reductions in fire-return interval. The magnitude of the shift in C balance will depend on the future distribution of forest and non-forest ecosystems across the landscape, other constraints on fire patterns not considered here (fuels, ignition factors, and landscape management), and the accuracy of the fire-climate model as future climate diverges increasingly from the past. If past climate-fire relationships can predict the future, by 2070 climate conditions projected by all three general circulation models would likely result in more fire than the current conifer forest ecosystem in the GYE could sustain.

The results from Question 2 suggest there will be many extreme fire years in the GYE in the coming century, thus suggesting the FRI threshold (< 90 years) identified by the CENTURY modeling for pre-1988 C recovery in mature stands will be crossed over much or most of the GYE landscape. Yet, the specific time-path of the extreme fire years through the coming century cannot be determined and must be estimated probabilistically. Furthermore, the trajectory of each grid cell, including time-since-fire and climate conditions as succession proceeds, must be estimated to scale up to the overall landscape. Thus far, we have developed a successful approach for representing statistically the emergent behavior of the CENTURY ecosystem model to project changes in total ecosystem C. **Figure 20** shows the results from fitting a statistical nonlinear total C trajectory as a function of time since fire (ignoring the first three years following fire that represent transient herbaceous dynamics). The points show the annual percentage change in total C from the CENTURY model runs for the CNRM-fast trajectory (all the FRI scenarios, pooled), as a function of time since fire. The red curve shows the smoothed, average fit to those trajectories. **Figure 20** shows the regression of the fitted values to simulated values captured by the smoothed line fit to the pooled CNRM fast scenarios and a no-fire CNRM fast-recovery total carbon scenario. Across all scenarios, the regressions were highly significant, explaining between $\sim 50\%$ to $> 80\%$ of the variance.

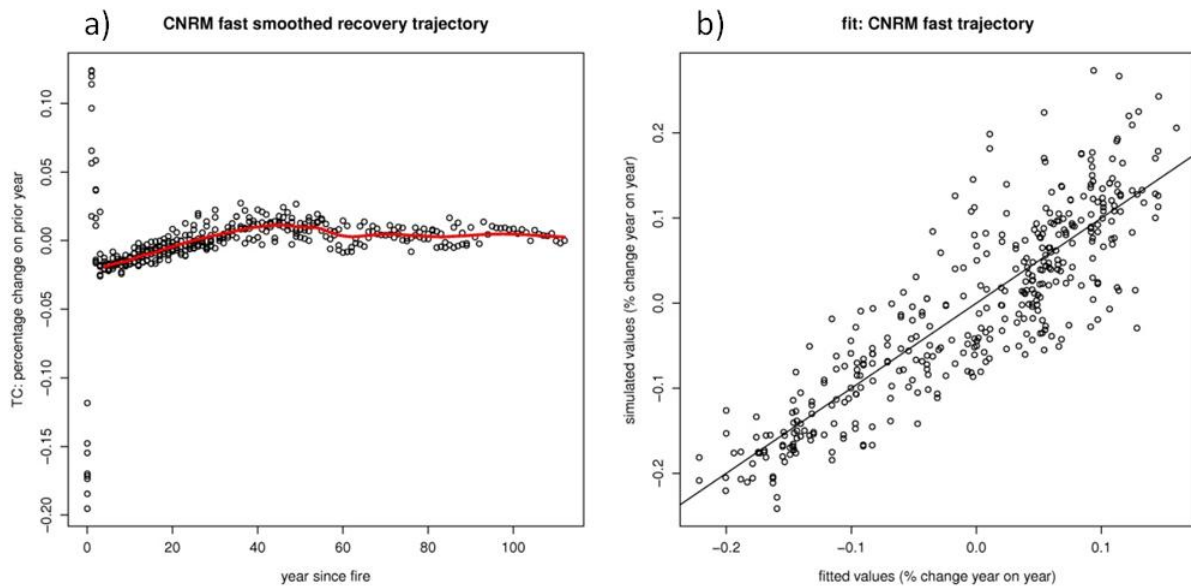


Figure 20. (a) CNRM fast scenario smoothed recovery trajectory, fit to annual ecosystem total carbon estimates forecast by CENTURY and (b) the fit of simulated versus fitted change

To estimate future landscape carbon balance for the future climate scenarios, our next steps will be to refine these statistical trajectories across the full suite of CENTURY-modeled scenarios, including the other vegetation communities in GYE. This will enable us to model changes in C stocks for the range in fire event pathways determined probabilistically in Question 2, rather than the select set initially parameterized by CENTURY. Given that these changes are likely to be extreme in the absence of other limitations such as fuel availability, the specific timing of individual fires in a given location is likely to be more critical for determining the likelihood of forest recovery than projections of an *average* fire return interval in the future climate period. Spatial variation in fuel (including potential shifts in dominant vegetation), ignition factors, and microclimatic conditions are likely to be increasingly important for constraining these fire event pathways and will be important in future efforts to understand spatial pattern in total ecosystem carbon stocks across the GYE landscape. However, given that NEP for Yellowstone National Park was likely to be negative for about 30 years after the 1988 fires (Kashian et al. 2006), even one or two additional fires as large as the 1988 fire would likely cause the GYE landscape to be a carbon source.

MANAGEMENT IMPLICATIONS

We suggest that five practical management implications emerge from the results of this exploratory research, along with a potential philosophical change in the way managers and society might view Rocky Mountain forests.

Practical Implications:

(1) Our climate-fire models show that fire incidence and size are very sensitive to small (0.5 – 1 °C) increases over average temperatures of the late 20th century. These climate-fire models and modeled climate scenarios predict that large severe forest fires are likely to become far more frequent over the next century than experienced during the previous 100 years or recorded in the longer historical record. This will be especially true for forest types that historically were characterized by centuries-long fire intervals and burned infrequently in the 20th century. Our study focused specifically on lodgepole pine in the GYE, but a substantially increased frequency of large severe fires probably can be expected in high-elevation forests throughout the central and northern Rockies because the kinds of climatic changes projected for the GYE will occur region-wide.

(2) The primary driver of increased fire frequency will be the climatic changes expected during the 21st century (notably the warmer temperatures and drier conditions): this means that fire control likely will become increasingly difficult and expensive, especially in high-elevation conifer forests where fuel conditions commonly are conducive to extreme fire behavior under very dry weather conditions.

(3) With increasing fire frequency and difficulty of fire control, fire-related threats to human life and to social and economic infrastructure within wildland forest areas will increase during the 21st century. Continued or enhanced programs of proactive mitigation (e.g., mechanical thinning, prescribed burning, land-use regulations) will be needed to reduce fire hazards to buildings, powerlines, communication facilities, etc.

(4) The more frequent fire projected by this study mean that many forests will re-burn before they have re-accumulated the C lost in the previous fire. As a result, high-elevation Rocky Mountain forests are likely to become C sources in the global C cycle, which could exacerbate global climate change. However, the degree to which vegetation change (e.g., expansion of warm-dry conifer species or sagebrush steppe) in response to warmer temperatures and longer growing seasons could potentially offset C losses is not known. Nevertheless, a persistent change from forest to non-forest vegetation would reduce C storage.

(5) More frequent fires also mean that mature and old-growth forests, which now cover large portions of high-elevation landscapes in the Central and Northern Rockies, will be increasingly replaced by young forests or even by non-forest vegetation during this century. It is also possible that fire frequency could preclude tree regeneration in some areas. This shift in forest age structure or forest extent and distribution will mean less habitat for old-growth-obligate species,

changes in watershed hydrologic processes, and a different aesthetic experience for recreational users of western landscapes.

Philosophical Implications:

This research has demonstrated that we are likely to witness “tipping points” during the 21st century, i.e., sudden large and/or qualitative shifts in ecosystem characteristics and processes in response to gradual or continuous changes in underlying driver variables. The most striking potential tipping point identified here is that more frequent fire produces a qualitative shift in high-elevation Rocky Mountain forests from functioning as a C sink to a C source. This is a surprising result: we had previously expected lodgepole pine ecosystems to be one of the most resilient Rocky Mountain forest types because of their historically long fire intervals and their capacity for rapid recovery after fire (e.g., Kashian et al. 2006, Smithwick et al. 2009b). However, our analyses indicate that even lodgepole pine forests are vulnerable to projected climate change and the associated increase in burning during the 21st century. The broad implication here is that management based on how ecosystems behaved in the past will in many cases be ineffective within the unprecedented environment of the not-too-distant future. Ignoring the potential for future state changes, e.g., shifts from forest to non-forest and from C sink to C source, and the spatial variation of these changes across heterogeneous landscapes, may lead to erroneous expectations for such values as biodiversity, productivity and ecosystem C storage.

As a consequence of the potential for ecological “tipping points” of the kind demonstrated in this study, a shift also may be needed in the way we think about ecosystems and their management in the coming years. Millar et al. (2007) have made a good start in charting this kind of thinking, but more is needed. Modeling experiments such as the one conducted here can be useful tools for forecasting likely ecological changes and giving managers a “heads-up” on what to anticipate in their planning process. An important component of planning will be to develop ways of mitigating expected undesirable changes. At the present time, we lack practicable means for preventing or mitigating the projected changes in fire regimes described above and the impact of those changes on ecosystem services of high-elevation Rocky Mountain forests. For other forest types characterized by frequent low-severity fires, e.g. southwestern ponderosa pine forests, creative thinking and experimentation are underway to develop appropriate mitigation techniques (e.g., Hurteau and North 2009). Such efforts also are needed for high-elevation forest types, where fire regimes historically were dominated by infrequent high severity fires, where the biota have different kinds of fire adaptations and responses, and where some fundamentally different approaches will be necessary.

RELATIONSHIP TO OTHER RECENT FINDINGS AND ONGOING WORK

Recent studies have emphasized the importance of understanding how changing climate and disturbance regimes—including wildfire—will alter the terrestrial C cycle (e.g., Kueppers and Harte 2005; CCSP 2007, 2008; Bond-Lamberty et al. 2007, Bowman et al. 2009; Frolking et al.

2009). Fire and recovery are fundamentally linked to regional C balance in forest landscapes, and other authors have suggested recently that terrestrial C sinks may be weakening (Fung et al. 2005, Canadell et al. 2007). Our work offers several new insights to ongoing studies of climate, fire and vegetation in western forests. As we suggested previously but had not demonstrated (e.g., Kashian et al. 2006, Smithwick et al. 2009b), our current findings indicate a threshold of fire-return interval beyond which current fire C stocks will not recover to their prefire levels. For lodgepole pine forests of greater Yellowstone, our simulations suggest this threshold may occur at approximately a 90-yr FRI—less than what has been observed in the historical record. Our previous work had focused on projected equilibrium conditions and did not emphasize the transient dynamics that may occur within the coming decades. In this project, we have explored more fully an important mechanism that could weaken the strength of terrestrial C sinks in western forests during this century.

Recent studies have documented an increase in the occurrence of large fires during the past few decades, with increases most pronounced in mid-elevation regions of the Northern Rocky Mountains (Westerling et al. 2006, Morgan et al. 2008, Littell et al. 2009). However, although general future trends in disturbance regimes have been recognized (i.e., fire activity is expected to increase in a warmer and drier climate), the probability of occurrence of future large fires has not been directly linked with the future climate scenarios at ecologically relevant spatial and temporal scales. We provide significant advancements in this area that complement and may enhance ongoing studies throughout the western US. Our downscaled climate change scenarios project that forests of the GYE may be regularly subject to climatic conditions by the later part of the 21st century that exceed the most extreme years in the instrumental record. Because these projections can be mapped across the landscape, scientists and managers can identify particular geographic locations that are more or less vulnerable to changing fire regimes and net C loss. Furthermore, we have developed methods that permit rigorous quantification of the uncertainty in projections, and these will be relevant for other studies.

The approach and results of our current project complement other studies of climate, disturbance and C dynamics. For example, flux towers are used to estimate terrestrial-atmospheric carbon exchange in different vegetation types (e.g.,). Flux tower estimates reveal significant releases of forest C to the atmosphere following fire (e.g., Law et al. 2004), but these studies cannot be used across large heterogeneous landscapes under future climate and fire regimes. Earth System Models represent climate and carbon flux at coarse scales but do not yet model disturbance dynamics (Houghton 2007). Stand-level measurements of carbon pools before and at various intervals after fire are another approach for estimating C losses and subsequent gains after forest fires, but such studies have been conducted in a limited number of sites and ecosystem types (e.g., Rothstein et al. 2004). Our results may inform current efforts to improve representation of disturbances and dynamic vegetation transitions (e.g., forest to nonforest) in the next generation of ESMs (Bond et al. 2005). Our results may also contribute to improved projections of vegetation change at regional scales. With changing climate, fire may catalyze abrupt changes in vegetation because species better suited to changed environmental conditions may establish in recently burned sites (Johnstone and Chapin 2003, Wirth et al. 2008). Our research thus contributes to these ongoing lines of inquiry by enhancing understanding of how both climate and fire regime may change across heterogeneous forest landscapes.

FUTURE WORK NEEDED

Model parameterization/additional vegetation types. To better forecast landscape C stocks for the GYE, our future work will be focused on parameterization of the CENTURY model for additional ecosystem types in the GYE landscape. Few data exist for validation of C stocks for additional forest types in the northern Rocky region, although several related efforts are underway (e.g., Donato, Turner et al., in prep.) that can inform this effort. We believe the forest (represented here by lodgepole pine) and nonforest simulations are representative of the dominant dynamics likely to be experienced in GYE under projected fire and climate scenarios. However, across heterogeneous landscapes, vegetation responses to climate and fire will be complex and interactive, as shown for boreal systems (Balshi et al. 2009; Bond-Lamberty et al. 2007). Fire-recovery patterns and climate-driven productivity responses may be species-specific (Bond-Lamberty et al. 2007, Littell et al. 2009). Integration of these additional vegetation types and fire/climate responses will refine the sensitivity of our projected responses and, in conjunction with additional data such as results from vegetation-specific fuel models at finer scales, help guide management efforts.

Biogeographic shifts. A fundamental question is whether the current tree species and forest types will be able to persist in the GYE given projected climatic conditions and fire-return intervals. Some models, using a “bioclimatic envelopes” approach, suggest substantial changes in the geographic distribution of major tree species in the northern Rocky Mountain region, including the GYE (e.g., Bartlein et al. 1997). However, for our work we assumed that the current dominant species were still present in the GYE at the end of the 21st century, for three reasons. First, our focus is on what will happen in the next 90 years; broad-scale biogeographic rearrangements like those depicted in Bartlein et al. (1997) probably will occur over a longer time period because of constraints on species migration, limitations to dispersal, etc. Second, we know that lodgepole pine persisted through variable climates and fire regimes during most of the Holocene (Whitlock et al. 2003), and the biogeographic models indicate that lodgepole pine and montane forests will still be present in the GYE a century from now even if their abundance is diminished (Bartlein et al. 1997, Rehfeldt et al. 2006). Finally, even if other conifer species replace the current dominants, the stand-level C dynamics probably will not be hugely different from what we are modeling for lodgepole pine; moreover, if future forests fail to regenerate altogether, then the tipping point from C sink to C source will be even more dramatic than our model predicts. However, the qualitative shift in fire regime predicted by our model underscores the importance of considering what vegetation types would be better suited to future climates in the GYE. Although this was beyond the scope of the present project, it is an important priority for future work.

Recovery time-paths. In addition to the inclusion of additional vegetation types, site-specific time paths of fire events and recovery will be more complex than the relatively straightforward scenarios we have developed. A major focus of our forthcoming papers will be to define path specific trajectories of C fluxes that account for probabilistic fire events and variation in recovery rates.

Ignition Factors, AR5 SRES and GCMs. We expect our results will be an underestimate of change in the GYE for several reasons. First, the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994; used here) underestimates extremes in moisture deficit, because *climatological winds* (i.e., varying seasonally but not interannually) must be used to drive hydrological simulations. Second, the VIC hydrologic model employs a parameterization that reduces the effects of temperature and radiation changes on *relative humidity*. Third, *A2 emissions scenarios*, while one of the more extreme emissions scenarios in the climate models used by the Intergovernmental Panel on Climate Change 4th Assessment Report, are increasingly recognized to be underestimates of current CO₂ emissions pathways (Le Quéré et al 2009). Finally, current global climate models do not adequately capture feedbacks from disturbance and land surface conditions which are likely to be positive over large areas under future climate projections (Stroeve et al. 2007; Canadell et al 2007).

DELIVERABLES

Proposed	Status
Peer-reviewed publication by Smithwick et al.	Drafted, to be submitted to Nature
Peer-reviewed publication by Westerling et al.	In prep., intended for Ecological Applications
Additional	Status
<i>Conference Oral Presentation</i> “Fire and carbon cycling for the Yellowstone National Park landscape” Ryan, M.G., Kashian, D.M., Romme, W.H., Turner, M.G., Smithwick, E.A.H., Tinker, D.B.	Delivered at the American Geophysical Union Fall Meeting, San Francisco CA, December 2010
<i>Conference Oral Presentation</i> “Fire, Vegetation, and Climate Interactions in the Greater Yellowstone Ecosystem: Tipping Points and Landscape Vulnerability” Smithwick, E.A.H., Westerling, A.L., Turner, M.G., Romme, W.H., Ryan, M.G.	Delivered at the American Geophysical Union Fall Meeting, San Francisco CA, December 2010
<i>Conference Oral Presentation</i> “Vulnerability of Landscape C Fluxes to Future Climate and Fire in the Greater Yellowstone Ecosystem.” Smithwick, E.A.H., Westerling, A.L., Turner, M.G., Romme, W.H., Ryan, M.G.	Delivered at The 10 th Biennial Scientific Conference on the Greater Yellowstone Ecosystem: Questioning Greater Yellowstone’s Future: Climate, Land Use, and Invasive Species; Mammoth Hot Springs Hotel, Yellowstone National Park, Wyoming, October 11-13, 2010
<i>Conference Oral Presentation</i> “Fire Regime Effects of Anthropogenic Changes in Rocky Mountains Climate and Hydrology” A. Westerling, T. Das, E. Bainto, D. Cayan, E. Maurer, F. Munoz-Arriola, S. Shrestha, E. Smithwick, M.G. Turner, W.H. Romme, M.G. Ryan	Delivered at The 10 th Biennial Scientific Conference on the Greater Yellowstone Ecosystem: Questioning Greater Yellowstone’s Future: Climate, Land Use, and Invasive Species; Mammoth Hot Springs Hotel, Yellowstone National Park, Wyoming, October 11-13, 2010
<i>Conference Oral Presentation</i> “Fire regime and ecosystem effects of climate-driven changes in Rocky Mountains hydrology.” A.L. Westerling, Smithwick, E.A.H., M. G. Turner, W. H. Romme, T. Das, K. Lubetkin	Delivered at the American Geophysical Union Fall Meeting, San Francisco CA, December 2009

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