CLIMATE CHANGE & FISCAL RISK: WILDLAND FIRE TECHNICAL SUPPLEMENT

Executive Summary

Research and Development, USDA Forest Service

Climate change is anticipated to raise land and sea temperatures globally, including in the United States, and this change is likely to lead to shifts in the rate, severity, and extent of wildfire on federal lands. Relevant to federal budgets, such changes bring with them the expectation that spending to suppress and manage wildfires would generally change as the climate changes.

We evaluated how changes in climate in the United States would lead to changes by the middle and the end of the current century in annual spending to suppress wildfires on USDA Forest Service (FS) and Department of the Interior (DOI) managed lands. To do this, we developed a two-stage model. In the first stage, we analyzed the historical relationships between area burned on FS and DOI lands and maximum daily temperatures and other variables. In the second stage, we analyzed historical relationships between area burned and suppression spending.

Then, using projections of climate obtained from general circulation models, we projected area burned, and used this projection in our second stage model to project spending on suppression. All spending projections were done with constant 2014 dollars. We made projections for mid-century (2041-2059) and late-century (2081-2099). Uncertainty in the area burned and suppression spending was quantified using Monte Carlo simulation methods, incorporating parametric uncertainty from the two stage models and climate uncertainty from the alternative climate projections.

Results show that median area burned on DOI lands is projected to increase, compared to the amount observed between 1995 and 2013, by 99% by mid-century and by 189% by late-century. For FS lands, the increases are projected to be 123% by mid-century and 221%, respectively. Given such changes in area burned, DOI spending is projected to increase by 45% by mid-century and by 72% by late-century. For the FS, annual spending is projected to rise by 117% and 192%, respectively. Such changes would entail an increase in dollars spent in total across both agencies from a historical average of $1.33 billion to a projected $2.63 billion in mid-century and $3.47 billion by late-century.

The statistical modeling approach used in this study and the projected results are conditional upon several assumptions, violation of any of which would alter both the projected changes in spending and the ranges of our uncertainty bands. We have grouped these into aggregation biases, omitted variables biases, and model structures:

(1) Aggregation bias. The statistical models of area burned and of suppression spending are estimated using data aggregated from the landscape to regions and nationwide. Such aggregation, in the presence of heterogeneity across spatial units in how area burned and expenditures are generated, would generally lead to statistical biases and inconsistencies of parameter estimates estimated at those larger spatial scales. Aggregation across space and time can interact with omitted variables, leading to Type II

errors—where significance is rejected when in fact significant effects exist. Such Type II errors would lead to selecting more parsimonious models than would emerge from finer scale modeling. The assumption involved for the reported models is that fine-scale wildfire area burned and suppression spending respond identically to annual average maximum daily temperature and other shifters, and that suppression spending at finer spatial units relates identically to area burned.

(2) Omitted variables bias. Our statistical models of area burned and suppression spending are parsimonious, with the former specified as a function of annual maximum daily temperature and a shift variable representing a structural shift upward in spending beginning in 2000. The statistical models of suppression spending for the FS included only area burned as the predictor for regional FS data, as well as a 2011 shift variable for Washington Office spending. Variables left out that could matter include wildland fuel quantity and condition, population and development, future unknowable structural shifts, input prices to all aspects of fire management, effects of altered fire return intervals, and other climate variables. In addition, we assumed that suppression strategies and technology, fuels management and allocation of effort across resources and regions will stay constant. Thus, we assumed that all of these omitted variables are orthogonal to the included variables, so that errors in predictions are contained in error terms that are unrelated to the included variables, or that they are perfectly correlated with the included variables, such that parameter estimates for included variables contain the effects of the perfectly correlated omitted variables.

(3) Model structures. We assumed that the included information from climate projections was adequate to capture uncertainty regarding the effects of temperature on area burned on federal lands. We assumed that these systems could be approximated by a linear relationship. We also assumed that the world of the future can be represented by a model of historical relationships among variables. Our models make long-run projections, without evaluating which factors that are typically assumed fixed might be variable in the long run, such as fire regimes, biomes, and suppression strategies. In addition, even at aggregate scales, today's forest and grassland ecosystems of U.S. federal lands may not bear much resemblance to ecosystems expected in the distant future under climate change.

Even with these caveats and assumptions, however, our models, along with the literature we have cited (and much that we have not), provide evidence that both wildfire extent and suppression expenditures are expected to increase with climate change. Our models, specifically, show that temperature alone can account for significant increases in area burned and that expenditures rise along with increases in area burned.

Introduction

There is little doubt that changes in climate will affect wildlands, wildland fire and suppression of fire (Abatzoglou 2013, Abt et al. 2009, Flannigan et al. 2005, Flannigan et al. 2006, Flannigan et al. 2009, Flannigan et al. 2016, Jolly et al. 2015, Littell et al. 2009, Littell at al. 2016, Liu et al. 2014, McKenzie et al. 2004, McKenzie et al. 2016, Mitchell et al. 2014, Prestemon et al. 2009, Westerling et al. 2006). Direct increases in area burned and numbers of fires, resulting from more days with extreme fire weather, longer periods of sequential days with extreme fire weather, and longer fire seasons in many parts of the world are to be expected (Lenihan et al. 2003, Jolly et al. 2015, Riley and Loehman in press). Ignition patterns may change with shifting storm tracks and lightning occurrence (Romps et al. 2014), as well as changes in human ignition patterns due to land use change. Using an approach similar to that used in Hope et al. (2016), this analysis evaluates a small aggregate set of data on US federal wildfire area burned and federal suppression expenditures and projects both area burned and expenditures to calculate the effect of climate on federal area burned and federal expenditures in mid-century (2041-2059) and late-century (2081-2099). We evaluate area burned and wildfire suppression expenditures for both the USDA Forest Service (FS) and the US Department of the Interior (DOI).

Our initial goal was to model changes in wildfire suppression expenditures under a variety of models, but in the end, only one of the models was completed and used in the projections—the two-step model where area burned was predicted, and then the predicted area burned was used in a model of suppression expenditures. The FS and DOI were modeled individually because the management objectives differ, as does the data availability.

We also tested a model of suppression expenditures as a direct function of climate and socioeconomic variables but eliminated this model from further consideration as the model was not significant. Initial tests using preparedness levels were likewise eliminated from further consideration. While preparedness levels were correlated with expenditures, we could not produce reasonable models to predict preparedness level from the data we have. Models based on fire season length were also not tested because we could not acquire projections of fire season length to 2100.

The models we selected projected area burned as a function of changes in maximum temperature and dummy variables that represent noted shifts in management, and projected expenditures as a function of area burned and shifts in management. Modeling area burned, in particular, requires some strong assumptions that, in the face of a changing climate, could be difficult to justify. We expect climate change to alter forest and range ecosystem compositions, and vegetation changes will, in turn, alter how many acres burn and how often and intensely they burn. In this analysis, we have assumed that these vegetation changes *will not matter* to either area burned, nor to the expenditures we make to suppress wildfire. It is possible that, to the extent these changes have already begun to occur across federal wildlands, our models incorporate some of these changes in ecosystems, but we cannot test this possibility using an aggregate model structure alone. Detailed vegetation modeling would be required to determine the extent to which these changes would occur and the extent to which these ecosystem changes would alter area burned or suppression expenditures.

Methods

We initially tested expenditure as a function of area burned to test for model feasibility, and found that these models performed well. However, we have a very short time series of usable data for area burned, beginning in fiscal year (FY) 1993 and ending in FY 2013. The expenditure series by FS region runs from FY 1995 to FY 2015, and the expenditure series for DOI is FY 1985-FY 2015. The intersection of these three sets resulted in FS models that covered FY 1995-2013, and DOI models that covered FY 1993-2013. This severely restricted our available degrees of freedom. To address this we (1) pre-selected a small subset of our variables to test based on previous research and consultations with experts, and (2) tested panel/fixed effects models for the area burned and expenditure models for the FS and for the area burned models for DOI (DOI does not have regional expenditure data).

Variable Preselection and Model Formulation

The climate variable we selected was the fiscal year annual average of daily maximum temperature. The decision to use the average daily maximum temperature as our only climate input was based on both our need to limit the number of explanatory variables, and consultations with Matt Jolly (FS), Michael Flannigan (University of Alberta), and existing literature. Temperature has been shown to influence fuel moistures, fire season length, extreme fire weather, and lightning and storm tracks—all conditions that are known to influence area burned (Flannigan et al. 2016, Flannigan et al. 2009, McKenzie et al. 2004, Romps et al. 2014, Wang et al. 2016). Abatzoglou and Kolden (2013) state that area burned is influenced by temperature, precipitation, and drought but contend that using temperature is merely a proxy for the many ways climate can influence wildfire. However, this proxy role of temperature is precisely what we are seeking for our parsimonious model specifications. More discussion regarding the use of temperature only is included in the Caveats section below.

We also tested regional and national population, regional and national average household income and a year 2000 shift (also known as a “dummy” or categorical) variable. Previous research on human-caused fires indicates that local population and income can influence ignitions (Mercer and Prestemon 2005, Prestemon et al. 2014) and area burned (Prestemon et al. 2016). In addition, anecdotal evidence implies that as population increases, buildings increase, which diverts suppression efforts from land protection to point protection. This, too, could lead to increases in area burned, all else held constant. Increases in income are hypothesized to influence the extent of local power and influence, which has been shown to lead to increased suppression expenditures (Donovan et al. 2011).

Finally, previous forecasting models developed for the FLAME Act and forecasts made for budgeting purposes have tested and used a shift variable corresponding to the National Fire Plan in FY2000. The National Fire Plan was enacted in FY2001 in response to the apparently sudden increase in area burned and expenditures that occurred in FY2000. Thus, this shift variable (which is set equal to 0 prior to FY2000 and 1 for FY2000 and all subsequent years) captures both the increase in area burned in FY2000 and the subsequent increase in spending that resulted from the National Fire Plan. This plan provided about $2 billion in additional funding to FS, DOI, and state partners for planning, prevention, fuels treatment, and suppression. We had not previously tested this variable in area burned models, where its significance would imply that some combination of climate and fuels had led to a jump in area burned in FY2000 and later, so we tested these models, as well. The use of this shift variable cannot provide evidence that changes in management alone led to changes in expenditures, as an increase in area burned from increasing fuels and temperatures is also a likely contributor to increases in expenditures. We tested this 2000 shift variable in both the expenditure and area burned models, and it entered both area burned models, and the DOI expenditure model.

While area burned appears to be log normally distributed, we opted to test both our area burned and expenditure models as both untransformed and natural log transformed models, as well as semilog models. Model selection between these models required back-transforming logarithmic area burned and suppression expenditures in cases where the models included these transformations. Therefore, all models were compared in predicted untransformed area burned and expenditures. Chosen models were based on the minimum root mean squared error (RMSE) calculated over the in-sample predictions, with preference for models with lower bias when RMSEs were similar in magnitude. Insignificant variables were dropped from further consideration.

Data

Our expenditure data are annual, based on the federal fiscal year (October 1 to September 30), and thus all data are aggregated to the fiscal year. We divided the United States into regions that coincide with the Geographic Area Coordination Centers of the National Interagency Fire Center and roughly with the USFS regions. Climate data are aggregated to these regions based on federal lands only; socioeconomic data are aggregated to regions based only on counties which include federal lands. Fire data are based on actual fire ignition locations from the FPA FOD (1993-2013) (Short 2013). Expenditure data for DOI are available nationally, while data for the FS are available nationally for 1985-2015 and for FS regions, which closely match GACC boundaries, for 1995-2015. More details on each of these data sources are below.

Climate data: We used the MACA-v2 downscaled climate data for both the historical observations and projections (http://maca.northwestknowledge.net/, Abatzoglou and Brown 2012, Abatzoglou 2013). Below is the description of the data.

"The Multivariate Adaptive Constructed Analogs (MACA) (Abatzoglou, Brown, 2011) method is a statistical downscaling method which utilizes a training dataset (i.e. a meteorological observation dataset) to remove historical biases and match spatial patterns in climate model output.

We have used MACA to downscale the model output from 20 global climate models (GCMs) of the Coupled Model Inter-Comparison Project 5 (CMIP5) for the historical GCM forcings (1950-2005) and the future Representative Concentration Pathways (RCPs) RCP 4.5 and RCP8.5 scenarios (2006-2100) [*sic*] from the native resolution of the GCMS to either 4-km or ~6-km."

We generated regional and national averages, monthly and annual, for maximum daily temperature, minimum daily temperature, minimum daily relative humidity, and the sum of daily precipitation. The regional and national averages are based on the grid cells (in a GIS) that coincide with federal lands (USDA Forest Service and DOI agencies) only. We created regional FY averages across the months of the FY and created a weighted FY nationwide value, weighting by the proportion of land in each region that was federal (DOI and FS only).

While we had originally intended to model two representative concentration pathways (RCP) and five general circulation models (GCM), we limited the scope of modeling for this preliminary assessment in order to minimize time to download, process and aggregate the large quantities of data (daily observations at the 4km geographic scale) for each of the potential emission/climate outcomes. We chose to model RCP 8.5, which is the emissions scenario most likely to reflect a 'business as usual' future (Sanford et al. 2014), and selected three GCMs based on their performance in matching the historical data.

Most of the general circulation models available in the MACA-v2 data set have been evaluated for their performance relative to historical climate observations. Based on the analysis by Sheffield et al. (2013), at the conterminous US scale, the models that had the least bias in temperature were MPI-ESM-LR and MRI-CGCM3. For precipitation, the models with the least bias were CNRM-CM5 and NorESM1-M. Using the metrics at the regional scale, the following models performed the best in the regional metrics: GFDL-CM3, CCSM4, IPSL-CM5A-LR, and HadCM3. Simulations of the 20th century by CMIP5 models have been conducted for regions of the United States: Pacific Northwest (Rupp et al. 2013), Southeast (Rupp 2016), and for the Southwest (Rupp Pers. Comm.). Based on these regional analyses, the top five models, based on 18 metrics, were CNRM-CM5, HadGEM2-ES, CCSM4, HadGEM2-CC, and MIROC5. We used the CNRM-CM5, the HadGEM2-CC, and the MIROC5 models in the projections below (see http://maca.northwestknowledge.net/GCMs.php for detailed descriptions of these models).

Figure 1 shows the historical and projected maximum temperature by region and area-weighted for nationwide by forecast period. While the actual projected values are different, there are consistent trends. The Pacific Northwest, Great Basin, Northern Rockies and Central Rockies all have higher expected percentage increases in temperature than do the 'warmer' regions—Southern Rockies, California, Southern and Eastern regions. The HadGEM2-CC model projects the highest average max temperatures for the two projection periods for all of the individual regions, and for the nationwide federal lands, as well.

Suppression expenditure data: All expenditures are in 2014$ (using deflators from the President's Budget, Table 10.1, Non-Defense Government Outlay Deflator, http://www.whitehouse.gov/sites/default/files/omb/budget/fy2016/assets/hist.pdf). We have national expenditures for both DOI and FS for 1985-2015 (31 years), and regional FS data for 1995-2015 (21 years). The national level data are from NIFC, and the FS regional data are derived from historical reports, the Foundation Financial Information System (FFIS) database (2005-2012), and the Financial Management Modernization Initiative (FMMI) since 2012.

Fire occurrence data: Area burned (in acres) and number of fires were provided by Karen Short from the Fire Program Analysis Fire Occurrence Database (Short 2013). This dataset includes only FY1993 to 2013, as the data were deemed incomplete/unreliable prior to 1992 and because data for 2014-2015 have not yet been updated. Thus, we have only 21 national and regional observations of area burned and number of fires. We used area burned for CONUS (excluding Alaska) for both FS and DOI. For the FS, Alaska represents a trivial acreage and expenditure. For DOI, however, Alaska represents a significant acreage in many years (averaging 31%, but ranging from 1% to 92% of total DOI area burned), but a much smaller expenditure (we only have five years of expenditure data by region, but the average is 8%, and the range is from 4-14% of total DOI expenditures). With this level of variability, and a clear disconnect between area burned and expenditures, along with inadequate data for modeling Alaska expenditures separately, we chose to not model area burned in Alaska and will use predicted CONUS area burned as the dependent variable in predicting total nationwide expenditures for both DOI and FS.

Socioeconomic data: The historical socioeconomic data, by county, is from Woods and Poole Economics (2015). Population was summed over all the counties with federal lands in each geographic region, and household income was averaged over the households in the counties with federal lands in each region.

Projections

To generate a no-further-climate change average for area burned and expenditures for 1995-2013 for FS and for 1993-2013 for DOI, we averaged the historical data. In addition, we produced a median of the backcast of the regression models using actual climate change variables. The projections for midcentury represent an average of 2041-59, and late-century are an average of 2081-2099 (the year 2100 is not included in the MACA dataset, and the adjustment to fiscal year removed 2040 and 2080 from consideration, so we used a consistent 18 years to project both periods). The historical period therefore covers 19 years for FS and 21 years for DOI.

We used the projected climate data in our selected models to generate area burned and then used area burned in the expenditure projections. There are two possible methods of projecting with the climate values from the GCMs: (1) use the historical observed data as the base and use the projected data as the change, or (2) use the climate model backcast projection as the base and the projected data as the change. We chose method 1, but we also include the model backcast from our statistical estimation as a second base from which to calculate change to show how bias in the estimation might affect the outcome.

We generated projected expenditures and area burned for each of the climate models. We then used these projections for each of the 19 years, and ran a Monte Carlo simulation of 1,000 draws from the historical data to re-estimate all models and use the random-draw equation estimates to project area burned and expenditures in each iteration. The Monte Carlo approach provides medians and confidence intervals for each projection period (mid- and late-) for DOI and FS areas burned and expenditures.

Results

Table 1 shows the selected regression model results. Tables 2-5 show the median projected changes in area burned and suppression expenditures for DOI and FS, and Figures 2-7 show the year-by-year projected area burned and suppression expenditure medians, and high and low 80 and 90 confidence bands for the projections.

Testing confirmed that area burned is endogenous in predicting expenditures for both the FS and DOI, and so we employed instrumental variables methods to predict expenditures. In the models where we regress expenditure levels on levels of predictor variables, we are assuming either that all variables are stationary or that all are nonstationary but cointegrated. Preliminary evaluations confirm that it is possible to find cointegrating relations among model variables. Tests show that area burned and maximum temperatures typically reject nulls of nonstationarity, so the area burned predictions meet least squares assumptions.

We first tested the simplest models of the effect of temperature on expenditures. Including a 2000 shift or dummy variable (D2000), population, and income, or not, temperature was not significant in predicting expenditures. No further modeling of expenditures directly on temperature was attempted. Expenditures were more robustly predicted using area burned as the main predictor.

The models of the non-geographic based expenditures (Rest of the Forest Service (RFS), including the Washington Office, Research, and NIFC expenditures) were weak, and including this model in the panel models led to wild swings in the predictions. RFS does not have regional area burned and so was predicted as a function of aggregate FS area burned. In an attempt to improve this model, we tested for structural shifts in FY2000 corresponding to the National Fire Plan, and in the early 2010s, corresponding to a change in the average RFS expenditures, which increased from $160 million for 1985-2010 to $484 million for 2011-2015, and identified a significant shift in FY2011. Adding a FY2011 shift variable to the model including total FS area burned, provided a reasonable prediction of the RFS expenditures, and removing RFS from the panel improved the panel outcome as well.

In the initial estimations, temperature was always significant, but income was rarely significant. Population and D2000 entered several of the models, and the 2011 shift variable was significant and positive in the expenditure model for RFS. We reduced our model choices by eliminating income as a predictor variable.

The next step involved testing both untransformed, natural log transformed, and semi-log models for area burned and expenditures. We evaluated both fixed effects panel models (except for DOI expenditures, for which we do not have adequate regional expenditure data) and aggregate models for area burned and expenditures. These sets of estimates were evaluated using in-sample RMSE to determine which models performed best. In the end, because the models in which population was significant were within 5% of the RMSE of the models without population (two of these), we chose to eliminate population. There is an additional concern of using population as a predictor: its likely correlation with aggregate fuel loads in the brief historical data set used to predict statistical models. Its inclusion increased the risk that projections of populations, in the absence of projections of aggregate fuels, would provide a spurious effect in the area burned projections.

In the area burned models for both DOI and FS, temperature was a significant predictor in both the fixed-effects panel models and alternative nationwide aggregate area burned models, with increasing temperatures leading to increased area burned (Table 1). The year 2000 shift variable was a significant predictor of both FS and DOI area burned in the panel area burned models. The explanatory power of the panel models was poor (R^2 of 0.06 for DOI and 0.12 for FS), but the models were statistically significant (in an F-test). Tests including a time trend, either with just temperature, or with temperature and the D2000 dummy variable, found that both the area burned models with D2000 and without the time trend had lower RMSE and bias.

In the models of expenditures as a function of area burned (two-stage least squares), we also tested population, income and D2000. In the FS models, both panel and aggregate, area burned was significant (and positive), while for the DOI aggregate (there is no DOI panel for expenditures), area burned was significant and also positive (Table 1). The R^2 for these models, when reported, was higher than for the area burned models, although the R^2 in the two- stage instrumental variables models is not bound between 0 and 1, so there is no general interpretation of R^2 for instrumental variables models (e.g., the R^2 can be negative) (see Table 1).

The final model selection was based on in-sample prediction errors (RMSE) of the various pairings of expenditure and area burned models for both DOI and FS, where all comparisons were made after back transforming the dependent variables. We tested these pairings of our models to determine the best pair for projecting expenditures, as that is the variable of interest.

For the FS, the best model pairing was the fixed effects panel model of untransformed area burned by region, combined with the fixed effects panel model of expenditures by region (two-stage least squares with instrumental variables). Combined, these models generated an in-sample RMSE of $304 million for expenditures. For DOI, the best model pairing was the fixed effects panel model of untransformed area burned by region, combined with the aggregate nationwide DOI expenditure model (two stage least squares with instrumental variables), with a combined in-sample RMSE of $68 million. The estimated models for both DOI and FS, and for both area burned and expenditures, have minimal bias (<1%) and do not tend to over- or under-predict the historical observed areas burned or expenditures. Errors in the area burned models are large, however, as reflected in the Mean Absolute Percent Error (MAPE). MAPE is higher for area burned (67% for FS and 88% for DOI) than for the paired area burned+expenditures model, where MAPE ranges from 18% for DOI to 28% for FS.

Projections

Historical observations and climate model projections of regional and national maximum daily temperatures, averaged over the historical data period (1993-2013) and the mid-century period (2041-2059) and the late-century period (2081-2099), are shown in Figure 1. The projections show that temperatures are projected to increase at a greater rate in the northwest one-third of the US (Pacific Northwest, Northern and Central Rockies, and Great Basin), and at a lower rate in the southern and eastern two-thirds (California, Southern Rockies, Southern and Eastern regions). The southern and eastern regions, however, have higher beginning and ending average daily maximum temperatures.

Projected area burned and expenditures for DOI and FS are shown in Figures 2-5. These figures show the median projected value for each of the projection periods as well as the high and low 80 and 90 percent confidence intervals. We evaluated the probability that a forecast from the expenditure model would reach or exceed the high-90 level every year for a 10-year period, and there is less than a 0.01% chance of this happening. Thus, while the probability that the high-90 level could be reached/exceeded for any single year is 5%, the probability that the high-90 will be reached/exceeded every year is unlikely.

Tables 2-5 show the results of the Monte Carlo simulations for DOI area burned, DOI expenditures, FS area burned and FS Expenditures. Because only maximum temperature is changing in these models, all of the changes shown in these tables derive from projected changes in fiscal year average daily maximum temperature. These tables provide the median backcast and the historical averages, which we used as the base values. The value and percent changes in median to both mid and late century are shown from both of these base values. In addition, these tables show the upper and lower 80% and 90% confidence bounds. These bounds result from the distribution generated by the Monte Carlo. The Monte Carlo simulations were completed using the same historical data for all four simulations (1995-2013).

For area burned, these tables show similar increases for both DOI and FS, with a doubling between current and mid-century, and increases to a total of more than 4 million acres by late-century. For expenditures, these tables show a larger increase for FS than for DOI to both periods. The FS expenditures more than double by mid-century and nearly triple by late-century. DOI expenditures increase by 45% to mid-century and by 72% by late-century. The projected total federal expenditures for wildfire suppression are $2.63 billion by mid-century and $3.47 billion by late-century.

Figures 6 and 7 provide a depiction of the median projected expenditures by general circulation model (GCM). The models show substantial agreement on the future levels of spending by both the FS and DOI, although interannual variations are evident, the result of the different modeling structures of the three GCMs, and differences emerge especially late-century. In particular, HadGEM2-CC, which contains the highest overall projected average annual maximum daily temperature rises across agency lands, produces expenditures that are typically one-sixth higher for DOI (Figure 6) and one-third higher for the FS (Figure 7) than those emerging from the GCM with the lowest projected rise in these temperatures (CNRM).

Conclusions

The models developed here show that expenditures respond to changes in area burned as expected, and that area burned increases with increasing average maximum temperatures. The projections using projected fiscal year annual average maximum daily temperatures in mid- and late- century show an increasing rate of burning and a corresponding increase in suppression expenditures.

While temperature is only one of several climate measures that have been linked to wildfire area burned, we found that unbiased backcasts of area burned and expenditures could be obtained from parameterizing this simple relationship. However, model simplicity likely trades off with higher uncertainty in making projections, so definitive conclusions about the long-run status of wildfire and associated suppression on federal lands in the United States may not be warranted without acknowledgment of these uncertainties. In the following section, we detail several reasons why uncertainty is large when envisioning the evolution of wildfire and expenditures.

Caveats and Assumptions

Our models involve a number of assumptions, violation of any of which would alter both the projected changes in spending and the ranges of our confidence bands. These assumptions, loosely grouped into aggregation bias (over space and time), omitted variable bias (including climate, fire and socioeconomic variables) and modeling limitations, are discussed in more detail below. Even with these caveats and assumptions, however, our models, along with the literature we have cited (and much that we have not) provide evidence that both wildfire extent and suppression expenditures are expected to increase with climate change. Our models, specifically, show that temperature alone can account for significant increases in area burned, and that expenditures increase with increases in area burned.

Aggregation

The statistical models of area burned and of suppression spending are estimated using data aggregated to regions and nationwide. Such aggregation, in the presence of heterogeneity in area burned and spending processes, would bias parameter estimates in unknown directions. Aggregation across space and time can interact with biases associated with omitted variables (next caveat), resulting in findings of insignificance when in fact significant effects exist (i.e., it can raise statistical Type II error rates). The assumption involved for the reported models is that fine-scale wildfire area burned and suppression spending respond identically to annual average maximum daily temperature and the shift dummies, and that suppression spending at finer spatial units relate identically to area burned.

Omitted variables

Our statistical models of area burned and expenditures are parsimonious, with area burned specified as a function of annual maximum daily temperature and a shift variable representing a structural shift upward in spending beginning in 2000, and expenditures as a function of area burned and shift variables. There is little doubt that potentially influential variables are omitted in our chosen specifications. Thus, these models assume that any omitted variables are orthogonal to the included variables, so that errors in predictions are contained in error terms that are unrelated to the included variables. Alternatively, it could be that the omitted variables are perfectly correlated with the included variables, in which case parameter estimates for included variables completely contain the effects of the perfectly correlated omitted variables, and no bias would exist in resulting projections.

One key factor potentially missing from the suppression spending models is direct attention to human populations, which can lead to higher demands to protect property at the expense of area burned and which can affect the distributions of aggregate wildland fuels. In addition, a specific kind of omitted variables bias would emerge if past wildfires are negatively related to future wildfires in the same locations, then wildfire area burned modeled without attention to this process would be biased upward compared to reality.

Our area burned models used only a single climate variable to project area burned. There were two practical reasons why we chose maximum temperature—time constraints and degrees of freedom. With only 21 observations, we needed to identify variables to use before we began modeling so that we did not use up all our theoretical/scientific degrees of freedom. In addition, we needed to select only a few variables to test because of the limitations of our statistical degrees of freedom (e.g., in ordinary least squares, the rule of thumb is to use one independent variable for each 10 observations).

Recent research has concluded both that temperature is a reasonable measure of climate change, but also that temperature is an insufficient measure of climate change influences on wildfire. In a statistical analysis of the relationship between meteorological variables and area burned in Canada, Flannigan and Harrington (1988) found that long sequences of days without rain, low relative humidity, and maximum temperatures were the best predictors of area burned, while rainfall and number of dry days per month were not significant. Romps et al. (2014) evaluated the impacts of climate change on lightning, and found that (a) the precipitation projections do not show overall increases that would lead to increased lightning, and (b) increased temperature is the major controlling factor leading to increased lightning projections. Temperature has been shown to lead to a need for additional precipitation to hold fuel moistures constant (Flannigan et al 2016). This results from the changes in amount of water the air can hold at higher temperatures—as temperatures increase the air can hold more water, which leads to drying of fuels, even if precipitation stays the same. Flannigan et al. (2016) also conclude that increasing temperatures lead to an increased number of extreme fire weather days.

For these analyses, we relied on mapping the association between temperature and area burned into the future. However, the association between temperature and area burned has been demonstrated to be relatively weak in the absence of some form of a dryness metric (Littell et al. 2009). It is reasonable to expect that temperature is only one, and perhaps not the most important one, of the climate variables affecting wildfire. However, this is a testable, and as yet untested, hypothesis in relation to predicting aggregate wildfire extent and expenditures. We show here only that temperature is significant, in the absence of other climate measures, in affecting area burned. We cannot speculate on the direction or magnitude of the other influences without testing them in combination with temperature, and in the absence of temperature. Given this critique, weak association would lead to low explanatory power of estimated models, leading to greater uncertainty about wildfire in our projections.

In our models, we assumed that many variables and conditions were constant when, in fact, we know this is unlikely. Thus, each of these assumptions represents an omitted variable. We assumed that wildfire suppression strategies and technology do not change, and so we did not need to include variables representing that change. We assumed that suppression will not become more or less effective at limiting wildfire. We assumed that wildland fuels management rates remain unchanged, in relation to overall wildfire activity. Research shows that management of aggregate fuels on landscapes can affect how wildfires burn, likely affecting suppression productivity and hence area burned or other damages upon which suppression is focused (Thompson et al. 2013, Loudermilk et al. 2014). However, Bessie and Johnson (1995) compared the composite influences of fuels and climate, and concluded that climate was the driving force in year over year changes in area burned. To the extent that fuels treatments are effective, and that managers respond to increases in area burned by increasing fuel treatments, our projections will be wrong. We assumed that allocations of suppression efforts across threatened people, property, and resources remain static. Historical data on suppression spending and area burned reflect averages of policies to protect people, property, and resources. Substantial changes in the ratios of these variables threatened by wildfires in the future could therefore affect spending when measured, as it is in our models, on a per-acre basis.

In this analysis, the general approach and structure of wildfire management was assumed constant over time. However, consequences to wildfires and costs from climate changes are outside the range of reliable futuring over long time frames, except that new climates will modify human activities and probably require alternative management approaches. Given the high level of uncertainty around the future fire environment and the recognition of the ineffectiveness of our current suppression-dominated management paradigm (Calkin et al. 2015), status quo management and associated cost structures are highly unlikely. Even within the near future (10 to 20 years) analyzed in the Quadrennial Fire Review (QFR) there exists "a strong possibility that today's regional wildland fire management dynamics will shift as a result of climate and environmental factors." Further, the QFR identified the potential for a shock-type wildfire event to instigate a fundamental realignment of federal land and fire management functions that would clearly alter the relationship between area burned and management cost. It is doubtful that biologists and foresters in 1900 could have predicted the magnitude of wildfire sizes, behaviors, damages to human and natural resources, and costs experienced today let alone the types of equipment and suppression responses that occur. Due to the increased uncertainty of both natural and human consequences of future climate and the need for an alternative fire management, paradigm future management cost projections should be evaluated with caution.

We also assume constant socioeconomic variables, including prices, population and income. If the per-unit cost of labor, capital, and other purchased inputs into suppression production were to rise at a rate higher than inflation, then suppression expenditures would tend to be higher, possibly also leading to lower overall suppression effort and then to greater area burned. Generally, wages and capital costs have not been rising faster than inflation in the last 20 years. However, as the economy and overall wealth grows, these per-unit prices of these inputs might.

Structural shifts have been shown to exist in the historical data. We assume these are permanent, and no further structural shifts will occur in the future in either wildfire area burned or suppression spending processes. Future shifts, if they were to occur, could bring suppression spending higher or lower relative to historical observations.

As the projected annual area burned increases, however, this means that substantially more acres would need to reburn, or fire would need to move into areas that historically have not burned, in order for these fires to have adequate fuel, at least in forested landscapes. Thus, our models would overestimate the projected area burned. Conversely, in drier, range ecosystems, it is possible that increases in burning rates could lead to the potential for more fire, as reburning rates are expected to be higher in these ecosystems. For these ecosystems, our models would underestimate the projected area burned. It is not known at what burning rate these limiting conditions would be reached in either forest or range ecosystems. Hope et al. (2016) capped their Canadian area burned estimates assuming a 20-year fire return interval, equivalent to burning 5% of the wildland each year. Our results suggest that by late-century, an average of nearly 6 million FS acres per year could burn, or about 3% of all FS land, and we felt we had little justification for capping our area burned estimates. In addition, the US has wide variation in fire return intervals (ranging from 13-203 years, on average, for US ecoregions (available at https://www.firescience.gov/projects/09-2-01-9/supdocs/09-2-01-9_Chapter_3_Fire_Regimes.pdf). Additional investigation in the future could calculate the regional fire return interval from LANDFIRE and ensure that the implied fire return interval fits within reasonable bounds. We included two shift variables in the model regressions, a shift in FY2000 corresponding to changes around the time of the National Fire Plan, and a shift in FY2011, which was identified from the data as a structural shift in Rest of Forest Service expenditures. These types of shifts can be recognized in the historical data, but cannot be projected in advance. Thus, we do not include any shifts in the projections, though it is reasonable to expect that significant shifts in both management and ecosystems will occur through this century.

We also assume that there is no significant tendency for wildfire to self-limit its spatial extent. When wildfire area burned reaches a high proportion of annual burnable acres, it is possible that overall wildland fuels levels would trend downward, leading to more effective suppression in the future. Such a phenomenon would tend to reduce the overall spending expected, on a per acre basis, compared to that observed in the historical record.

Modeling

We assumed that the included information from climate projections was adequate to capture uncertainty regarding the effects of temperature on area burned on federal lands. We assumed that these systems could be approximated by a linear relationship. We also assumed that the world of the future could, in fact, be represented by a model of the past. Our models make long-run projections, without evaluating which factors that are typically assumed fixed might be variable in the long-run, such as fire regimes, biomes, and suppression strategies. In addition, even at aggregate scales, the highly-modified forest and grassland ecosystems of U.S. federal lands may not bear much relation to either natural ecosystems or to ecosystems expected in the distant future under climate change.

Any model is an abstraction, and simplification, of reality. One key modeling limitation is that we used only three climate projections from one climate scenario. Thus, we assumed that three general circulation model realizations of climate with an assumed 2100 greenhouse gas concentration level yielding climate forcing of 8.5W/m2 were sufficient to capture uncertainty regarding the temperature and climate futures on federal lands. Future investigations could integrate additional projections of climate.

While our Monte Carlo simulations address uncertainty in the estimated coefficients as well as uncertainty reflected in the multiple GCM temperature projections, we did not incorporate any within-GCM uncertainty. The assumption here is that the multiple models can proxy for uncertainty within the GCMs.

Uncertainty in wildfire prediction exists even at the incident level, over the timeframe of hours to days, and is compounded when working at decadal or century-long scales (Riley and Thompson, in press). One reason for compounding uncertainty is that shifts in vegetation assemblies and even biomes are likely during this timeframe due to climate change, meaning fire regimes will also shift (Loehman et al. 2014, Lenihan et al. 2003). Take, for example, the changes in fuels and vegetation documented since the turn of the 20th century (Loope and Gruell 1973, Gruell 1983, Gruell 2001). By first removing Indian burning (Lewis 1973, Barrett 1980), and then attempting to remove wildfires, European settlement altered vegetation composition and structure, insect outbreaks, and wildfire behavior beyond recognition in just 100 years of relatively subtle climate changes. Feedbacks between shifting vegetation assemblies, changing climate, and altered ignition patterns will be complex and produce no-analog states.

Caveat summary

Wildfire and fire management, including suppression, is a complex system where individual factors interact in complex, non-linear, unpredictable ways. What happens in one component of the system will cascade through the system altering other components, and these cascades are multidirectional. Climate change is expected to influence ignition patterns, fire weather, ecological community composition, local community development, and our willingness and ability to manage wildfire. Each of these changes will reverberate through the system. Our knowledge of this complexity leads to concerns with using models to project wildfire and fire management to the end of the century.

Agency Contributors
Karen Abt and Jeff Prestemon, Southern Research Station

Linda Joyce, Matt Jolly, Dave Calkin and Mark Finney, Rocky Mountain Research Station

Mark Lichtenstein, USDA Fire and Aviation Management

Acknowledgements
We would like to thank David Coulson, Karen Short and Karin Riley for their assistance, and Dr. Michael Flannigan, University of Alberta; and Dr. Donald McKenzie, USDA Forest Service for their reviews and suggestions.

References

Abatzoglou JT, Brown TJ. 2012, A Comparison of Statistical Downscaling Methods Suited for Wildfire Applications, Intl J of Climatology. doi:10.1002/joc.2312

Abatzoglou, JT. 2013. Development of gridded surface meteorological data for ecological applications and modelling. Int. J. Climatol. 33: 121–131. doi:10.1002/joc.3413

Abatzoglou JT, Kolden CA. 2013. Relationships between climate and macroscale area burned in the western United States. International Journal of Wildland Fire 22:1003–1020. http://dx.doi.org/10.1071/WF13019

Abt KL, Prestemon JP, Gebert KM. 2009. Wildfire suppression cost forecasts from the US Forest Service. Journal of Forestry: 173-179

Barrett SW. 1980. October. Indian fires in the pre-settlement forests of western Montana. In Proceedings of the Fire History Workshop. USDA Forest Service, General Technical Report RM-81, Fort Collins, Colorado (pp. 35-41).

Bessie WC, Johnson EA. 1995. The Relative Importance of Fuels and Weather on Fire Behavior in Subalpine Forests. Ecology 76:747–762. doi:10.2307/1939341

Brown TJ, Hall BL, Westerling AL. 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States: an applications perspective. Clim Change 62: 365–388. doi: 10.1023/b:clim.0000013680.07783.de

Calkin DE, Thompson MP, Finney MA. 2015. Negative consequences of positive feedbacks in US wildfire management. Forest Ecosystems. 2:9: doi:10.1186/s40663-015-0033-8.

Donovan GH, Prestemon JP, Gebert K. 2011. The effect of newspaper coverage and political pressure on wildfire suppression costs. Soc and Nat Res 24(8):685-698.

Flannigan MD, Harrington JB. 1988. A study of the relation of meteorological variables to monthly provincial area burned by wildfire in Canada (1953–80). J. Appl. Meteorol. 27:441–452.

Flannigan MD, Wotton BM, Marshall GA, deGroot WJ, Johnston J, Jurko N, Cantin AS. 2016. Fuel moisture sensitivity to temperature and precipitation: climate change implications. Climatic Change 134: 59. doi:10.1007/s10584-015-1521-0

Flannigan MD, Krawchuk MA, de Groot W, Wotton BM, Gowman LM. 2009. Implications of changing climate for global wildland fire. Int J Wildland Fire 18: 483–507. doi: 10.1071/wf08187

Flannigan MD, Logan KA, Amiro BD, Skinner WR, Stocks BJ. 2005. Future Area Burned in Canada. Clim Change 72: 1–16. doi: 10.1007/s10584-005-5935-y

Flannigan MD, Amiro BD, Logan KA, Stocks BJ, Wotton BM. 2006. Forest Fires and Climate Change in the 21ST Century. Mitigation and Adaptation Strategies for Global Change 11: 847–859. doi: 10.1007/s11027-005-9020-7

Gruell GE. 1983. Fire and vegetative trends in the Northern Rockies: interpretations from 1871-1982 photographs. Gen. Tech. Rep. INT-158. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 117 p.

Gruell GE. 2001. Fire in Sierra Nevada forests: a photographic interpretation of ecological change since 1849. Mountain Press. photographs.

Hope ES, McKenney DW, Pedlar JH, Stocks BJ, Gauthier S. 2016. Wildfire Suppression Costs for Canada under a Changing Climate. PLoS ONE 11(8): e0157425. doi:10.1371/journal.pone.0157425

Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, and others. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. Nat Commun. 6: 7537. doi: 10.1038/ncomms8537. pmid:26172867

Lenihan JM, Drapek R, Bachelet D, Nielsen RP. 2003.Climate change effects on vegetation distribution, carbon, and fire in California. Ecological Applications 13(6): 1667-1681.

Lewis, HT. 1973. Patterns of Indian burning in California: ecology and ethnohistory (No. 1). Ballena Press.

Littell 2009Littell JS, McKenzie D, Peterson DL, Westerling AL. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. Ecol Applic 19(4):1003-1021.

Littell JS, Peterson DL, Riley KL, Yongquiang L, Luce CH. 2016. A review of the relationships between drought and forest fire in the United States. Glob Chang Bio. Apr 19. doi: 10.1111/gcb.13275.

Liu Y, Goodrick S, Heilman W. 2014. Wildland fire emissions, carbon, and climate: Wildfire–climate interactions. For Ecol and Manag. 317: 80-96.

Loehman, RA, Reinhardt E, Riley KL. 2014. Wildland fire emissions, carbon, and climate: seeing the forest and the trees – a cross-scale assessment of wildfire and carbon dynamics in fire-prone, forested ecosystems. Forest Ecology and Management 317: 9-19.

Loope LL, Gruell GE. 1973. The ecological role of fire in the Jackson Hole area, northwestern Wyoming. Quaternary Research 3(3):425-443.

Loudermilk EL, Stanton A, Scheller RM, Dilts TE, Weisberg PJ, Skinner C, Yang J. 2014. Effectiveness of fuel treatments for mitigating wildfire risk and sequestering forest carbon: A case study in the Lake Tahoe Basin. For Ecol and Manage. 323(1):114-125.

McKenzie D, Gedalot ZM, Peterson DL, Mote P. 2004. Climatic change, wildfire, and conservation. Cons Bio 18:890-902.

McKenzie D, Littell JS. 2016. Climate change and the eco-hydrology of fire: will area burned increase in a warming western U.S.? doi: 10.1002/eap.1420

Mercer DE, Prestemon JP. 2005. Comparing production function models for wildfire risk analysis in the Wildland-Urban Interface. Forest Policy and Economics 7(5):782-795.

Mitchell RJ, Liu Y, O'Brien JJ, Elliott KJ, Starr G, Miniat CF, et al. 2014. Future climate and fire interactions in the southeastern region of the United States. For Ecol Manage. 327: 316–326. doi: 10.1016/j.foreco.2013.12009..003

Prestemon JP, Abt KL, Gebert K. 2009. Suppression cost forecasts in advance of wildfire seasons. Forest Science 54: 381–396.

Prestemon JP, Hawbaker TJ, Bowden M, Carpenter J, Brooks MT, Abt KL, Sutphen R, Scranton S. 2013. Wildfire Ignitions: A Review of the Science and Recommendations for Empirical Modeling. Gen. Tech. Rep. SRS-GTR-171. Asheville, NC: USDA-Forest Service, Southern Research Station. 20 p

Prestemon JP, Shankar U, Xiu A, Talgo K, Yang D, Dixon E IV, McKenzie D, Abt KL. 2016. Projecting wildfire area burned in the south-eastern United States, 2011–60. International Journal of Wildland Fire 25(7): 715-729. DOI: http://dx.doi.org/10.1071/WF15124

Riley KL, Thompson MP. In press. Uncertainty in modeling wildland fire. In: Riley, Karin L., Matthew P. Thompson, and Peter Webley (editors). Uncertainty in Natural Hazards. New York City: Wiley and American Geophysical Union Books.

Riley KL and Loehman RA. In Press. Mid-21st century climate changes increase predicted fire occurrence and fire season length, Northern Rocky Mountains, US. Ecosphere.

Romps DM, Seeley JT, Vollaro D, Molinari J. (2014), Projected increase in lightning strikes in the United States due to global warming, Science, 346(6211), 851-854.

Rupp, D E. 2016. An evaluation of the 20th century climate for the Southeastern United States as simulated by Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models. US Geological Survey Open-File Report 2016-1-47. 32 p.

Rupp D E. 2016. Pers. Comm. Figures from an analysis of the Southwestern United States.

Rupp DE., Abatzoglou J T, Hegewisch K C, Mote P W. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research: Atmospheres 118: 10,884-19,906

Sanford T, Frumhoff PC, Luers A, Gulledge J. The climate policy narrative for a dangerously warming world. Nat Clim Chang. 2014;4: 164–166. doi: 10.1038/nclimate2148

Short KC. 2014. A spatial database of wildfires in the United States, 1992-2011. Earth System Science Data. 6: 1-27.

Sheffield J, Barrett, AP, Colle B, Fernando D N, Fu R [and others]. 2013. North American Climate in CMIP5 experiments. Part I: Evaluation of historical simulations of continental and regional climatology. Journal of Climate 26: 9209-9245

Smith MS, Kolden CA, PaveglioTB, Cochrane,MA and others. 2016. The Science of Firescapes: Achieving Fire-Resilient Communities. BioScience 66 (2): 130-146.doi:10.1093/biosci/biv182

Thompson MP, Vaillant NM, Haas JR, Gebert KM, Stockmann KD. 2013. Quantifying the Potential Impacts of Fuel Treatments on Wildfire Suppression Costs. J. of Forestry 111(1):49-58.

Wang,X, Thompson DK, Marshall GA et al. 2015. Increasing frequency of extreme fire weather in Canada with climate change. Climatic Change 130: 573. doi:10.1007/s10584-015-1375-5

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. Science 313(5789):940-943. DOI: 10.1126/science.1128834

Woods and Poole Economics. 2015. Complete economic and demographic data source. Woods and Poole Economics, Washington, DC (on CD).

Table 1. Econometric model results for predicting area burned and wildfire suppression expenditures for both DOI and FS

Management and geography	Type of model	Dependent variable	Independent variables						Years included	Num. obs.	R^2	Instr. Var.
				Constant	Ln(FY Max Temp)	D2000	Acres burned	D2011				
FS regions, except Alaska	Area burned fixed effects panel	Acres burned	Coef.	-835,406 **	52,610 ***	103,671 ***			1993-2013	168	0.12	
			Std. err.	13,083	241,767	25,077						
FS regions, except RFS	Expenditure fixed effects panel 2SLS	Expenditures $2014	Coef.	8,698			0.52 ***		1995-2013	152	na	Num FS fires CONUS
			Std. err.	-15,652			-0.08					
FS RFS	Expenditure OLS	Expenditures $2014	Coef.	103,219 **			0.05 *	282,682 ***	1995-2013	19	0.71	
			Std. err.	-35,565			-0.02	-57,555				
DOI regions, except Alaska	Area burned fixed effects panel	Acres burned	Coef.	-921,504 *	61,303 **	33,307 **			1993-2013	168	0.06	
			Std. err.	463,903	26,328	13,682						
DOI nationwide	Expenditure 2SLS	Expenditures $2014	Coef.	8.53E+07 *		1.82E+08 ***	77.99 **		1993-2013	21	0.73	Num DOI fires CONUS
			Std. err.	4.14E+07		3.66E+07	27.21					

*** p<0.01, ** p<0.05, * p<0.1

Table 2. Summary statistics of changes in area burned from historical to mid and late century for the Department of the Interior from the Monte Carlo simulations (1,000 iterations per climate projection).

	Units	Average 1995-2013	Average 2041-2059	Average 2081-2099
90% Upper Bound	Million Acres	2.03	4.58	7.29
80% Upper Bound	Million Acres	1.93	4.21	6.61
Median	**Million Acres**	**1.55**	**3.10**	**4.50**
80% Lower Bound	Million Acres	1.18	2.15	2.74
90% Lower Bound	Million Acres	1.08	1.89	2.25
Historical	Million Acres	**1.56**		
Absolute Change from 1995-2013 Median	Million Acres		1.55	2.94
Absolute Change from 1995-2013 Observed	Million Acres		1.54	2.94
Percent Change from 1995-2013 Median	Percent		100	190
Percent Change from 1995-2013 Observed	Percent		99	189

Table 3. Summary statistics of changes in wildfire suppression expenditures from historical to mid and late century for the Department of the Interior from the Monte Carlo simulations (1,000 iterations per climate projection).

	Units	Average 1995-2013	Average 2041-2059	Average 2081-2099
90% Upper Bound	2014 $ Million	396	651	890
80% Upper Bound	2014 $ Million	381	604	796
Median	**2014 $ Million**	**340**	**493**	**584**
80% Lower Bound	2014 $ Million	299	424	455
90% Lower Bound	2014 $ Million	285	404	426
Historical	2014 $ Million	**339**		
Absolute Change from 1995-2013 Median	2014 $ Million		152	243
Absolute Change from 1995-2013 Observed	2014 $ Million		153	244
Percent Change from 1995-2013 Median	Percent		45	72
Percent Change from 1995-2013 Observed	Percent		45	72

Table 4. Summary statistics of changes in area burned from historical to mid and late century for the USDA Forest Service from the Monte Carlo simulations (1,000 iterations per climate projection).

	Units	Average 1995-2013	Average 2041-2059	Average 2081-2099
90% Upper Bound	Million Acres	1.70	4.23	6.53
80% Upper Bound	Million Acres	1.62	3.95	6.04
Median	**Million Acres**	**1.36**	**3.04**	**4.39**
80% Lower Bound	Million Acres	1.11	2.33	3.10
90% Lower Bound	Million Acres	1.04	2.15	2.79
Historical	Million Acres	**1.37**		
Absolute Change from 1995-2013 Median	Million Acres		1.68	3.02
Absolute Change from 1995-2013 Observed	Million Acres		1.68	3.02
Percent Change from 1995-2013 Median	Percent		124	222
Percent Change from 1995-2013 Observed	Percent		123	221

Table 5. Summary statistics of changes in wildfire suppression expenditures from historical to mid and late century for the USDA Forest Service from the Monte Carlo simulations (1,000 iterations per climate projection).

	Units	Average 1995-2013	Average 2041-2059	Average 2081-2099
90% Upper Bound	2014 $ Million	1,151	2,724	3,956
80% Upper Bound	2014 $ Million	1,112	2,590	3,709
Median	**2014 $ Million**	**983**	**2,137**	**2,884**
80% Lower Bound	2014 $ Million	851	1,783	2,210
90% Lower Bound	2014 $ Million	812	1,694	2,058
Historical	2014 $ Million	**987**		
Absolute Change from 1995-2013 Median	2014 $ Million		1,154	1,901
Absolute Change from 1995-2013 Observed	2014 $ Million		1,150	1,897
Percent Change from 1995-2013 Median	Percent		117	193
Percent Change from 1995-2013 Observed	Percent		117	192

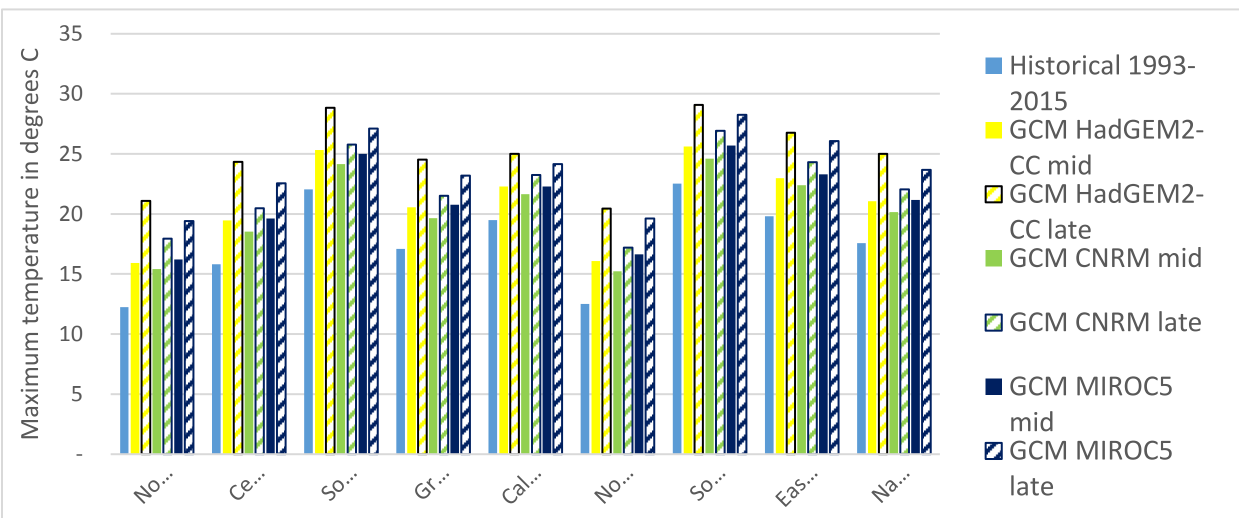

Figure 1. Changes in fiscal year average daily maximum temperatures on federal lands for the historical period (1993-2013) and for the GCMs used in the projections for the mid-century period (2041-2059) and late-century period (2081-2099).

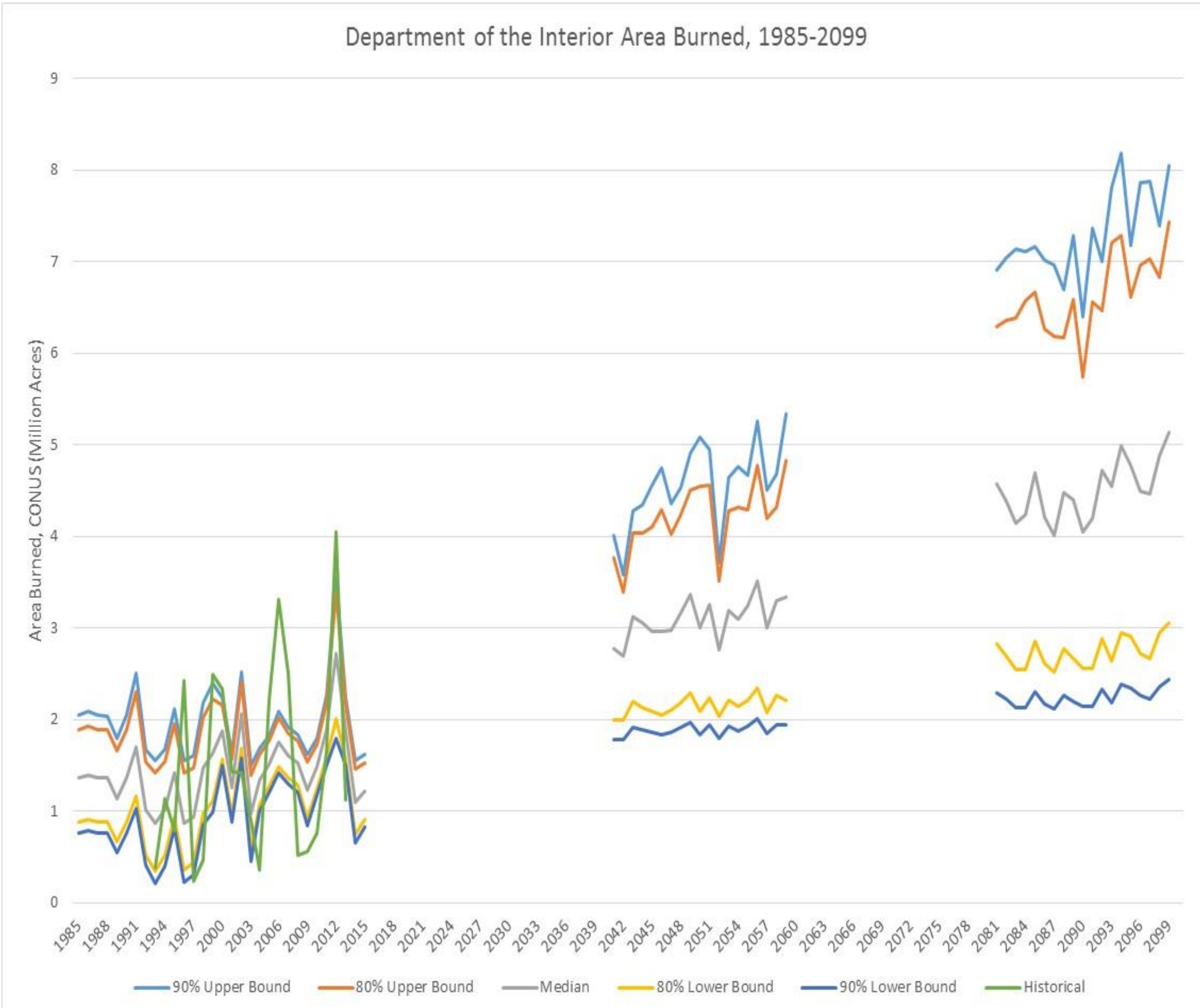

Figure 2. Area burned, historical and projected, 1985-2099, Department of the Interior

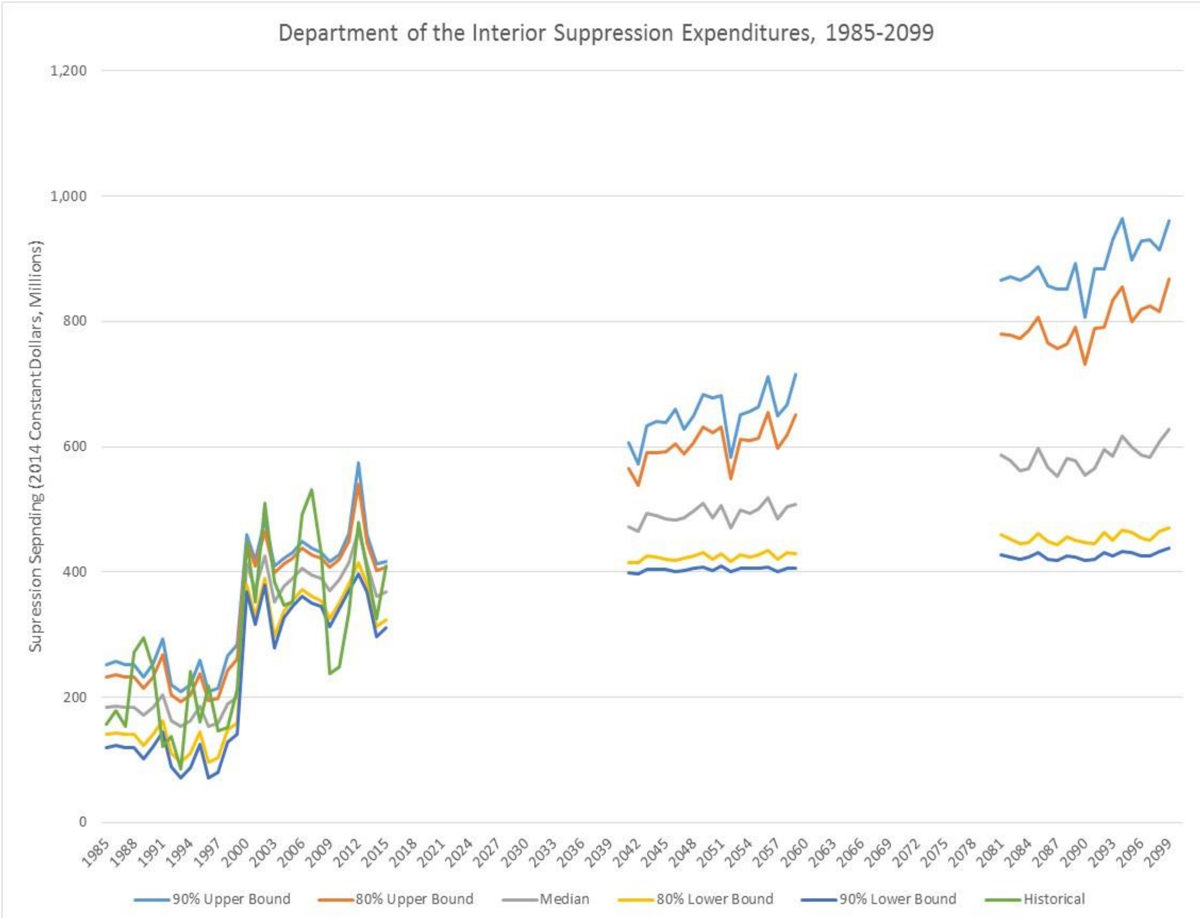

Figure 3. Suppression expenditures, historical and projected, 1985-2099, Department of the Interior

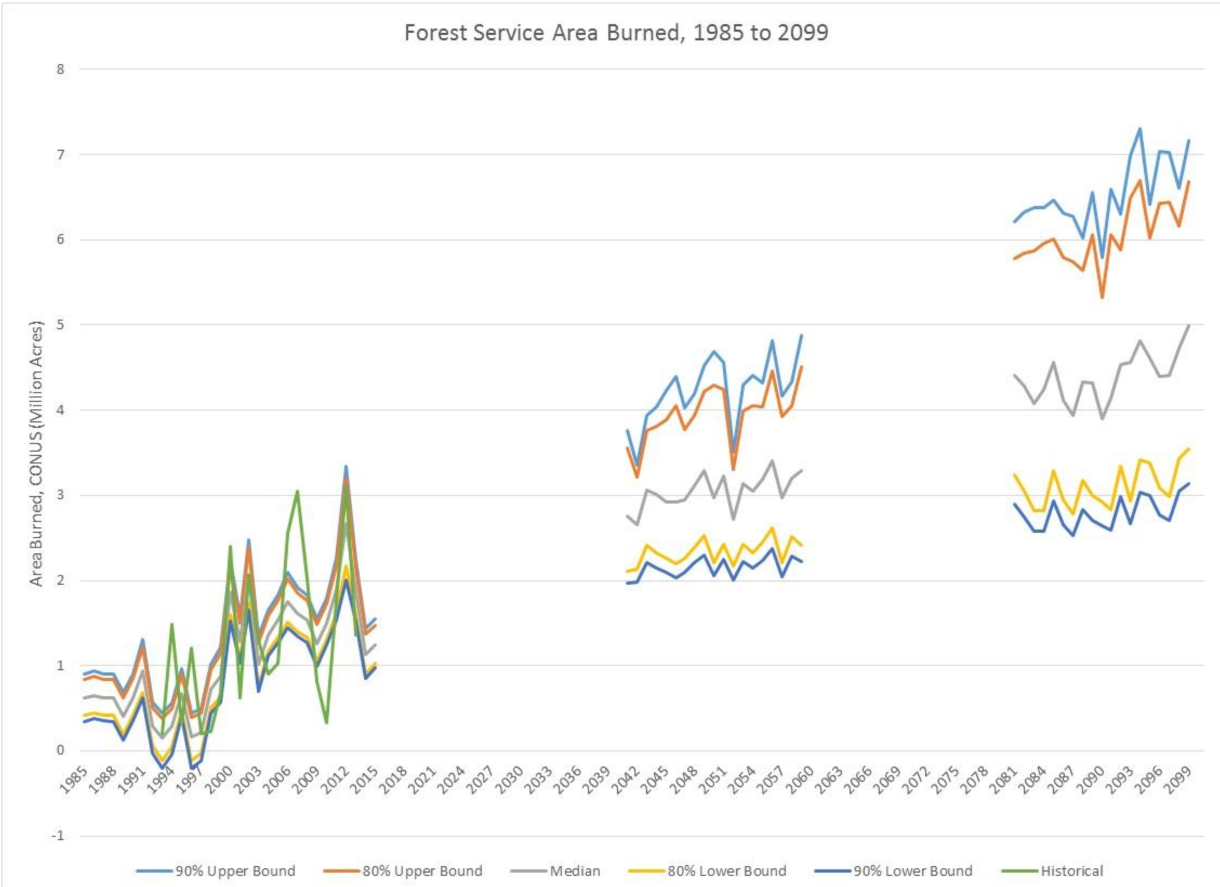

Figure 4. Area burned, historical and projected, 1985-2099, Forest Service

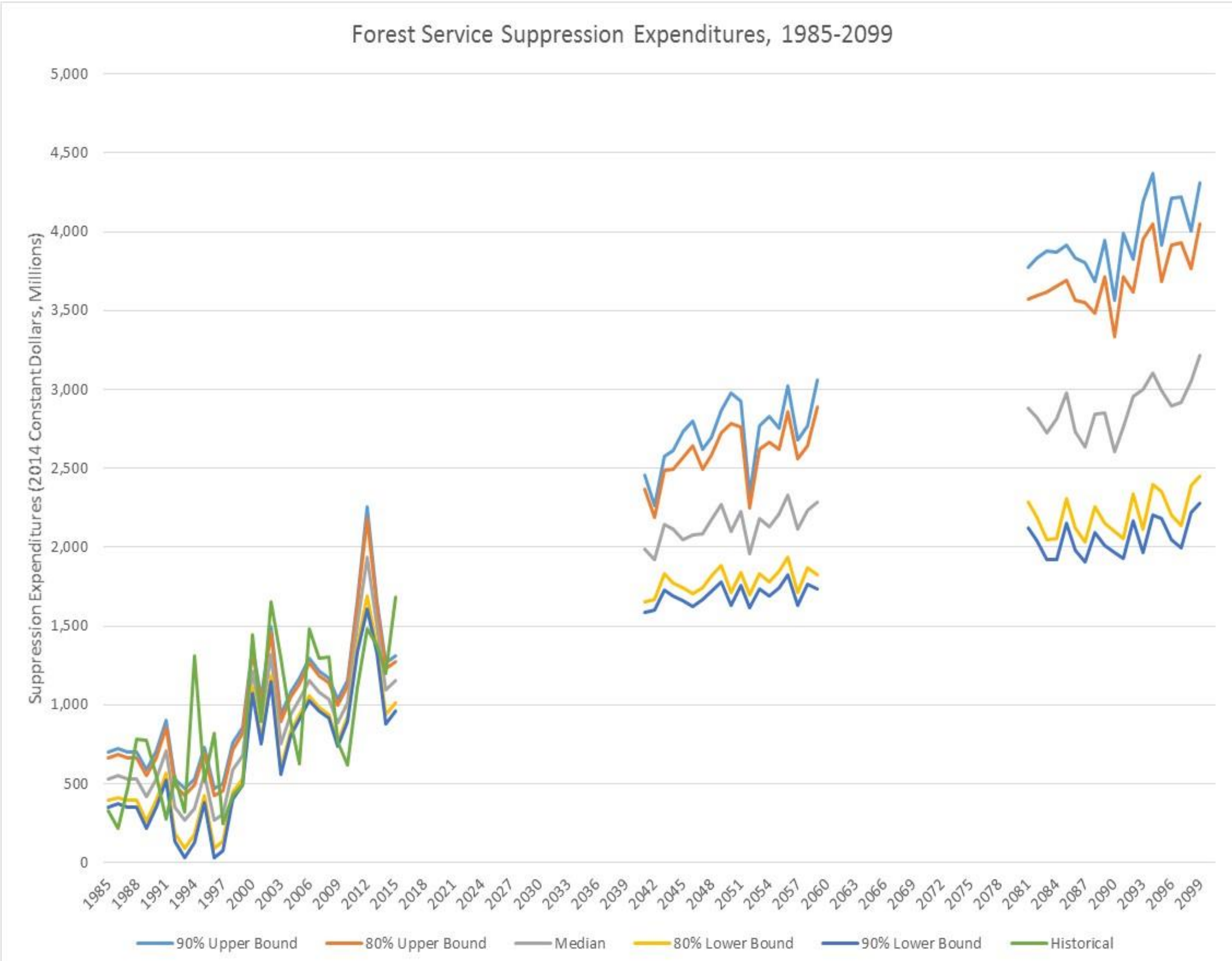

Figure 5. Suppression expenditures, historical and projected, 1985-2099, Forest Service

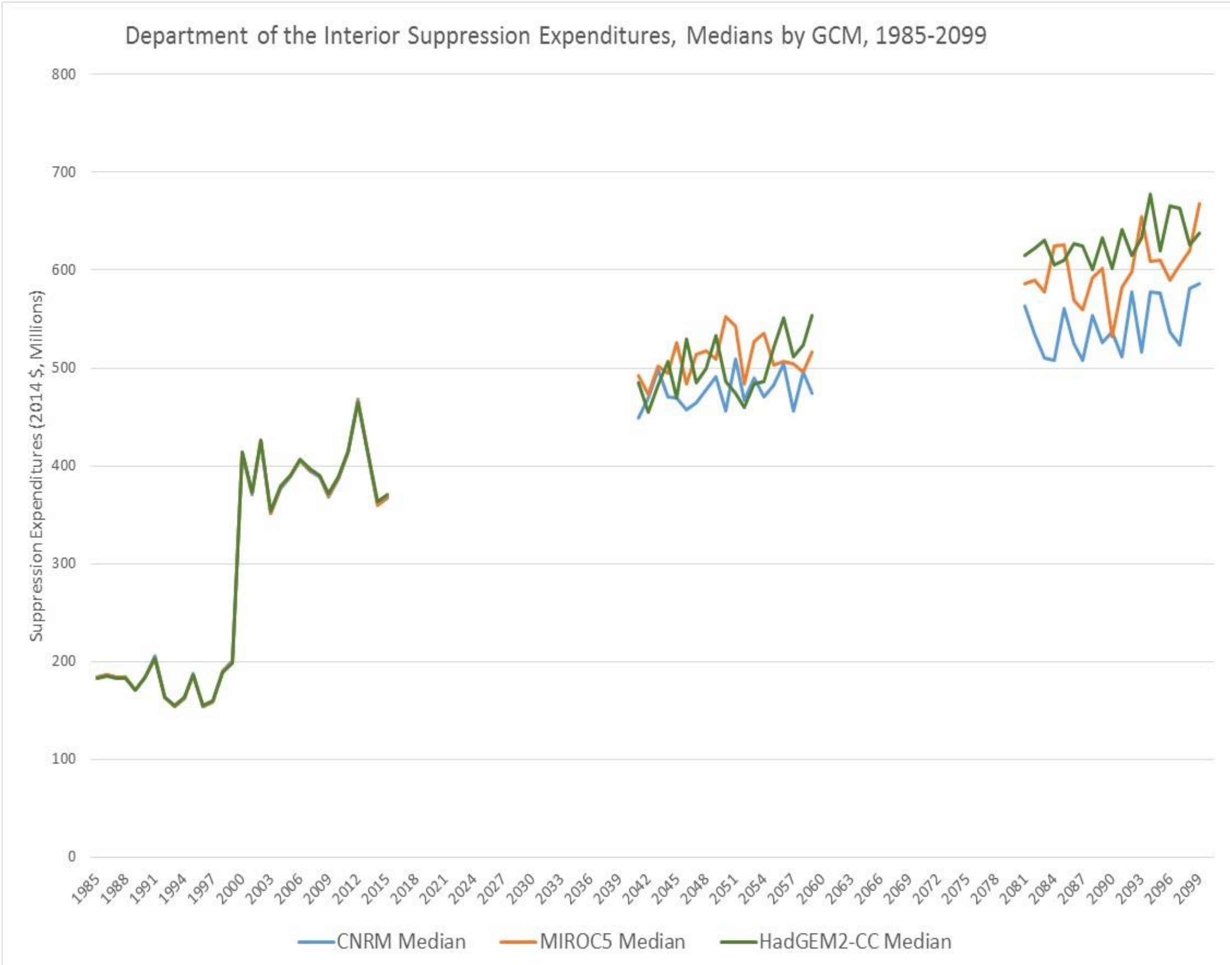

Figure 6. Department of the Interior suppression expenditure medians, projected for 1985-2015 using actual temperatures and for 2041-059 and 2081-2099 by general circulation model.

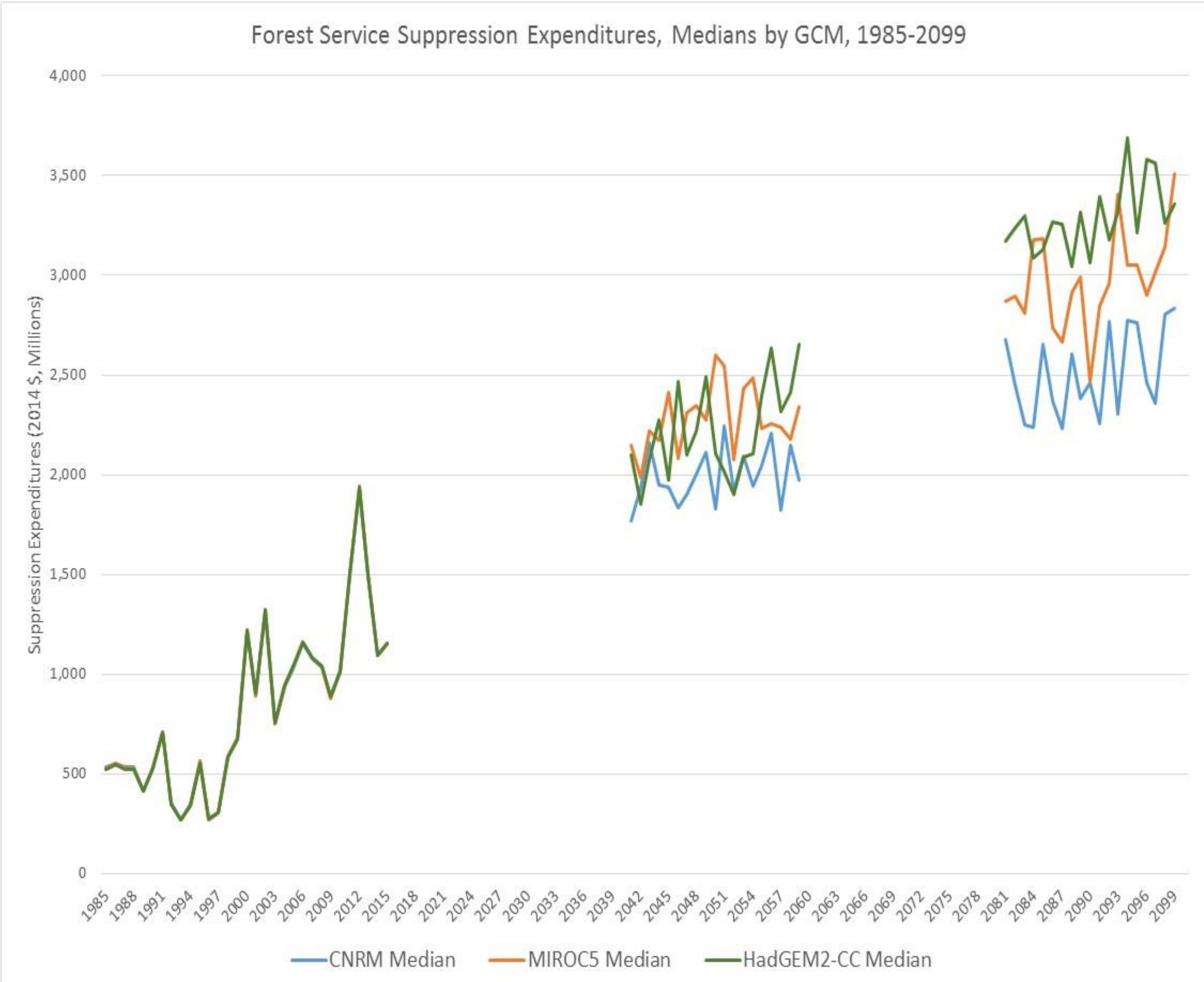

Figure 7. Forest Service suppression expenditure medians, projected for 1985-2015 using actual temperatures and for 2041-059 and 2081-2099 by general circulation model.