Photo by John McColgan, Bureau of Land Management, Alaska Fire Service

FLAMMABLE PLANET:

Wildfires and the Social Cost of Carbon

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The Cost of Carbon Project is a joint project of the Environmental Defense Fund, the Institute for Policy Integrity, and the Natural Resource Defense Council.

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KEY TAKEAWAYS

- Each year, global wildfires burn roughly 865 million acres of land—an area more than five times the size of Texas. In the United States, approximately 7 to 9 million acres burn each year.
- The current scientific consensus is that wildfire risk will increase in many regions of the world as climate change leads to warmer temperatures, more frequent droughts, and changing precipitation patterns. Fires are expected to become more frequent and intense, and fire seasons are projected to last longer. Additionally, more areas are expected to face fire risk, and scientists expect an increase in fire sizes (in terms of area burned).
- Most continents are expected to experience an increase in forest fires, with Australia, Europe, and North America likely to be particularly affected. In some cases, changes in forest fire patterns from climate change have already been identified.
- Some studies predict a 50 to 100 percent increase in area burned in the United States by 2050, with the most severe changes occurring in Western states.
- Damages from climate change-induced wildfires are not currently included in the social cost of carbon (SCC). The SCC is used by the government to evaluate regulations impacting greenhouse gas emissions. The omission of wildfires from the SCC could lead policymakers to underestimate damages from climate change when crafting important policies.
- Society faces multiple types of costs from wildfires: market damages (such as from lost timber and property), non-market damages (such as health effects and loss of ecological services), and adaptation costs (for fire prevention, suppression, and rehabilitation). While researchers regularly analyze the costs of many of these damages, few studies have attempted to quantify the total costs from wildfires.
- After analyzing research about each of these wildfire damage categories, we have compiled low, middle, and high estimates for various types of wildfire damages, per 100 acres burned (see Table 1 on p. 26).
- Research suggests that the total costs of a wildfire are typically 10 to 50 times its suppression costs. Given that the United States spends roughly $2.0 to $2.5 billion on wildfire suppression per year, we estimate that the total cost of U.S. wildfires is presently between $20 billion and $125 billion annually.
- Combining our estimates with scientific projections of wildfire increases from climate change, we attempt to quantify the future economic costs of *climate change-induced* wildfires in the United States. (We apply these estimates to additional wildfires expected to occur as a result of climate change, above natural wildfire rates. Given that wildfires are a natural part of most ecosystems and provide ecological balance to them, these estimates should only be utilized to value damages that deviate from historical fire behavior.)
- We predict that future climate change-induced wildfires will cost the United States between $10 billion and $62.5 billion annually by 2050, with a middle estimate of $22.5 billion. This represents roughly 0.06 percent to 0.36 percent of projected U.S. GDP.
- Similar estimates for *global* climate change-induced wildfires imply potential damages of $50 to $300 billion annually in 2050, with a middle estimate of $100 billion.
- These estimates depend on a number of assumptions (explained below) and should be interpreted cautiously. However, the estimated values indicate that climate change-induced wildfires represent a significant risk, and further research in this area is warranted.
- We recommend that the models used to calculate the social cost of carbon be updated to include wildfire damages from climate change, in order to better inform future policies.

ABSTRACT

The three Integrated Assessment Models that underlie the U.S. Social Cost of Carbon—DICE, FUND, and PAGE—do not account for the costs of wildfires caused by climate change. According to the current scientific consensus, climate change will increase wildfire frequency, size, and intensity in many global regions. The United States will be particularly affected; scientists predict a 50 to 100 percent increase in area burned by 2050. Given this potential increase and the Obama administration's recent political emphasis on the link between wildfires and climate change (Bump, 2014), this omission is particularly problematic.

This report assembles preliminary estimates of the costs of wildfire increases from climate change to the United States and the world. The paper reviews the various market damages (timber, property, and tourism), non-market damages (health, ecological, and non-use), and adaptation costs (prevention, suppression, and rehabilitation) associated with wildfires. However, many studies that estimate the magnitudes of these impacts are fire-specific, and lack generality. Using various fire-specific estimates from the economic literature, we assemble a ratio of suppression costs to total wildfire costs of 1:4 to 1:75, with a central estimate of 1:20. This matches a similar range of 1:10 to 1:50 from the literature.

Using these ratios, along with U.S. suppression costs and U.S. GDP predictions, we find U.S. wildfire damages from climate change in the range of 0.05 to 0.36 percent of U.S. GDP in 2050 (with a central estimate of 0.13 percent). In 2100, we find damages of 0.05 to 1.31 percent of U.S. GDP (with a central estimate of 0.29 percent). Due to the magnitude of these damage estimates, we believe additional research in this area should be prioritized, in order to more accurately estimate the costs of climate change-induced wildfires. These cost estimates should be included in integrated assessment models to improve the U.S. social cost of carbon estimate.

Cost of Climate Change-Induced Wildfires to the United States
(Midpoint Estimates in 2050 and 2100, by Damage Type)

Damage Type	Percentage of Total Cost	Cost From Climate Change-Induced Wildfires in 2050 (Billions of dollars)	Cost From Climate Change-Induced Wildfires in 2100 (Billions of dollars)	Reference Page
Market Damages				
Timber	8%	1.74	9.56	9, 14
Other market goods	3%	0.60	3.32	15-16
Property loss	11%	2.44	13.44	15
Tourism	3%	0.71	3.89	10-11, 16
Indirect costs (taxes and property values)	41%	9.28	51.01	16-17
Non-Market Damages				
Ecosystem Services	10%	2.20	12.12	10, 17-18
Health	1%	0.20	1.12	9-10, 18-20
Non-use	3%	0.67	3.67	20
Adaptation Costs				
Suppression	5%	1.12	6.15	21-23
Evacuation	0.1%	0.03	0.18	23
Prevention	7%	1.49	8.20	23
Rehabilitation	9%	2.02	11.09	23-25
Total Costs				
Total	100%	22.50	123.75	-

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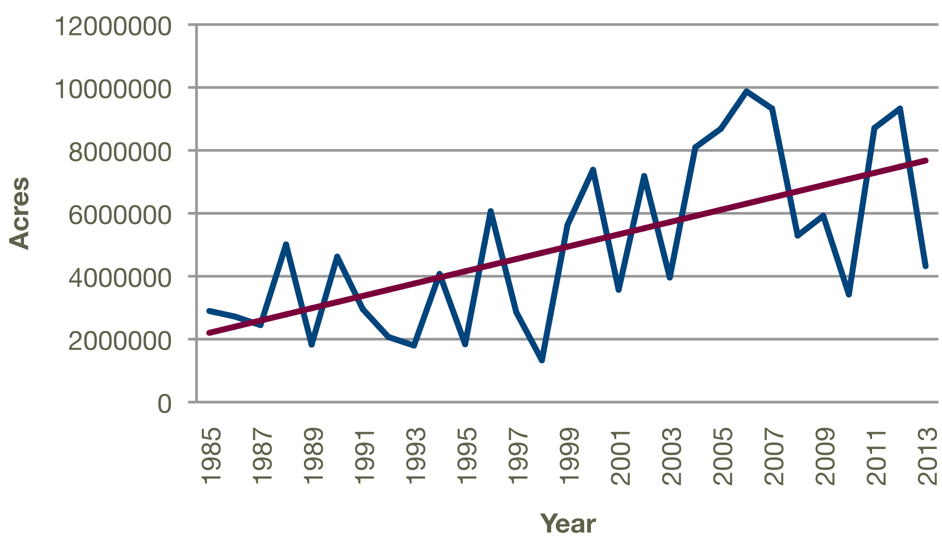
The social cost of carbon (SCC) is an estimate of the total cost of damage done by each ton of carbon dioxide that is emitted into the air. In 2013, the U.S government's Interagency Working Group on the Social Cost of Carbon updated its official estimate of the SCC to approximately $40.[1] This figure is used in official cost-benefit analyses of regulations that reduce greenhouse gas emissions. While some industry and conservative groups argue that the SCC is too high, a recent report, *Omitted Damages: What's Missing from the Social Cost of Carbon* (Howard, 2014), shows that this estimate is most likely too low. This is because the models that underlie this official estimate, known as Integrated Assessment Models (IAMs), only partially account for many significant impacts of climate change or omit them altogether.

This report, which focuses on the omission of wildfires, is the first in a series of reports from the Cost of Carbon Pollution project that will analyze specific damages partially and fully omitted from the SCC. Through this research, we will assess the potential magnitude of the underestimation of the SCC.

A wildfire is an unrestrained fire that predominately burns undeveloped areas, including forests, woodlands, grasslands, peat, or shrubs (forest fires, brush fires, etc. are subcategories of wildfires).[2] Each year, roughly 865 million acres (an area more than five times the size of Texas) burn globally (Sánchez et al., 2013) and 7 to 9 million acres (an area about 1.5 times the size of Massachusetts) burn in the United States (Sánchez et al., 2013; NIFC, 2014a; and Bjerga, 2014).[3,4] These amounts are expected to increase significantly due to climate change and other factors; see Figure 1 for a look at the trend within the United States over the last three decades.[5] The omission of wildfire costs resulting from climate change may lead to a significant underestimation of the SCC.

According to the Intergovernmental Panel on Climate Change (IPCC) Working Group II's 2014 Report (IPCC, 2014), the current scientific consensus is that wildfire risk will increase in many regions of the world as a result of climate change.[6] As discussed by the IPCC (2014) and Howard (2014), this increase in wildfires will result in damages to economic sectors, human health, and the environment. The increase in

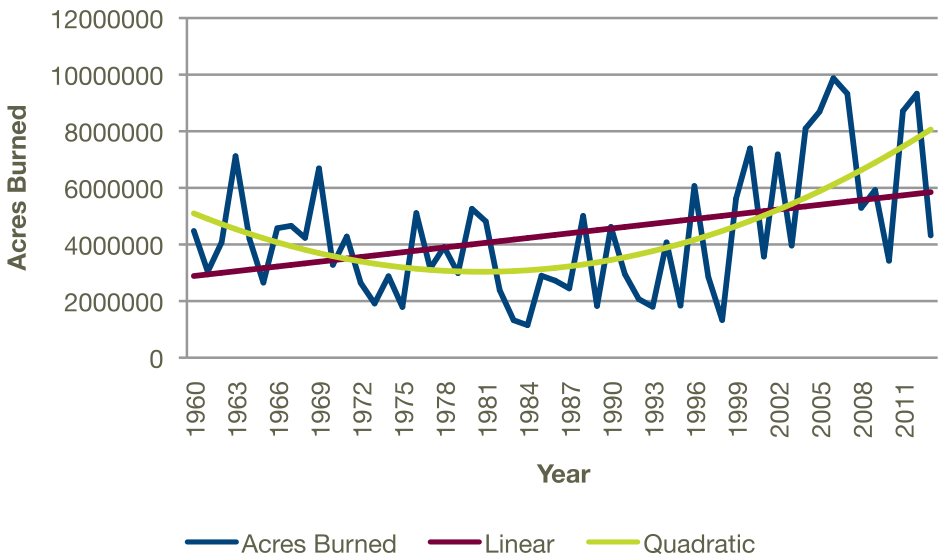
Figure 1. Acreage Burned By Wildfires in the United States Over Time (Blue) and the Corresponding Linear Trend (Red), 1985 to 2013



Source: NIFC (2014a)

wildfires could have significant market effects, hurting the forestry sector—and the economy as a whole—through the loss of property and infrastructure. Additional wildfires and more severe wildfires will also lead to health damages, including fire deaths and public health impacts from smoke pollution; and environmental costs, including damages to terrestrial and freshwater ecosystems. Fires can also trigger climate feedback effects by releasing carbon dioxide (CO_2) stored in forests and permafrost—potentially increasing the rate of climate change. Finally, there are costs incurred from adapting to increased wildfire pressures: fire prevention, fire suppression, fire rehabilitation, and costs associated with evacuation.

Figure 2. Acreage Burned by Wildfires in the United States Over Time and the Corresponding Linear and Quadratic Trends, 1960 to 2013



Source: NIFC (2014b)

Increased wildfire risk is a significant damage from climate change, and should be included in IAMs. While Tol (2009) argues that many damages are small enough to ignore because they are balanced out by omitted benefits, wildfires can be quite expensive. In particular, the increased frequency and intensity of wildfires and other weather events associated with climate extremes are likely to be more costly to society than the often-cited rise in global average surface temperature (IPCC, 2014).[7] While extreme weather events, like wildfires, are expensive, their effects are insufficiently studied—partially because of the difficulty of including them in Earth system models—and there are few damage estimates in the current academic literature (IPCC, 2014).[8] It is likely that the exclusion of wildfires from IAMs is due to their insufficient study, rather than IAM modelers' beliefs that their effects are insignificant.

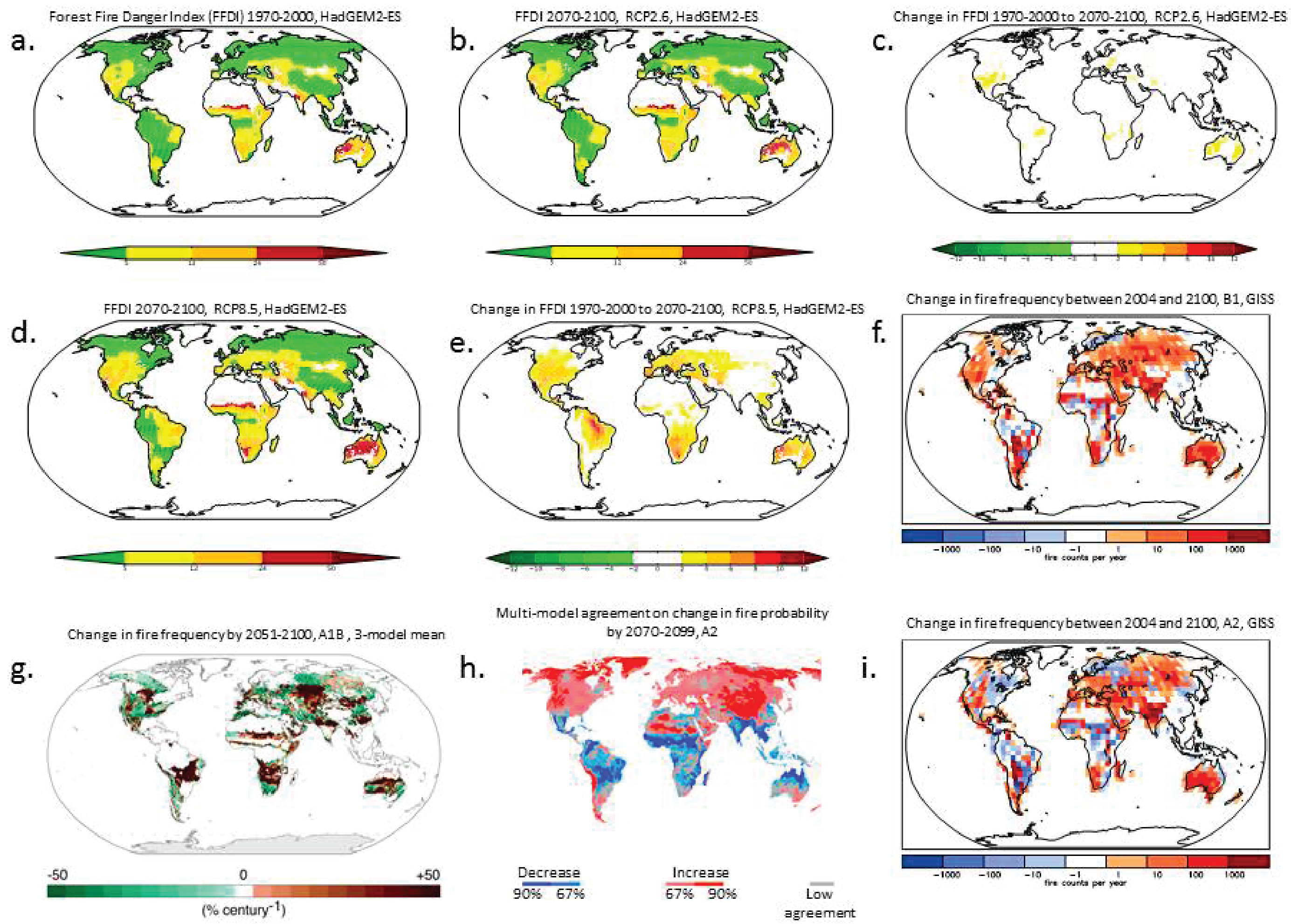
This report focuses on identifying the potential magnitude of wildfire damages from climate change. First, we review the science behind the increase in wildfire risk due to climate change, and discuss the potential impacts. Next, we review the economics of wildfire impacts more generally, due to a lack of damage estimates from climate change-induced wildfire risk. We then attempt to roughly approximate the increase in wildfire damage due to climate change. While the resulting estimates indicate that the potential cost of wildfires could be significant, they should be interpreted only as rough calculations. Finally, we conclude with a discussion of the findings and their implications for the future estimation of wildfire damages from climate change.

SCIENCE OF WILDFIRES AND CLIMATE CHANGE

According to the current scientific consensus, the risk of wildfires will increase in many regions as climate change leads to warmer temperatures, more frequent droughts, and changing precipitation patterns (including earlier spring melt). Thus, wildfires will be increasingly likely according to scientific models, even with temperature increases less than 4° Celsius. In addition to frequency, wildfire risk is increasing along several other vectors, including longer fire seasons, larger fire sizes (in terms of area burned),[9] and more intense fires[10] (Abt, et al, 2008; IPCC, 2014; de Groot et al., 2013).

As seen in Figure 3 below, models predict that many regions will face significant increases in fire risk (as measured by the McArthur Forest Fire Danger Index) as well as fire frequency and fire probability. Under medium- and high-emission scenarios, global forest fire risk is likely to increase substantially (specific regional risk predictions are

Figure 3. Projected Changes in Meteorological Fire Danger, Fire Probability, and Fire Frequency With Different Methods and Climate Models



Projected changes in meteorological fire danger, fire probability and fire frequency with different methods and climate models. (a)-(e) 30-year annual mean MacArthur Forest Fire Danger Index (FFDI) and change simulated with the HadGEM2-ES Earth System Model, with areas of no vegetation excluded (Betts et al., 2013; (a) FFDI 1970-2000; (b) FFDI 2070-2100, RCP2.6; (c) change in FFDI by 2070-2100 relative to 1970-2000, RCP2.6;(d) FFDI 2070-2100; RCP8.5 (e) change in FFDI by 2070-2100 relative to 1970-2000, RCP8.5. (f) Change in fire frequency by 2100 relative to 2004, SRES B1, simulated using climate and land cover projections from the GISS GCM and IMAGE IAM (Pechony and Shindell, 2010). (g) Change in fire frequency by 2051-2100 relative to 1951-2000, SRES A1B, simulated with the MC1 vegetation model driven by 3 GCMs (CSIRO-Mk3.0, HadCM3, MIROC 3.2medres; mean over 3 simulations; Gonzalez et al., 2010). (h) Agreement on changes in fire probability simulated with a statistical model using climate projections from 16 CMIP3 GCMs, SRES A2 (i) Change in fire frequency by 2100 relative to 2004, SRES A2, simulated using climate and land cover projections from the GISS GCM (AR4 version) and IMAGE IAM (Pechony and Shindell, 2010). Changes in FFDI (a)-(e) and fire probability (h) arise entirely from changes in meteorological quantities, whereas changes in fire frequency (f) (g) (i) depend on both meteorological quantities and vegetation. ***Source: IPCC (2014)*** less certain). Most continents will experience an increase in forest fires, with Australia, Europe, North America, and Russia likely to be particularly affected. In some cases, changes in forest fire patterns from climate change have already been identified (IPCC, 2014).[11]

Fire probability is likely to increase in part due to the interaction of fires with other drivers of forestry dynamics. Climate change affects the distribution of disease and insects, often widening their geographic range and making outbreaks more likely. Greater pest and pathogen risks may increase fire susceptibility (IPCC, 2014; Kaiser et al., 2012; Kipfmueller et al., 2002; Kurz et al., 2008).[12] Higher temperatures also increase the risk of invasive species, which heighten fire risk and intensity by making additional plant biomass susceptible to fire. These higher temperatures also contribute to the geographic shift of plant species over time, leaving dead biomass that has the potential to further increase the risk of wildfire.[13] Further, the combined effect of increased drought brought on by climate change (and worsened by the El Nino and La Nina cycles (Cleetus and Mulik, 2014)) and land use change from human incursion into forests could dramatically alter forest ecologies and fire risks. For instance, these factors could decrease the density of the Amazon forest while adding new ignition sources (arson and other intentional fires, campfires, cigarettes, debris burning, power lines, sparks from equipment, vehicle fires, etc.). Finally, logging, especially selective logging, increases the risk of wildfires by thinning the protective canopy of forests and increasing the presence of potential ignition sources related to human activity (IPCC, 2014). Similarly, silvicultural practices on forestry plantations can increase the size and intensity of wildfires due to high tree density and the corresponding overlapping of tree canopies common in monoculture (Graham, 1994, McKelvey et al., 1996).[14]

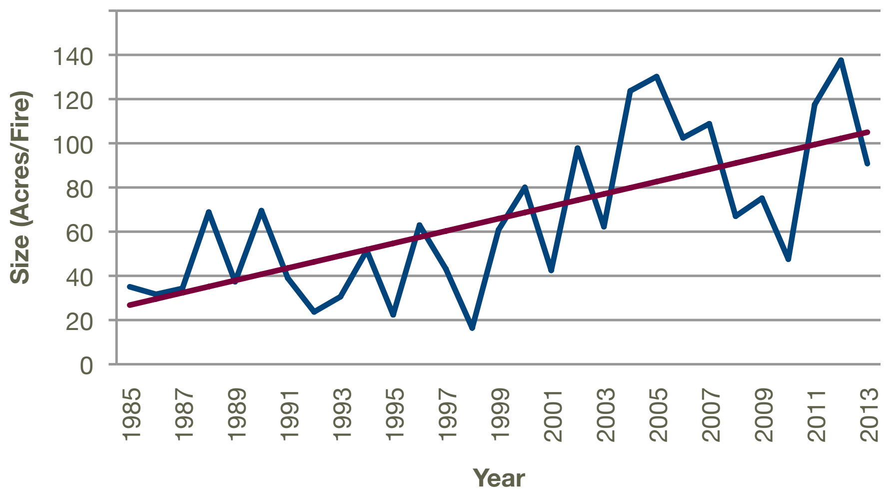
While the interaction of forest and wildfire dynamics often increases fire risks, climate change could also decrease certain risks. An increased CO_2 fertilization effect will increase the level and rate of growth of woody plants in savanna ecosystems, such that they are more likely to escape low-lying grass fires.[15] However, in Australia, this CO_2 fertilization effect may very well increase the amount of biomass susceptible to burning. Taking the effect of climate change on other drivers of forestry dynamics into account may imply a greater increase in fire risk and intensity than depicted in Figure 3 for many regions of the world (IPCC, 2014; Gorte, 2013).

While fire risks are projected to increase globally (de Groot et al., 2013), several areas face acute risks. The sclerophyll forests of Southern Australia face increased fire risk, as highlighted in the latest IPCC (2014) report. Temperate forests in North America, Europe, and Russia all face increasing climate stress, while conifer and boreal forests, Mediterranean ecosystems, and tundra in North America and Europe are projected to experience fires of increased frequency, duration, and size (IPCC, 2007; IPCC, 2014). Boreal forests in temperate climates will face the earliest and greatest increase in risks according to de Groot et al. (2013), while IPCC (2007) emphasizes the vulnerability of Mediterranean ecosystems. The area burned in North America could increase by 2 to 5.5 times by the end of the century (De Groot et al., 2013).

Tropical forests in South America and Asia are also at risk. Due to the combined effect of droughts and fire during dry periods, moist tropical forests face ecological tipping points that can result in large-scale changes. This effect can be exacerbated by human land use changes that increase ignition sources. This interaction resulted in a large increase in tree mortality in the Amazon in 2005, and could potentially contribute to a majority of the Amazon being under threat of loss by 2030. Dry tropical forests also face increased fire risks, and may in fact disappear (IPCC, 2014).

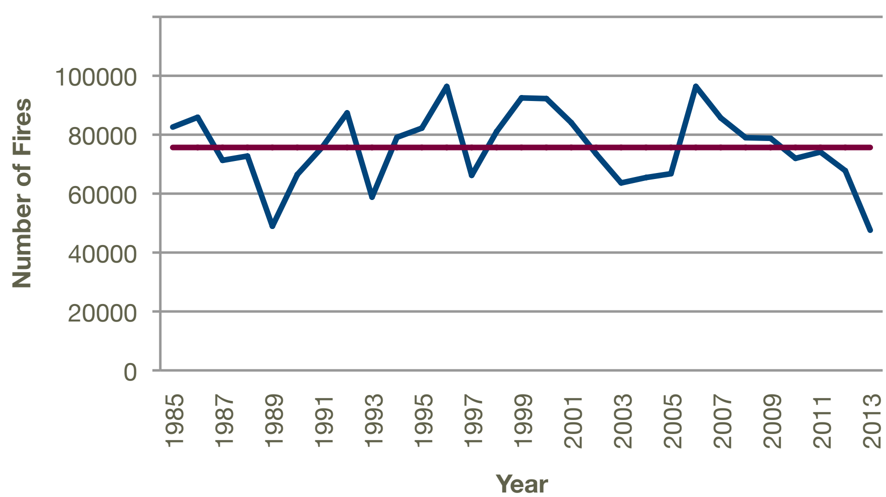
In the United States, Western states face the greatest fire risks.[16] In a summary of existing literature, Liu et al. (2014) predicts a 50 to 100 percent increase in the area burned in the United States by 2050, with particular risks to Western states (Davenport, 2014; Schultz, 2013; USDA, 2013).[17] California alone could experience a 36 to 74 percent increase in area burned by 2085 under a high emissions path (Westerling et al., 2011). These increases would continue an already increasing trend (relative to the late 1970s and early 1980s), as area burned in the U.S. almost doubled from 3.6 million to 6.5 million acres from the 1990s to 2000s (Moeltner et al, 2013); see Figure 1. Along with the increase in area burned, the United States is expected to experience a significant increase in large, potentially catastrophic, wildfires.[18] Using the results from Littell (2009), NRC (2011) finds a 300 percent increase in the area burned by the median-size fire in the Western United States for a 1° Celsius increase in the current global average mean temperature. The number and size of *large* fires in the Western United States has already been increasing steadily in recent years according to Dennison et al., (2014) and Florec et al., (2012). Interestingly, while the NIRC (2011) data exhibit an increase in the size of wildfires (see Figure 4), they do not demonstrate any upward trend in the number of fires in the United States since the 1980s (see Figure 5).

Figure 4. Average Size of Wildfires in the United States Over Time (Blue) and the Corresponding Linear Trend (Red), 1985 to 2013



Source: NIFC (2014a)

Figure 5. Number of Wildfires in the United States Over Time (Blue) and the Corresponding Linear Trend (Red), 1985 to 2013



Source: NIFC (2014a)

Crowning fire in spruce forest. Photo by Murphy Karen, U.S. Fish and Wildlife Service

Forestry

Many of the current forest yield models suggest significant future increases in forest production due to the CO_2 fertilization effect. However, just as in agricultural models, the positive effects of increased atmospheric CO_2 levels may by exaggerated due to a failure to account for the effect of climate change on natural disturbances, including forest fires and their interaction with other omitted impacts, including pests and pathogens. Even without modeling these additional drivers of forestry dynamics, there is significant variability across forest productivity models. There is a consensus of decreased forest production (from declining timber yields) in already dry and future dry regions, and increased production in currently cold regions with limited areas available for forestry (e.g., areas characterized by tundra, permafrost, and frozen soils). However, fires, pests, pathogens and other dynamics further complicate these predictions, and make yield declines more significant and likely (IPCC, 2014). Current IAMs, which rely on these forest yield models, suffer from similar shortcomings.

Risks of forestry losses from fires differ substantially by region, and partly depend on past forest management practices. In the United States, in addition to climate change, the risk of wildfires is increasing partially because of a historic buildup of forest “fuels”: living and dead plant material (e.g., grass, foliage, needles, branches, tree stumps, and fallen trees) that is particularly susceptible to fire. This buildup is due to historic overgrazing of forests (particularly Western national forests), logging practices,[19] and fire suppression practices that aim to prevent all wildfires. This latter practice prevented frequent, low severity fires that clear out dead vegetation (Gorte, 2013).[20] Given these exacerbating factors, fire risks due to climate change in the United Stated make the U.S. forestry sector particularly vulnerable.

Health

In the 21st century, the increase in wildfire risk from climate change will increase morbidity and mortality relative to a future without climate change. While there are morbidity and mortality effects from direct exposure to fire, the predominant negative health impact from wildfires is direct exposure to smoke. Wildfires increase the levels of particulate matter and toxins in the air for a period of days or months. Increased particulate matter is known to cause earlier mortality and morbidity by leading to cancer, respiratory problems (asthma, bronchitis, chronic obstructive pulmonary disease, reduced lung function, chest pain), discomfort (eye irrigation, fatigue, headache, dizziness, and distress), cardiovascular effects, and depressed immune defenses (especially respiratory).[21] A recent study, Johnston et al. (2012), attributes 339,000 premature deaths annually to decreased air quality from wildfires. While the majority of these deaths occur in Sub-Saharan Africa and Southeast Asia, developed nations are not immune, as seen in the case of Australia (IPCC, 2014).[22]

Elderly people and children will bear the majority of these injuries and deaths due to wildfires (IPCC, 2014; Richardson et al., 2013). However, pregnant woman and their fetuses, smokers, and individuals with chronic illnesses (particularly respiratory illnesses, diabetes, cystic fibrosis, primary pulmonary hypertension, and genetic polymorphisms) will also be susceptible (Jayachandran, 2009; Weinhold, 2011). Working-age adults who are affected will also suffer additional costs from missed work.

In addition to health effects from direct fire exposure and particulate matter, wildfires can cause negative health impacts more indirectly. Wildfires often increase ozone for very short periods, leading to negative health impacts associated with respiratory disease, including asthma, and heart disease. Wildfires can also decrease water quality by shifting mercury from soils to waterways (Physick et al., 2014; Weinhold, 2011). Additionally, the depletion of vegetation from wildfires limits rainwater absorption, sometimes leading to flash floods and corresponding health effects, including drowning, infections (skin and respiratory), and increases in infectious diseases (including vector borne and diarrheal diseases) (Few et al., 2004).

Environmental Services

Fires, along with floods and storms, are climate disturbances that are essential to maintaining biodiversity. However, if the frequency or intensity of wildfires in a region exceeds that to which the local species are adapted, biodiversity can be negatively affected (IPCC, 2014, chapter 4). Because forests are one of the predominant types of natural land cover and are home to a large fraction of the Earth's organisms, changed fire regimes from climate change could have a significant effect on biodiversity (IPCC, 2014). In cases where fire contributes to decreased plant biodiversity, genetic services could be lost, including contributions to the development of medicine and other products (IPCC, 2014).

The burning of forests and the regeneration that follows can threaten many ecosystem services that humans value. For example, wildfires affect water availability through several avenues, including decreased water quantity as forests regenerate after wildfires, and decreased quality as vegetation loss results in erosion and increased runoff. Ash from fires can also drift and settle into reservoirs (Cleetus and Mulik, 2014). Dale (2009) and Lynch (2004) suggest that watershed damages may be the most costly of all societal impacts from wildfires. Wildfires also damage the recreational, aesthetic, and cultural services of an affected area. In some cases, wildfires may negatively affect local tourism and create both economic and cultural damages in affected communities (IPPC, 2014, chapter 10). However, because wildfires are a necessary ecological process in many ecosystems, the short-term loss of ecosystem services from wildfires may sometimes be offset by the long-term provision of ecological services made possible by burnings.

Over the medium-run and long-run, fires also contribute to the shift of plant species across the geographic landscape. Some areas will become too hot for wood plant species, such that their loss is irreversible. In particular, intense fires may favor new vegetation by consuming organic matter in the soil that traditional vegetation thrives on. For example, this favors the recruitment of deciduous species over conifer forests in North

America.[23] Globally, in some key instances, forest ecosystems will be unable to shift because other suitable habitats will be unavailable, such as for alpine and Arctic ecosystems. Increased fire risk, along with other pressures, may push some threatened habitats such as dry tropical forests to the brink of extinction (IPCC, 2014, Chapter 4; Miles et al., 2006). Wildfires can accelerate the loss of permafrost in the Arctic tundra, leading to the establishment of woody species in these areas. Wildfires are also contributing to the conversion of forests to savannas, including in the Amazon (IPCC, 2014). It is important to note that species shifts will further increase fire risks, as these shifts will leave dead biomass to burn (Gorte, 2013).

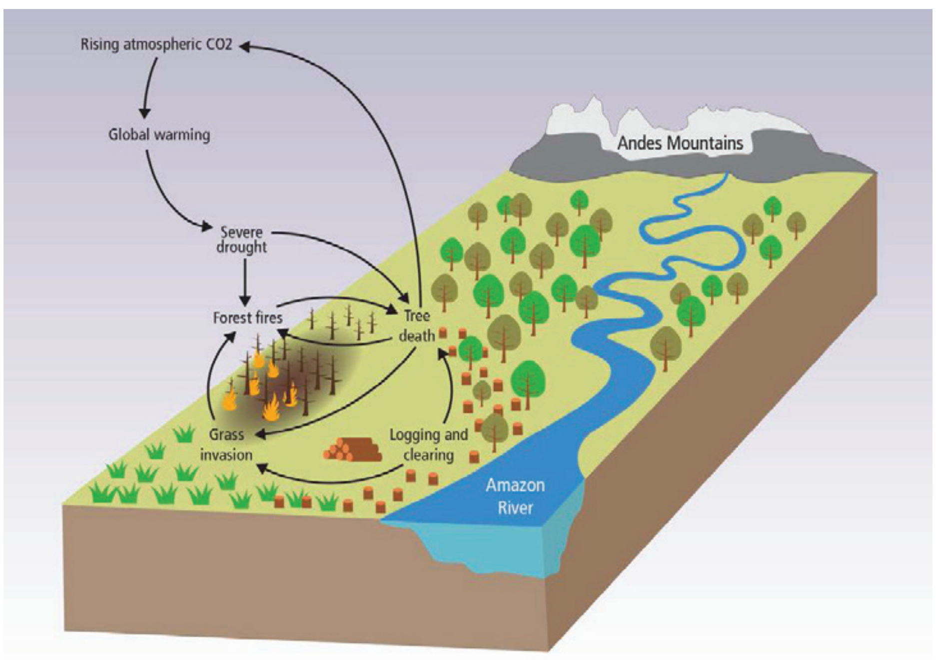
Finally, increased fire risks may put conservation and fire prevention goals in conflict, as has been seen in Oceania. Prevention goals may restrict public access to at-risk natural resources as some communities work to prevent wildfire risks and allow vegetation to recover from fire (IPCC, 2014, Australia Chapter).

Carbon Sequestration

Models suggest that fires and other natural disturbances affected by climate change will weaken forests' global carbon sequestration capabilities, and potentially turn them into a net carbon emission source. Some evidence indicates that Canadian forests have already shifted from carbon sinks to carbon sources (IPCC, 2014). Because wildfires are one of the primary channels through which carbon shifts from terrestrial sinks into the atmosphere (Sommers et al., 2014), additional (and more intense) wildfires may contribute to positive feedback loops that increase the rate of climate change. In particular, a feedback effect can arise when fires prompt the release carbon from plant biomass, soil, and permafrost sources into the atmosphere, further increasing temperatures and future wildfire risk (IPCC, 2014); see Figures 6 and 7. These feedback loops are compounded by human-driven land use change and logging (IPCC, 2014). As a consequence, terrestrial ecosystem carbon stocks are vulnerable to rising fire risks in the 21st century.

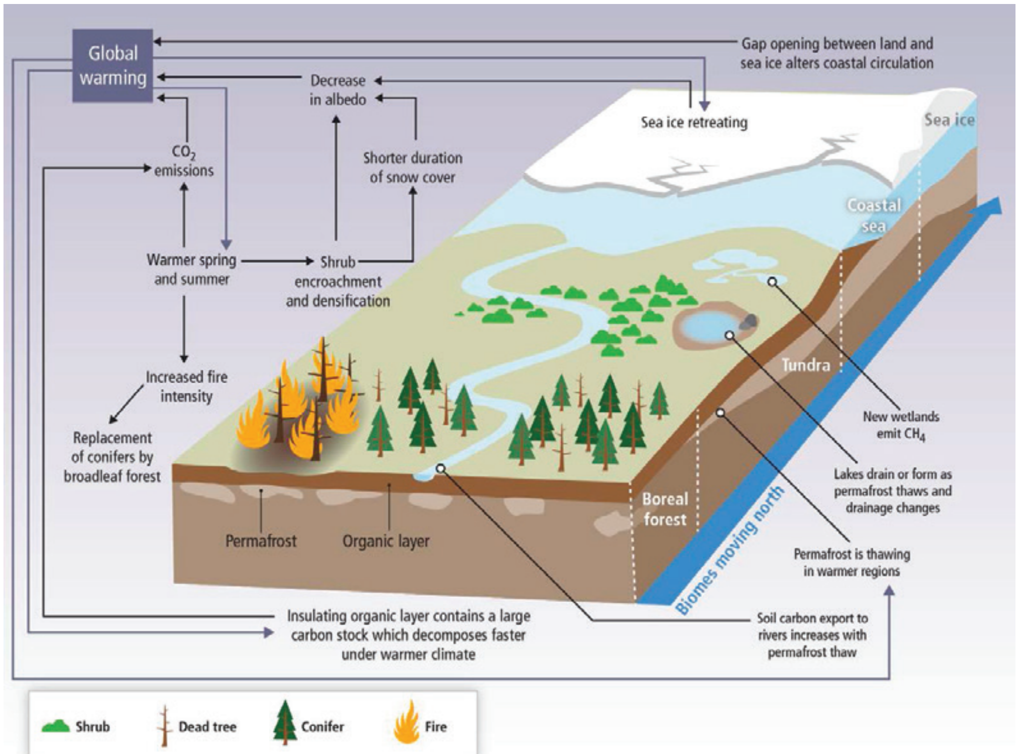
In addition to the effects of fires on the global climate system in the long run, fires can also have local climate effects in the short

Figure 6. Positive Climate Feedback Effect in the Amazon Basin



The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin (medium confidence; medium evidence, medium agreement).] ***Source: IPCC (2014)***

Figure 7. Positive Climate Feedback Effect in the Arctic



Tundra-Boreal Biome Shift. Earth system models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra-forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets, and net ecosystem carbon balance, permafrost thawing and methane emissions, with net feedbacks to additional climate change. ***Source: IPCC (2014)***

run and medium run. During the fire season, fires can reduce overall local and regional solar radiation—lowering temperatures locally—through the radiative forcing of smoke particles, which decrease Earth's absorption of solar radiation during fire events. Fires can also prevent cloud formation, increasing the likelihood of drought locally, and thereby further increasing fire risk. Additionally, the black carbon from smoke can accelerate snow melting (USDA, 2013; Liu et al, 2014; Andreae et al., 2004; Mongabay, 2005).[24] Recent research has also identified large soot particles from wildfires, known as superaggregates (SAs), which have a 90 percent greater warming potential than standard soot particles.[25] Due to these particles, wildfires may have a greater warming potential than previously thought, and also might have additional local climate effects (Harball, 2014; Chakrabarty et al., 2014). More research is necessary to clarify the overall effect of wildfires on regional climates.

QUANTIFYING WILDFIRE DAMAGES

The costs of increased wildfire risk from climate change can be placed into several groups: market damages (lost timber and property), non-market damages (health, ecological services, and non-use values),[26] and adaptation costs (the costs of prevention, suppression, and rehabilitation). Due to a lack of existing damage estimates for increased wildfire risk from climate change, this section focuses on economic estimates of the costs of wildfires to society. In particular, it attempts to quantify some of the damages discussed in the science section and calculate them on a per-one-hundred-acre (5/32 square miles) basis. Most of the estimates in the academic literature are specific to a particular fire or group of fires, and lack generality for extrapolation. Furthermore, most estimates are averages rather than marginal estimates[27]—an exception being the morbidity estimates from Moeltner et al. (2013). Thus, the average estimates highlighted in this paper should be seen as illustrative of the potential importance of the corresponding impacts. Finally, estimates of non-market damages, specifically the value of ecological services and non-use values, are complicated by the fact that wildfires are necessary for the health of many ecosystems, and so may provide net ecological benefits over time.

There is substantial heterogeneity in published forest fire damage estimates. Damage estimates differ across studies by the type of forest affected and the severity of the wildfire considered. The growth stage of the affected forest is important. For example, in the case of forest plantations, the value of timber loss is partially determined by stand age—physical loss from fire decreases with age and value of timber increases with age. More generally, damages also heavily depend on whether the land use of an area changes after a fire. Other important factors include a site's non-timber products (including firewood, hunting and fishing, and recreation) and non-market values (recreational and aesthetic values).

Other characteristics of the affected area, including its slope and vegetation structure, can also affect damages by influencing forestry dynamics such as recovery time (Rodríguez and Rodríguez, 2013). In particular, location matters because a major determinant of societal cost is proximity to humans.

Characteristics of the particular fire also affect the level of damages. The severity of a fire, in terms of intensity and acreage burned, is of particular importance. In terms of costs, this impacts short-term losses, such as the level of tree mortality and the quantity of salvage wood, as well as the medium- and long-term damages, such as the potential for significant flooding and erosion. While suppression costs and damages to human infrastructure increase with intensity and area burned, ecological damages may not be incurred until the level of fire activity to which ecosystems are adapted is exceeded (and ecosystems may actually benefit up until that level).

In addition to these heterogeneity issues, damage estimates differ across studies due to the choices made by the analysts. Some analysts account for indirect economic losses, non-market values, and non-use values in their studies, while others omit some or all of these factors. Analysts also use different estimates for the damages associated with these factors.

Generalization is possible to the extent that analysts capture heterogeneity within fires or between fires in their study. Within a particular fire, topology, vegetation type, and other factors can greatly affect the severity of the fire across the landscape. The extent to which an analyst considers these differences within an affected area can greatly influence the total damage estimate. Alternatively, cross-sectional fire analyses, which are often conducted using a series of fires in a given year, can be particularly valuable in identifying the effect of various attributes of the fire on total damages. However, case studies are far more common in the wildfire literature than cross-sectional analyses, making the extrapolation of damage estimates difficult.

Market Damages

Market damages consist of direct market losses of timber, non-timber goods and services (such as grazing and tourism), property, and infrastructure. These direct losses can be significant, as evidenced by the 2009 bushfire in Victoria, Australia that caused $4 billion worth of damage. Fires also lead to indirect economic losses, such as decreased property values in the surrounding area, slower economic growth, lost jobs, and lost tax revenue (from renting of timber land, declines in property values, and decreased economic activity) (Lynch, 2004; Dale, 2009).

TIMBER – The effect of forest fires on the timber industry is difficult to determine. This is because, in many cases, tree mortality from forest fires actually increases timber production in the short run due to timber salvage following a fire. Given that much of U.S. timber is on public lands, which are managed for many objectives other than timber production (e.g., the provision of environmental services and recreational areas), it is not surprising that the effects of fires on the U.S. timber industry are mixed and fires can actually increase timber production.[28] On privately managed forestlands where the aim is to maximize profits, the forestry sector may experience economic losses.

Without timber salvage operations, timber losses can be either small (in cases such as the burning of understory) or large (such as when the organic layer of soil is lost in addition to trees). In the 2000 Bitteroot National Forest wildfire, which burned 307,028 acres,[29] the value of timber lost without salvage was $8.9 million (with a possible range of $6 to $12.9 million). This is equivalent to $2,899 per 100 acres. A forest service study estimates the corresponding effect on welfare, as measured by the sum of producer and consumer surplus,[30] was also $8.9 million from this fire (Prestemon et al., 2006).[31]

In the case of small to moderate fires, post-fire logging can mitigate market damages from timber loss. In the case of the 2000 Bitteroot National Forest wildfire, if timber from 15 percent of the land area had been salvaged, the same forest service study finds that the fire would have resulted in a net increase in the value of timber (Prestemon et al., 2006). Salvage value increases if salvage efforts are undertaken quickly to prevent wood rot, and if larger areas are salvaged. However, the resulting welfare effects are complex given that salvaging timber results in a short-run spike in timber supply. In the short run, timber prices decrease and timber supply increases, such that: (1) consumers benefit, (2) producers of salvaged timber benefit, and (3) timber companies not involved in the salvage effort are potentially hurt by any decline in price that occurs. In the long run, the opposite welfare effects occur as prices increase and supply decreases. In the above example, there is a net welfare gain to society that reverses the welfare loss from lost timber due to the forest fire (Prestemon et al., 2006).[32]

Similarly, in another Forest Service study, Prestemon and Holmes (2008) analyze the 2002 Biscuit Fire—a 499,965-acre fire in Oregon and California that killed 40 percent of the trees in the affected area. With an assumed price of $333 per million board feet taken from a 2003 USDA forest service report, the welfare loss was $52.1 million without salvage efforts. Under various salvage efforts (20 percent to 100 percent), the benefits from salvaging the timber again outweighed timber losses from the fire. A 60 percent salvage rate was even sufficient to produce a net welfare gain equal to the cost of fire suppression.

These studies may exaggerate the benefits of forest fires to societies from post-fire salvage timber production increases. Forest fires may negatively affect timber yields in the medium run and long run. Timber stands are often not completely lost to fire, and are often allowed to continue to grow post-fire. A 2011 study in Kentucky looked at long-term timber loss from wildfires by conducting a comparison of similar stands, some of which had been affected by fire. The authors found that forests lost 47 percent of their value in fires, but only a quarter of this loss was due to tree mortality. The remaining loss came from changes in stand structure, which hindered future timber production and lowered future timber value. The total loss was estimated at $40,400 per 100 acres, of which $30,000 was due to changed stand structure (Reeves and Stringer, 2011).[33]

Additionally, post-fire timber salvage efforts come with a cost—environmental degradation. Salvage efforts slow natural regeneration, introduce and facilitate invasive species, reduce soil fertility, increase surface water runoff and erosion, cause further damage to aquatic systems, and eliminate, disturb, or alter potential habitat for many species—particularly cavity-nesting birds and vertebrates (Peterson, 2010; Linenmayer and Noss, 2006).[34] Given that the above studies do not account for these additional market and non-market costs, the optimal salvage rate and the net welfare effect cannot be determined from them.

Fire-specific timber damage estimates vary widely. In the United States, estimates for timber loss range from a slight benefit with salvage (as discussed above) to a net welfare loss of $10,421 per 100 acres (Prestemon and Holmes, 2008), to a market loss of $30,000 per 100 acres (Reeves and Stringer, 2011, as discussed above). However, these estimates are still below the Buntry et al. (2001) welfare loss estimate for the 1998 Florida pine wildfires, of $65,600 to $118,000 per 100 acres burned with salvage. Lynch (2004) provides a case study of the Hayman fire in Colorado, finding timber losses to be only $2,686 per 100 acres. This is similar to the value of $2,899 per 100 acres from Prestemon et al. (2006).

Other studies offer estimates from fires in other nations. Rodríguez et al. (2013) offer a case study of a 200-hectare (494-acre) fire in a national pine forest in Spain, finding timber and firewood losses of €460 per hectare (approximately $26,000 per 100 acres). Similarly, a six-hectare fire on a pine plantation in Cuba cost 15,432 Cuban pesos per hectare (approximately $23,500 per 100 acres). These estimates are similar to those from Reeves and Stringer (2011).

OTHER MARKET GOODS – In addition to lost timber production, wildfires can negatively affect non-timber goods and services, including grazing and hunting. In 2011, more than 1,000 fires in East Texas burned 207,763 acres. As a result, Texas suffered $150 million in agricultural losses (lost grazing areas, animals and lost capital) as well as $97 million in losses from timber. Total damages were $118,885 per 100 acres, of which 61 percent came from non-timber market damages (Ledbetter, 2011).

PROPERTY AND INFRASTRUCTURE – Property and infrastructure damage is a commonly cited threat from wildfires. In particular, the loss of buildings, roads, physical infrastructure (including energy infrastructure such as electric lines), and livestock can be particularly expensive. These losses can occur directly through fires, or result from related events, such as landslides in areas where wildfires have destroyed protective vegetation (IPCC, 2014). Homeowners can avoid some damages through simple preventative steps—this is discussed in the following section.

Threats to property from wildfires differ regionally. In developed nations, land development trends have tended to increase the amount of property at risk. Since 2000, the United States has seen a 25 percent increase in housing construction in the urban-forest interface. This has increased the number of at-risk homes from 37 million to 47 million (Foster, 2014). Given that only 16 percent of land in the Western U.S. urban-forest interface areas is developed, property risk may continue to rise with further development (Gorte, 2013). Similar growth has occurred in Australia, Canada, Europe, and other countries (Florec et al., 2012).[35]

The development of housing in urban-forest interface areas also raises political pressures to prevent all forest fires, leading to fire suppression efforts that can ultimately increase the risk of wildfires. Fire suppression strategies tend to divert fire prevention funds away from programs such as biomass reduction in high-risk areas, instead emphasizing efforts in the urban-wildlife interface. Firefighting efforts also tend to change under these development patterns, focusing more on protecting homes rather than preventing the spread of wildfires. These pressures can also significantly increase fire prevention and firefighting costs (Gorte, 2013).

Property damage from fires is often calculated using insured values. For example, in the Hayman fire, Lynch

A type one heavy air tanker takes off from air command to fight the Hayman fire southwest of Denver.
Photo by Michael Rieger/FEMA News Photo

(2004) found insured property losses of $28,100 per 100 acres.[36] However, this method underestimates the value of property loss because it excludes (1) uninsured property losses, (2) infrastructure losses, and (3) indirect losses due to landslides and flash floods caused by the wildfires.[37,38]

RECREATION AND TOURISM – Wildfires can lead to short-run and long-run effects on recreation. In the short run, fires can lead to the closing of parks, and thus, the loss of recreation opportunities. Due to the overlap of fire season and tourist season, these losses occur frequently and can be significant. For example, the lodging industry experienced losses of $61 million during the 1998 Florida wildfire season (Thapa et al., 2013),[39] and Yellowstone National Park lost $21 million in tourism revenue due to fires that same year (Rodríguez and Rodríguez, 2013). In 2002, Colorado experienced its largest wildfire season to date, and tourism losses totaled $1.7 billion (Lynch, 2004)—a cost of $338,000 per 100 acres.

In the medium and long run, fire damages decrease the number of travelers to an area (Sánchez et al., 2013).[40] This change not only affects the tourism industry, but can affect consumer welfare as well—hikers, bikers, and campers must travel farther or make use of less desirable locations (Sánchez et al, 2013).

INDIRECT DAMAGES – Wildfires also have indirect economic costs, which can be especially high when fires are large or catastrophic. These costs include long-term economic losses, such as decreased economic activity and increased unemployment, and decreases in the tax base due to lower property values and reduced sales (IPCC, 2014, Handmer and Proudley, 2004; Silva et al., 2013). Lynch (2004) estimates that approximately $3 million in tax revenue was lost over two years due to the Hayman fire—$2,178 per 100 acres. In a recent newspaper article, Ledbetter (2011) argues that the indirect cost of the 2011 East Texas fires was $3.4 billion, which comes out to $1.6 million per 100 acres. While this number may not account for salvageable timber and other economic adjustments and adaptations, it does indicate that indirect losses can be significant (Ledbetter, 2011).

Wildfires can also affect property values, reducing wealth. Englin et al. (2008) have found that property values change as perceived fire risks increase. Values decline based on proximity to forests, tree cover volume, and investments in preventative measures such as fire resistant roofs (however, proximity to forests had only a temporary effect). Batker et al. (2013) cite a 3 to 17 percent decline in property values near recently burned areas in California. These declines include lost aesthetic services in addition to declines from perceived risk increases.

Non-Market Damages

In economics, non-market goods and services include damages to health and the environment. Wildfires can have substantial impacts on these values.

ECOSYSTEM SERVICES – Forests provide numerous ecosystem services, such as erosion control and habitat for wildlife. The value of such services can be substantial, but this value is often excluded from forest fire cost estimates. In addition to the complicated issue of valuing environmental services, the inclusion of the cost of lost ecosystems services is made more difficult by the fact that wildfires are a natural and necessary part of ecosystems. Healthy ecosystems are dynamic, and it is natural that they only provide particular services at certain times. Thus, wildfires produce short-run costs (i.e., loss of some services while the system rehabilitates) and short-run, medium-run, and long-run benefits (i.e., potentially more and higher quality ecosystem services from a healthier and more sustainable ecosystem (Keane and Karau, 2010)). In this sense, it could be argued that the ecological costs and benefits from a normal fire regime should not be counted, and should be considered as a natural part of any ecosystem. From this perspective, only costs from fires outside of the natural regime should be counted—increased frequency, size, and intensity of wildfires above their natural regime from climate change.[41] Thus, we should see the following discussion through the lens of potential costs associated with fire activity caused by climate change (above natural activity).[42]

To illustrate the type of environmental services that are lost due to wildfires, Lynch (2004) cites the case of the Buffalo Creek Fire in Colorado where erosion after a fire eliminated 15 to 20 tons of soil per acre. Forests play a significant role in controlling erosion, and large-scale erosion has many environmental consequences. The soil loss in Buffalo Creek would have likely been prevented without wildfire.

Forests also help to absorb rains. After this fire, the inability of soils to absorb water resulted in flash floods, causing damages equal to $29,600 per 100 acres. Additionally, forests help maintain water quality. The sediment from the erosion after the Buffalo Creek fire lowered the water quality in the surrounding area. As a consequence, the state had to spend $15 to $20 million on dredging and pipelines—approximately $126,000 per 100 acres.

In total, lost ecosystem services accounted for approximately half of the lower-bound fire damage estimate provided by Lynch (2004). Thus, the value of lost environmental services, which is often approximated by replacement cost, can be substantial. However, given that wildfires are a natural part of an ecosystem, such that a wildfire is somewhat inevitable, some level of soil erosion, flooding, and sedimentation may have eventually occurred—though potentially not as severely. In terms of climate change, increased soil erosion, flooding, and sedimentation from increased fire intensity and strength is clearly a cost.

Several estimates for the environmental cost of wildfires have been published. One study, which excluded carbon sequestration and tourism losses (New Zealand (BERL, 2005)), puts the costs of lost environmental services at $1,500 per hectare, or $37,608 per 100 acres lost. Batker et al. (2013) estimate a loss of environmental benefits worth $39,276 to $289,025 per 100 acres for the Rim Fire in California. In this study, the authors consider many benefits: aesthetics, air purification, biological control, carbon sequestration, habitat and biodiversity, moderation of extreme events, pollination, recreation and tourism value, soil retention, and water regulation. Some of these services, such as tourism and lost property values, are considered elsewhere in this report. The resulting wildfire damage estimates exclude some of these benefits for various land types (eight are considered) and eight other categories of benefits (including food provisions, raw materials, medical resources, soil formation, science and education) due to lack of scientific data and/or a lack of appropriate valuation estimates. Furthermore, while the study focuses on the cost of wildfires in terms of lost benefits, it fails to monetize the benefits of the wildfire (such as reduced risk of severe fires by limiting fuel buildup (Keane and Karau, 2010)),[43] and it assumes that all ecological services are lost from all burned vegetation.[44]

Forests also provide habitat services. Lynch (2004) notes that 47 percent of the habitat of an endangered butterfly was lost in the Hayman fire. Using a conservative annual willingness to pay of $6 per household (values of up to $95 per household have been found in the literature), Lynch (2004) values the loss at $10.85 million annually. In the second year after the fire, the butterfly habitat had failed to regenerate, and trout fishery value decreased due to increased runoff. Given that these habitat services for butterflies and trout may be lost for additional years, the estimated losses could be substantially higher.[45] However, Lynch (2004) fails to consider more than two species of plants and animals. This is problematic because burned areas can provide habitat services to a variety of plant and animal species, and are necessary in many species' lifecycles. Thus, as long as they are within their pre-settlement patterns to which ecosystems are adapted, the net value of habitat services from wildfires may be positive (Hanson, 2014; Keane and Karau, 2010; Smith et al., 2000).

The values of ecosystem and habitat services are included in the SCC through biodiversity valuation. However, SCC models represent damages to these services in a limited way. Specifically, they are often estimated in general terms, unconnected to specific causes of damage (such as wildfires), and used as a proxy for any ecosystem damage that may be caused by climate change. In these instances, models tend to estimate damages that are very small relative to their potential magnitude (and relative to the other impacts explicitly accounted for in the models). See Howard (2014) for more details. Thus, while double-counting of ecosystem and habitat damages is a concern, this is somewhat diminished given the limited way that these damages are currently addressed in IAMs.

HEALTH – Monetizing the health costs of wildfires from climate change often requires three steps. First, one must determine the change in health outcomes (mortality and morbidity) from a wildfire event. This step may include additional sub-steps, such as determining the change in air quality (i.e., the amount of particulate matter released) from a wildfire event and the health outcomes from this change in air quality (Kochi et al, 2010a; Kochi et al., 2010b). Second, one must determine the monetary costs of the resulting mortality and morbidity by multiplying each outcome by its per unit cost; see Kochi et al. (2010a; 2010b) for lists of potential values, including those used by the EPA. Finally, one must measure the estimated change in wildfire events due to climate change, and monetize the health outcomes due solely to climate change. The complexity of this process may partially explain the sparse number of publications on the health costs of wildfires, particularly as they relate to climate change.

Most economic studies focus on the economic cost of smoke exposure, since few individuals in the United States and developed nations die from direct wildfire exposure.[46] Kochi et al. (2010a) calculate the total cost of health effects from forest fire smoke exposure (without including the direct cost of fire exposure), finding a range from $200,000 to $1.2 billion per fire.[47]

The variation in these health costs estimates is the result of multiple factors. First, analysts can choose a number of different estimation strategies, each of which captures different types of health damages and offers different advantages and disadvantages.[48] Studies can include many types of costs: medical expenditure, lost labor, time and monetary costs of defensive behavior to prevent health impacts (i.e., adaptation cost), and the cost of discomfort and lost leisure time (Kochi et al., 2010a).[49] The type of health effects considered greatly depends on the estimation method chosen. Additionally, the method employed to quantify health impacts affects the health cost estimates—most studies use either vital statistics or hospital discharge data. Lastly, costs differ based on the attributes of a specific fire: size, intensity, length, location, and resulting average/peak particulate matter. Given these variations, a meta-analysis is necessary to: (1) determine the features of a fire that affect health via air quality, and (2) clarify methodological differences. Findings can then be utilized to estimate the fire-related health costs of climate change, based on climate model predictions of fire changes.

Several recent economic studies have analyzed the effects of wildfire smoke on health. Richardson et al. (2013) estimate the health costs of morbidity from smoke exposure during the 2009 California Station Fire—a large fire near Los Angeles—using multiple methods. Health costs are estimated between $3 and $17 per symptom-day per person, when accounting for medical expenses and time costs (lost wages and the cost of time at the hospital).[50] When using more extensive approaches, the study finds costs between $87 and $95 per symptom-day (Richardson et al., 2013). Given that many types of health damages are omitted from the lower estimates, the latter two are likely more accurate.

Moeltner et al. (2013) analyze only the treatment costs of respiratory and cardiovascular illnesses that resulted in hospital admissions from a series of fires in California. They calculate treatment costs of between $121 and $467 per 100 acres of vegetation burned.[51] As in the first pair of estimates derived by Richardson, this range of estimates omits many of the costs of exposure to smoke. Using the ratio of preferred estimates (willingness to pay estimates) to underestimates (cost of illness estimates) derived in Richardson et al. (2013), i.e. *87/3=29*,[52] the full range of morbidity costs are between $3,509 and $13,543 per 100 acres, for exposure to wildfire smoke. Both

Active flame front of the Zaca Fire. U.S. Forest Service photo by John Newman.

of these estimates exclude the mortality costs of smoke from wildfires.

Rittmaster et al. (2006) analyze the health damages from one day of smoke exposure in Edmonton, due to the 2001 Chisholm fire. Including mortality and morbidity,[53] the study finds a similar range of $3,489 to $4,186 (though the authors emphasize that wind movement and fire location could increase or decrease these health costs).

Kochi et al. (2012) examine mortality from smoke exposure, finding 133 deaths from a 2003 Southern California wildfire (this fire burned 750,043 acres and 4,856 structures, costing $123,247,243 to suppress). Using the EPA's value of statistical life methodology (of $7.4 million in 2006 dollars), the study identifies the cost of mortality from this one event to be $984 million in $2006 dollars—over $1.1 billion in current dollars. This is equivalent to $1,312,000 per 100 acres. Even small changes in mortality levels can translate to significant economic damages, as these costs far exceed morbidity costs. Together, these studies imply a range of between $121 and $1,325,000 per 100 acres for total wildfire costs.[54]

A major shortcoming in this literature is that analysts often rely on dose-response functions to extrapolate future health outcomes. Analysts often use dose-response functions for urban air pollution, but this method biases wildfire health outcome estimates because urban air pollution features lower particulate matter levels and longer exposure times than air pollution from wildfires. Preliminary research indicates that mortality and morbidity estimates are biased upward and downward, respectively (Kochi et al., 2010a).

NON-USE VALUE – Non-use value is the value that humans place on a good or service, usually the environment, even if they will not consume it. While you may never see a blue whale, a polar bear, or a tiger, you are likely willing to pay some money for their survival. Rodríguez et al. (2013) estimate the costs of the *Cerro Catena* fire, a 200-hectare fire in a national pine forest in Spain. The study finds that 31 percent of damages correspond to non-use value, with a non-use value of €409 per hectare ($23,009 per 100 acres).

The High Park Wildfire on the Arapaho and Roosevelt National Forests and Pawnee National Grassland.

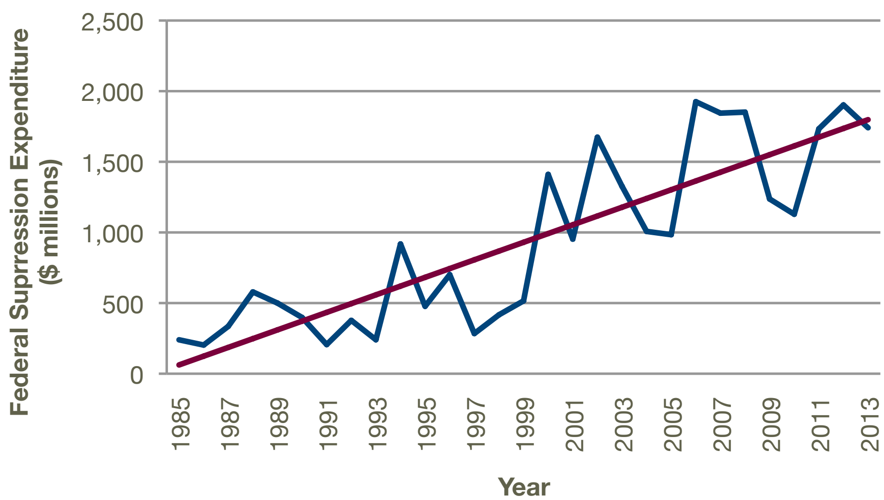
Adaptation Costs

There are four key types of wildfire adaptation: prevention, suppression, aid (evacuation and temporary housing), and rehabilitation and reforestation. The former two methods aim to prevent damages, while the latter two methods attempt to speed up recovery—a faster recovery mitigates damages by making land more productive earlier—and prevent further damages. Even with regeneration efforts, ecosystem dynamics can change due to wildfire, such that a forest may not regenerate and/or ecological services may not return to their pre-fire levels.

Humans may be able to adapt to wildfire increases, but these adaptations, in terms of preventing and fighting wildfires and repairing damages, will come at a cost. In addition to financial costs, adaptation through suppression also includes the cost of increased future fire risks (Taylor et al., 2009; Bekker and Taylor, 2010; Danahy, 2013; Keane and Karau, 2010). The fire management models used by most governments attempt to minimize both costs and net value change. Under these models, the responsible agency minimizes the total cost of wildfires in terms of prevention costs (e.g., installing firebreaks and conducting prescribed burning), suppression costs (e.g., fighting fires), and economic losses. Due to the increasing fire risks discussed above, all three types of costs are likely to rise under climate change (Abt et al., 2008).[55] Additional adaptation costs, such as evacuation and rehabilitation, will also increase.

PREVENTION AND SUPPRESSION – The cost of fire control is likely to rise as climate change makes fires larger, stronger, and more frequent. Suppression costs will likely increase at an increasing rate rather than decrease, due to economies of scale[56] (de Groot et al, 2013). For example, a doubling of fire suppression expenditures in Ontario would be necessary to meet only a 15 percent increase in fire loads (de Groot et al, 2013). Furthermore, a longer fire season with more intense fires will likely increase the number of crown fires, which travel between treetops rather than along the ground. Because these fires are more difficult to control, future fire suppression efforts could be more likely to fail. In fact, the combined effects of cost increases and greater difficulty controlling fires may change fire management practices, as governments may choose to allow more fires to burn (de Groot et al., 2013).

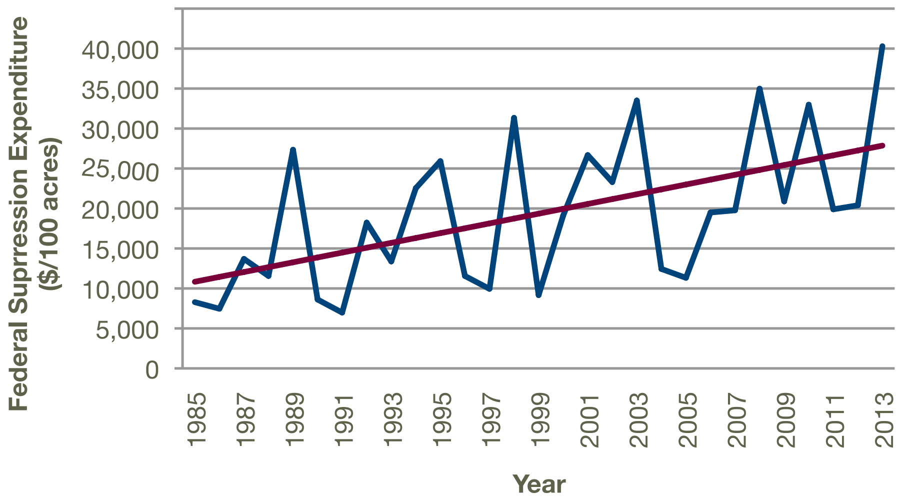
Figure 8. Federal Cost of Wildfire Suppression in the United States Over Time (Blue) and the Corresponding Linear Trend (Red), 1985 to 2013



Source: NIFC (2014a)

In the United States, the Obama administration recently warned of the increasing cost to fight fires, and announced a plan to shift fire suppression funding to the natural disaster fund. This change was prompted by the increasing annual cost to the federal government of preventing and fighting forest fires[57]—this total has increased three-fold since the 1990s, to $3.5 billion annually (using 2002 to 2012 data). Roughly $1.5 billion of this total comes from suppression costs; average suppression costs tripled from the 1990s to the 2000s; see Figure 8.[58] These cost increases are the result of a significant increase in large wildfires[59] and areas burned, as well as other factors that may include increases in intensity of fires and/or increased development in the forest-urban interface.[60] These increases have occurred in all regions of the United States (Abt et al., 2009).[61] In 2007, the federal government spent $1.8 billion to suppress fires in 9.32 million acres of forests. This amounts to a per-100-acre cost of approximately $19,773 for suppression (NIFC, 2014a). For the 27 largest fires, suppression efforts cost $547.5 million for 2,949,798 acres—a cost of $18,561 per 100 acres burned (Brookings Institution, 2008).[62]

Figure 9. Average Federal Cost of Wildfire Suppression per 100 Acres in the United States Over Time (Blue) and the Corresponding Linear Trend (Red), 1985 to 2013



Source: NIFC (2014a)

This increase in federal costs does not account for all fire prevention, fighting, and relief spending. State and local agencies spend considerable sums on fire fighting and prevention—states spend between $1 and $2 billion annually, and local governments spend an unknown amount (Gorte, R., 2013). Lynch (2004) found that the state of Colorado and various Colorado counties (Teller, Park, Jefferson, Douglas Counties) racked up $1 million in unreimbursed costs for a single 138,000-acre fire.[63] State and local government expenditures typically aim to protect private lands instead of national forests and parks.

The Federal Emergency Management Agency (FEMA) is often responsible for relief spending after major wildfire disasters, of which there were 19 between 2000 and 2012. The agency spent an average of $71.2 million per event—representing a threefold increase since the 1990s. There are also additional cost-sharing programs between the federal government and state and local governments, such as the state fire assistance and volunteer fire assistance programs. Federal funding for state and local wildfire protection assistance programs averages $141 million annually. This total also does not include the value of volunteer hours spent fighting wildfires. These volunteer totals can be very large. Ashe et al. (2009) estimate that the millions of volunteer hours spent fighting bushfires in Australia each year have a value of $2 billion Australian dollars ($1.86 billion U.S. dollars). All told, the annual cost of fighting wildfires exceeds the $3.4 billion total mentioned above.

While federal spending on forest fire suppression is currently increasing, these expenditures will likely rise further in the future (both in the United States and worldwide). In addition to increases in area burned, higher probabilities of catastrophic forest fires (which are low-probability, high-cost fires) will likely force increased expenditures.[64] As shown above, these forest fires have high suppression costs per acre. Under climate change, the probabilities of catastrophic fires in a given year will increase (Abt et al., 2008; Keating and John Handmer, 2013; Holmes et al., 2013). Thus, the likelihood of a year with large suppression costs will become increasingly more likely.[65]

Canadian officials fear that increased fire risk due to climate change will make current levels of fire suppression and control fiscally impossible. Assessing the Canadian government's perspective, de Groot et al. (2013) state that, "maintaining current levels of fire protection success will be economically and physically impossible, as well as ecologically undesirable."[66] Thus, Canada may move towards a plan of accommodating some fires as a natural part of the ecology (de Groot et al., 2013).[67]

The evacuation shelter at Norton Air Force Base held over 3,000 evacuees following the fires in Southern California. Photo by Andrea Booher/FEMA News

In South America, adaptation measures might help avoid ecological tipping points, such as the loss of the Amazon rainforest to drought and fire (discussed in the science section of this report). This would require increased fire suppression efforts and expenditures (particularly on managed lands), decreased deforestation, and reforestation initiatives. These measures are costly, but less so than the large-scale loss of the Amazon, which is a possibility (IPCC, 2014). In other words, human adaptation is possible, as predicted by many economists, but it will be especially costly in the case of protecting the Amazon.

EVACUATION – Due to evacuations, few individuals die from forest fires in developed nations. While these evacuations lower the cost of wildfires by preventing deaths, they are expensive. Evacuation, like suppression, is a form of adaptation, and its cost should be included in forest fire damage estimates. While Gould et al. (2012) places the total cost of physical evacuation in Canada at $1.9 million CAD annually ($200 USD per 100 acres burned), Lynch (2004) puts the cost of temporary housing at $556 per 100 acres for the 2002 Hayman fire. However, the physical evacuation costs also underestimate the total cost of evacuation, which includes the value of time lost and the mental anguish experienced by the evacuees.[68] This latter cost is likely high, and currently not included in damage estimates. Furthermore, after evacuations, governments must undertake other disaster relief expenditures.

HOME AND COMMUNITY BUILDING – Homeowners and communities can take measures to adapt to higher fire risks. Households can invest in fire-resistant building materials, fireproof their homes, and increase the vegetation-free area around their homes. Such steps can be encouraged though building and fire codes (California has already taken these steps). During fires, households can also minimize their exposure to smoke by reducing outdoor activities, wearing masks, and using air filters; these choices can be aided by improved monitoring of air quality. Communities can also develop evacuation routes and warning systems. Additionally, communities can encourage less development in the forest-urban interface through local zoning and development policies. Higher insurance premiums can also encourage adaption and prevent future risky development. These changes not only reduce the cost of fires to homeowners and communities by reducing potential damages, but they also reduce the risk of home fires spreading to forested areas (Cleetus and Mulik, 2014)[69]

REHABILITATION AND RESTORATION – Following wildfires, governments sometimes invest in site rehabilitation and restoration. Rehabilitation consists of the emergency planting of new trees and other measures to protect affected lands from future damages (human health and property and degradation of natural resources and

Sagebrush planting rehabilitation, Photo by U.S. Fish and Wildlife Service

environmental services) while vegetation returns. In the United States, government rehabilitation includes expenditures up to three years following a wildfire event. Non-emergency expenditures on site restoration three years or more after a wildfire event qualify as restoration, which often consists of the continuation of rehabilitation activities. In the United States, this distinction between rehabilitation and restoration reflects the different agencies that are responsible for funding and oversight (Dale, 2009; Robichaud, 2009).[70] From this point forward we will utilize the terms interchangeably.

Proponents of rehabilitation argue that these efforts potentially prevent or mitigate future damages from erosion, flooding, invasive species, runoff, and sedimentation (Dale, 2009).[71] Rehabilitation costs can include reforestation, reseeding and re-mulching, invasive species removal, the erection of erosion- and flood-control barriers, and fuel reduction (removing dead debris, thinning trees, removing underbrush, and prescribed burns). It can be particularly expensive to rehabilitate cultural sites, such as the Puye Cliff Dwellings, which were damaged in the Cerro Grande fire (NM 2000).

Rehabilitation costs can vary substantially by site, and they can be significant in some cases. Dale (2009) finds that they range from 23 percent to 872 percent of suppression costs in six examples of catastrophic fires, with an average close to 350 percent of suppression costs.[72] These high costs likely stem from the large scale of fires studied and the long-term nature of rehabilitation, which requires a series of payments over time; suppression costs are often one-time expenditures. In the Dale (2009) sample, rehabilitation costs ranged from $12,319 to $427,675 per 100 acres burned, and averaged $90,979. Lynch (2004) finds much lower rehabilitation costs of $13,400 per 100 acres in the Buffalo Creek Fire (over one year) and $34,791 per 100 acres for the Hayman fire (over two years). Given that it is economically efficient to let natural regeneration processes function if rehabilitation costs are too high (Robichaud, 2009) and that these estimates focus on catastrophic fires that are unlikely to be representative, the lower boundary of these cost estimates may be more representative of the average cost of forest rehabilitation.

In many cases, rehabilitation efforts focus on the protection of human life and property (Robichaud, 2009). While this may be economically efficient, it may come at the cost of ecosystem restoration. For example, Kruse et al. (2004) find that the use of grass seed and mulch to reduce post-fire erosion may introduce non-native species. Similarly, significant post-fire timber recovery is damaging to ecosystems, and is unlikely to be beneficial from a rehabilitation standpoint (Lindenmeyer and Noss, 2006; Beschta et al., 2004).[73] Finally, building structures around streams to prevent erosion and capture sediment may negatively affect aquatic habitats (Beschta et al., 2004). Thus, some rehabilitation practices may be counter to ecological health goals. However, demand for rehabilitation and restoration activities is increasing with fire activity and the expansion of the wildland-urban interface (Robichaud, 2009). Unless perceptions change significantly in the future, rehabilitation, like fire suppression, is likely to be part of future attempts to mitigate the cost of wildfire increases due to climate change.

Total Costs of Forest Fires

There have been few comprehensive attempts to calculate the total costs of forest fires. Lynch et al. (2004) analyze a sample of four Colorado fires between 1996 and 2003, finding costs of $95,391 per 100 acres (after one year) and $166,752 per 100 acres (after two years). Suppression costs accounted for 18 percent of these damages. However, these estimates do not include many of the medium-run and long-run (after two years) costs of the categories discussed earlier: non-market costs (including smoke health costs), rehabilitation costs, and ecosystem damages.

Rodríguez et al. (2013) estimate the costs of a 200-hectare fire in a national pine forest in Spain (the *Cerro Catena* fire), finding damages of €262,688 (€1,257 per hectare, with a dollar value of $354,629).[74] Of this total, 37 percent was attributed to market value, 32 percent to non-market value, and the remaining 31 percent to non-use value. Adaptation costs (suppression and prevention) and reforestation costs are not included in this estimate.[75]

In analyzing a fire at a Cuban pine plantation with a 25-year-old stand, Rodríguez and Rodríguez (2013) estimate the total cost (market and adaptation) to be $40,055 per hectare ($16,210 per acre) using the Cuban government's method. While this study accounted for direct losses, including reforestation, harvested timber, standing timber, non-timber forest product, suppressions, and protection work, it failed to account for non-market costs (health and environment). Of these direct losses, protection work was the most significant (60 percent) and suppression costs (0.3 percent) the least. Indirect economic costs were estimated to be 5.59 times larger than direct economic costs.

Butry et al. (2001) calculate costs of $600 million to $800 million from the 1998 Florida fires, accounting for timber, property loss, prevention, suppression, tourism, trade, and health. This is equivalent to $120,000 to $160,000 per 100 acres, though this total excludes the value of environmental services. Suppression and relief expenditures account for 12.5 to 17 percent of total costs.

Finally, Rahn (2009) found that the suppression costs of the 2003 San Diego Fire were $43 million, and the long-term costs of the fire were $2.45 billion (this accounts for infrastructure losses, water quality, habitat, erosion and flood control, watershed restoration, property loss, tourism, economic activity and employment, recreation, and health).[76] Given the size of the fire, the total fire cost was $650,000 per 100 acres, and suppression costs accounted for 2 percent of the total.

Two estimates drawn from the grey literature[77] provide ranges for the ratio of total wildfire costs to suppression costs in the United States. Zybach et al. (2009) estimated that the total costs of forest fires (including suppression, property loss, public health, vegetation, wildlife, water pollution, air pollution, soil erosion and productivity loss, recreation and aesthetics, energy, and heritage) are approximately 10 to 50 times the total suppression costs of those fires.[78] While the suppression costs of the 2008 California wildfires were $1 billion, total costs were closer to $10 to $30 billion for just one year.[79] Long-term costs from these fires are potentially much higher (Zybach et al., 2009). Dale et al. (2009) find a similar result when analyzing six fires, with the ratio of suppression cost to total cost between 2 and 30. These ranges are consistent with those drawn from the studies discussed previously.

Based on the available research, a 10 to 50:1 ratio of total costs to suppression costs seems defensible. Using our own results above, we construct a lower, middle (i.e., best guess), and upper-bound economic estimate and find a ratio of approximately 4 to 75:1, with a best guess of 20:1 (see Table 1). The overlap indicates that these ratios seem relatively valid. Table 2 details the studies we used to create our ranges for each type of damage.

Table 1. Range of Forest Fire Costs (per 100 Acres)

Damage Type	Low Estimate	Central Estimate ("Best Guess")	High Estimate
Timber	-$16,432	$30,000	$65,600
Other market goods	$0	$10,400	$59,443
Property loss	$28,100	$42,150	$56,200
Tourism	$0	$12,200	$338,000
Indirect costs (taxes and property values)	$2,178	$160,000	$1,600,000
Ecosystem Services	$0	$38,000	$250,000
Health	$0	$3,500	$1,325,000
Non-use	$0	$11,505	$23,009
Evacuation	$0	$556	$756
Suppression	$16,432	$19,300	$52,500
Prevention	$21,909	$25,733	$70,000
Rehabilitation	$13,000	$34,791	$90,979
Total Costs	$65,187	$388,135	$3,931,487
Suppression %	25.2%	5.0%	1.3%
Total: Suppression	4	20	75

Table 2. Sources and Assumptions for Estimated Range of Forest Fire Costs (per 100 Acres)*

Damage Type	Low Estimate	Central Estimate ("Best Guess")	High Estimate
Timber	Prestemon and Holmes (2008) We assume a 60% salvage rate. This also naively assumes that there are no ecological costs from post-fire timber recovery.	Reeves and Stringer (2011) We assume only a change in stand structure.	Buntry et al. (2001) We utilize the lower-bound timber loss estimate.
Other market goods	Assuming no other market losses, we set this value equal to zero.	Given the overly high estimate of other market damages in Ledbetter (2011), and our lack of a good alternative, we assume that other market good losses equal the value of lost timber due to tree mortality (Reeves and Stringer, 2011).	Ledbetter (2011)
Property loss	Lynch (2004) We utilize the estimate for insured property loss.	Lynch (2004) We adjust upwards the damage estimate for insured property loss by 50% to account for uninsured property loss.	Lynch (2004) We adjust upwards the damage estimate for insured property loss by 100% to account for uninsured property loss.
Tourism	Assuming no tourism loss, we set this value equal to zero.	Thapa et al. (2013)	Lynch (2004)
Indirect costs (taxes and property values)	Lynch (2004)	Ledbetter (2011) We reduce the estimate from Ledbetter by 90% since the estimate is likely an outlier. The resulting estimate is approximately 10 times the magnitude of Lynch (2004) and 10 times smaller than Ledbetter (2011).	Ledbetter (2011)
Ecosystem Services	Based on the argument that wildfires may actually be beneficial to ecosystems, we assume ecosystem damages are zero.	BERL (2005) and the lower estimate of Batker et al. (2013)	High estimate from Batker et al. (2013)
Health	Assuming no health impacts, we set this value equal to zero.	We assume that the lower estimate from Rittmaster et al. (2006) holds, which is equivalent to the lower-bound estimate from Moeltner et al. (2013) that we calculate.	Kochi et al. (2012)

Damage Type	Low Estimate	Central Estimate ("Best Guess")	High Estimate
Non-use	Assuming no non-use value exists, we set this value equal to zero.	Rodríguez et al. (2013) We assume that the non-use value is 50% the size of Rodríguez et al. (2013)	Rodríguez et al. (2013)
Evacuation	Assuming no evacuations, we set this value equal to zero.	Lynch (2004)	Gould et al. (2012) and Lynch (2004) We assume both the cost of physical evacuation and temporary housing.
Suppression	Kochi et al. (2012)	Blazer et al. (2007) In 2007, the federal government spent $1.8 billion to suppress fires in 9.32 million acres of forests. This comes out to a per-100-acre cost of approximately $19,300 for suppression.	Lynch (2004)
Prevention	We calculate the prevention expenditure using the federal ratio of prevention expenditure to suppression expenditure. We assume that of the $3.5 billion federal budget to fight wildfires, $1.5 billion was spent on suppression and the remainder on prevention.	We calculate the prevention expenditure using the federal ratio of prevention expenditure to suppression expenditure. We assume that of the $3.5 billion federal budget to fight wildfires, $1.5 billion was spent on suppression and the remainder on prevention.	We calculate the prevention expenditure using the federal ratio of prevention expenditure to suppression expenditure. We assume that of the $3.5 billion federal budget to fight wildfires, $1.5 billion was spent on suppression and the remainder on prevention.
Rehabilitation	Lynch (2004) and Dale (2009) We assume that the rehabilitation cost is approximately equal to the minimum rehabilitation cost in both studies.	Lynch (2004) We assume the rehabilitation cost from the Hayman fire (over two years).	Dale (2009) We assume that average rehabilitation cost.

* *As can be seen in this table, some estimates that appear to be outliers are adjusted using author discretion. These adjustments reflect attempts to best represent the range of possible monetary impacts, taking into account the existing literature. As consequence, the range of estimates is unsurprisingly wider than that of Dale (2009) and Zybach et al. (2009). A more detailed discussion of our assumptions and justifications can be found in the relevant sub-sections of this paper.*

A PRELIMINARY ESTIMATE OF WILDFIRE COSTS FROM CLIMATE CHANGE

Based on the data discussed above, we estimate the cost of wildfire increases from climate change in 2050 and 2100 for the United States and the world. First, we estimate the current cost of wildfires by multiplying the ratio of wildfire suppression costs to total wildfire costs by total suppression costs. Second, to estimate the monetary cost of wildfire increases due to climate change, we multiply the current cost of wildfires by the predicted percentage increase in wildfires due to climate change in the respective year. Finally, we divide this amount by the corresponding GDP prediction for the A2 climate scenario[80] to find the cost of wildfires due to climate change, as a percentage of GDP.

Calculation for the United States

Using the Zybach et al. (2009) estimate that the total costs of wildfires are 10 times to 50 times the suppression costs, we can make a rough calculation of the total cost of wildfires to the United States due to climate change.[81] Based on Table 1, we assume that the distribution of these costs is right-skewed and that the central estimate (i.e., the most likely outcome) is 20 times the suppression cost. As stated earlier, total federal spending on fire suppression is approximately $1.5 billion per year. However, given that this amount excludes local and state expenditures, we will assume that the U.S. expenditure for forest fire suppression is between $2 and $2.5 billion annually.[82] Using the ratios supplied by Zybach et al. (2009), we estimate that the total cost of U.S. forest fires is between $20 billion and $125 billion annually, with a central estimate of $45 billion.

Following Liu et al. (2014), we assume a 50 percent increase in the area burned in the United States by 2050. Similarly, Spracklen et al. (2009)[83] and Yue et al. (2013)[84] predict 54 and 60 percent increases, respectively, in area burned in the Western United States by 2050 due solely to climate change (i.e., due to predicted changes in meteorological data under climate change scenarios).[85] Using this prediction, we estimate that climate change-induced wildfires will cost the United States between $10 billion and $62.5 billion annually by 2050 (with a central estimate of $22.5 billion), assuming a linear damage function with respect to area burned.[86] Given that the United States is projected to have a GDP of $17.5 trillion in 2050,[87] we predict that damages from wildfires will be equivalent to 0.05 to 0.36 percent of U.S. GDP with the most likely outcome equaling 0.13 percent.

Following De Groot et al. (2013),[88] we predict that area burned in North America will increase to between 2 and 5.5 times the current level by 2100. Similarly, Flannigan et al. (2004)[89] predict that area burned will increase by 98 percent on average in Canada for a three-fold increase in atmospheric carbon dioxide concentrations by the end of the century. Additionally, Balshi et al. (2009)[90] predict a 3.5- to 5.7-fold increase in area burned of North American boreal forests under the IPCC B2 and A2 climate scenarios, respectively. For the end of the century, our estimated range of damages increases to 0.05 to 1.31 percent of GDP, with an increase of 0.29 percent as the most likely outcome. This assumes that wildfires and climate change in general do not affect the growth of the U.S. economy.

These estimates should be interpreted cautiously for a number of reasons. As temperatures rise due to climate change, total climate damages are generally assumed to rise at increasing rate. If this is also true for damage from wildfires, the linear damage function for area burned assumed above represents a lower-bound estimate.

Table 3. Estimated Cost of Wildfires Due to Climate Change in the United States and Globally for 2050 and 2100

Ratio of Total Wildfire Costs to Suppression Costs	Suppression Cost ($ billion)	Total Cost ($ billion)	Increase in Wildfires in 2050 (%)	Cost of Wildfire due to Climate Change in 2050 ($ billion)	Cost of Wildfire due to Climate Change in 2050 (% GDP)	Increase in Wildfires in 2100 (%)	Cost of Wildfire due to Climate Change in 2100 ($ billion)	Cost of Wildfire due to Climate Change in 2100 (% GDP)
United States								
10	$2	$20	50%	$10.0	0.06%	100.00%	$20	0.05%
20	$2.25	$45	50%	$22.5	0.13%	275.00%	$124	0.29%
50	$2.50	$125	50%	$62.5	0.36%	450.00%	$563	1.31%
World*								
10	$200	$2,000	50%	$1,000.0	1.19%	100.00%	$2,000	0.82%
20	$225	$4,500	50%	$2,250.0	2.69%	275.00%	$12,375	5.05%
50	$250	$12,500	50%	$6,250.0	7.47%	450.00%	$56,250	22.96%

* *These estimates assume that the global costs of wildfires are 100 times the costs to the United States, based on the finding (cited earlier) that global acreage burned is 100 times greater than acreage burned in the United States. (An alternate calculation method is discussed in the early part of this report's "Calculation for the World" sub-section.)*

This shortcoming is further amplified by increased future willingness to pay for non-market services and the avoidance of climate change-induced wildfire impacts, as environmental services become relatively scarcer relative to manufactured goods and services (Sterner and Persson, 2008; Hoel and Sterner, 2007). However, temperature increases will eventually result in vegetation changes, which are currently excluded from the current statistical models used to predict wildfires—these changes have the potential to reduce the risk of wildfire (NRC, 2011).[91]

Additionally, many of the cost estimates utilized to develop the ratio of suppression to total wildfire costs were based on forest fires, though grassland and shrub fires, which may have lower relative social costs, account for a significant share of area burned.[92] Moreover, we assume that society's current ability to prevent and fight wildfires will not improve, biasing these estimates upwards. Finally, the predictions for the increase of burned area for 2100 were drawn from studies focusing on boreal forests of Canada, and may not be representative of the United States as a whole. Thus, our calculations are only meant to illustrate that U.S. wildfire damage due to climate change could be economically significant.

Our calculations depend on a number of assumptions, and we have tried to make our logic clear so others can easily explore the effect of changing any of the assumptions that underlie these estimates. For example, if we are uncertain about the indirect costs of $160,000 per 100 acres used for the central estimate, one can utilize an alternative assumption, such as $2,178 from Lynch (2004). This puts the ratio of total costs to suppression costs at 12:1 instead of 20:1 for the central estimate. Using the ratio of 12:1, the cost of wildfires due to climate change in 2050 is $13.5 billion (0.08 percent of GDP) and $74 billion (0.17 percent of GDP) in 2100. We invite readers to explore the effects of a variety of assumptions.

Calculation for the World

We can extend this domestic calculation into a global estimate of wildfire damages due to climate change, again using rough estimates. If we make the assumption that wildfire costs as a percentage of GDP are the same irrespective of region, we can use the U.S. range of damage estimates globally: 0.05 to 0.36 percent (with a central estimate of 0.13 percent) of world GDP in 2050 and 0.05 to 1.31 percent (with a central estimate of 0.29 percent) of world GDP in 2100. Using global GDP predictions for 2050,[93] we estimate potential global damages from climate change-induced wildfires in 2050 of $50 to $300 billion annually, with a central estimate of $100 billion.

These global estimates should also be interpreted cautiously. In addition to the reasons given with respect to the U.S. damage estimates, these global damage estimates imply wildfire damages in developing countries that are potentially too high. Willingness to pay to prevent wildfires is likely much lower in developing nations due to lower incomes.[94] Significant fires may also be less common due to a historical lack of aggressive fire suppression in developing nations. It is also important to note that many forest fires in developing countries are intentional and therefore unaffected by climate change. However, costs may also be higher in developing countries than in the United States, as most of these countries have less capacity to adapt and a greater number of individuals living within the forest-urban interface. Thus, theoretically it is unclear whether the failure to account for spatial heterogeneity biases the estimates upwards or downwards.

These global estimates also fail to account for existing differences in fire risk between North America and the rest of the world. In particular, the United States only accounts for 1 percent of wildfires globally (see earlier). However, if we make this proportional adjustment to the calculations above, we get global damage estimates that appear to be extremely high; see Table 3. This is likely the result of the differences discussed earlier in this and the previous sub-section and differences in vegetation. Specifically, higher proportions of grassland and savannah fires in regions outside of North America (Flannigan et al., 2013) imply lower predicted cost increases due to the lower social cost of grassland fires compared to forest fires (see earlier discussion). Therefore, while our range of United States damage estimates, for which much of the data are available, are reliable, more sophisticated means of benefit-cost transfer are necessary to develop accurate global damage estimates for wildfires.

Inclusion of Wildfire Damages in Integrated Assessment Models

Given our range of fire damage estimates, additional research is necessary to more accurately predict future wildfire costs attributable to climate change (particularly for non-U.S. regions), so that wildfires can be precisely accounted for in IAMs. However, in integrating future wildfire damages into the social cost of carbon, analysts should be careful to avoid overlap with current damage estimates. In particular, some non-market damages, such as biodiversity and ecosystem values, may already be partially captured by IAMs. Additionally, the value of forests' carbon sequestration services may also be partially or fully accounted for by IAMs, through the climate component of the models. Thus, some of the values included in this discussion may require downward adjustments before they are used in calibrating IAM damage functions.

CONCLUSION

This report highlights an omitted damage from the SCC—the increase in wildfire risk due to climate change. It lays out the science and economics of wildfires in an attempt to assess the potential magnitude of their economic effects. Wildfires affect forests and other vegetation types (including grasslands used for grazing) as well as human health and the environment. Additionally, wildfires can result in feedback effects that speed up the rate of climate change, and could lead to an environmental tipping point in the Amazon that could result in the rapid loss of this irreplaceable resource.

Given these negative effects, the magnitude of forest fires (2.36 percent of the world's land area burns annually), and the potential for significant increases in wildfire risk due to climate change, the science appears to indicate that wildfire damages should be given more attention by the developers of integrated assessment models.

The economic literature is less developed than the scientific literature with respect to understanding increased wildfire costs due to climate change. There is a fairly significant body of research on market damages (timber, non-timber goods, tourism, and indirect costs), non-market damages (health, environmental, and non-use), and adaptation costs (prevention, suppression, evacuation, and rehabilitation) from wildfires to date, but no estimates for future wildfire damages as climate change advances. The existing literature on past wildfires indicates that the total costs of fires are likely between 10 to 50 times greater than the suppression costs for those fires.

Given the U.S. federal expenditure of $1.5 billion annually on suppression, and this estimated range of non-suppression costs, we make a basic calculation of the potential range of U.S. and global damages from climate change-driven increases in annual acres burned by 2050 and 2100. The potential damage is high enough to indicate that future research on the economics of wildfires, specifically with respect to climate change, is important.

Much of the science necessary to produce economic damage estimates for increases in wildfire risk is already available. Some additional information is needed to estimate the distributions of wildfire size and intensity for different regions, and how these distributions are likely to be affected by climate change. Additionally, the dose-response function for the health effects of wildfires should be estimated. Furthermore, understanding how the various attributes of a fire, such as its intensity and size, affect forests, ecosystems, human health, and the human ability to adapt, is critical in order to make accurate economic damage predictions. In order to achieve this goal, scientists should ideally work with economists to ensure that their scientific output corresponds to the needs of economists.

Currently, there is no economic estimate of the increase in wildfire costs due to climate change. This is likely due to the many costs that arise from wildfires and the heterogeneity of fires in terms of fuel source (dead debris, grass and underbrush, and type of tree), size and intensity, location with respect to humans and economic activity, and the ecosystems and habitats in a fire's path. The wildfire damage literature focuses largely on case studies of particular fires in the United States and Europe, and few studies have tried to generalize results. To generalize the results to a point that they can be utilized in climate damage estimates, it is necessary to estimate wildfire damages in developing nations and other geographical locations. Further, an up-to-date meta-analysis of wildfire damage would be valuable—the results of such a study could be employed for the purposes of benefit transfer.[95] Using benefit-transfer methods and spatially explicit data, more accurate estimates of regional and global damages due to increased wildfire risks from climate change might be estimated.

The 2010 and 2013 Interagency Working Groups used the most up-to-date models to estimate the U.S. social cost of carbon. However, the models underlying these estimates omit many significant damages, including the effect of climate change on wildfires. While the developers of integrated assessment models must be careful to avoid the double-counting of damages when including wildfire impacts in their models, it is important that they capture wildfire damages in SCC estimates. This report indicates that their omission may result in a significant downward bias. Economists and scientists must come together to face climate change by expanding and improving climate damage estimates, including the development of an estimate of the cost of increased fire risk due to climate change.

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NOTES

1 The precise, central value for a ton of carbon dioxide emitted in 2015 is $37, in 2007 USD (http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf).

2 Other subcategories include bush fires, grassland fires, peat fires, shrub land fires, and vegetation fires.

3 According to Sánchez et al. (2013), 8.7 million acres burn annually within the United States. This differs from Bjerga (2014) who cites 7.7 million acres burned annually within the United States in the last decade (Bjerga, 2014). Using data from NIFC (2014), we calculate that 6.99 million acres burned annually within the United States between 2003 and 2013.

4 A 1 percent ratio of global to U.S. acreage burn is confirmed by Giglio et al. (2006).

5 We should be careful in interpreting the upward trend in area burned within the United States over the last three decades, as displayed in Figure 1. First, a variety of factors other than climate are also responsible for this upward trend, including the long-run effects of aggressive fire suppression and increased human habitation within fire prone areas (Bump, 2014). Thus, the increase in fire activity in Figure 1 should not be attributed solely to climate. Second, because this increase is relative to its base—in this case 1985—the trend in Figure 1 should not be interpreted as an increase relative to other reference periods—particularly, the pre-industrial period (Banse, 2014). Specifically, this upward trend started in the late 1970s to early 1980s after a downward trend the prior two decades (see Figure 2). The area currently burned in the United States may be less than or equal to the amount burned at the pre-industrial period. This possibility is emphasized by Figure 1 in Littell et al., (2009) for the Western United States. However, given that less undeveloped area is available to burn now and there is greater expenditure on fire suppression in the current period than in the pre-industrial period, this result should not be surprising. The extent of wildfire in relative terms (i.e. as a percentage of flammable areas) may be more severe today.

Climate change likely has increased the area burned within the United States. The significant upward trends in area burned began in the 1970s (Littell et al., 2009) despite the continued downward trend in undeveloped area and the upward trend in suppression expenditures. While aggressive suppression may have partially induced the U-shape trend in area burned over time displayed in Figure 1b, Littell et al. (2009) demonstrates that climate is still an important determinant of area burned over the last century (1916–2003) and since the late 1970s (1977–2003). In particular, climate variables seem to better explain area burned during the period of significant global warming over the last three and a half decades (Littell et al., 2009). Littell et al. (2009) states that "roughly 39% (1916–2003) to 64% (1977–2003) of the fire area burned can be related directly to climate."

6 The IPCC WGII (2014) specifically states that "It is possible now not only to detect and attribute to anthropogenic climate change some impacts such as changes in extreme precipitation, snowmelt and snowpack, but also to examine trends showing increased insect outbreaks, wildfire events and coastal flooding. These latter trends have been shown to be sensitive to climate, but, like the local climate patterns that cause them, have not yet been positively attributed to anthropogenic climate change." In other words, wildfire activity will likely increase, but, as of yet, has not been definitively linked to increases in CO_2 concentrations in the atmosphere from the burning of fossil fuels. Additionally, many factors affect wildfires other than climate change, including fire suppression, such that the effects of climate change on wildfires depends greatly on how humans react to these changes. These two qualifications should be kept in mind when reading this report.

7 The IPCC (2014) argues that natural and human systems have shown particular vulnerability to current climate variability and extreme events, such as wildfires. As a consequence, the effect of climate change on the frequency and/or intensity of extreme events, including large fires, will be more costly in its effect on the economy and the environment than changes in average climate variables.

8 The IPCC (2014) states that "The effects of changes in the frequency or intensity of climate-related extreme events, such as floods, cyclones, heat weaves, exceptionally large fires on ecosystem change are probably equal to or greater than shifts in the mean values of climate variables. These effects are insufficiently studied, and in particular, are seldom adequately represented in Earth system models."

9 This is relative to the current time period, and not the pre-industrial time period. See footnote 5.

[10] Fire intensity is the amount of energy released during a fire. It is measured using a variety of metrics, including "reaction intensity, fireline intensity, temperature, heating duration and radiant energy" (Keeley, 2009). See Keeley (2009) for a more in-depth discussion of wildfire intensity.

[11] IPCC (2014) states that "changes in the fire regime have in some cases been attributed to climate change (Westerling *et al.*, 2006; Littell *et al.*, 2009; Turetsky, 2011; Westerling *et al.*, 2011; Moritz *et al.*, 2012)."

[12] Some scientists disagree with this conclusion. For example, Black et al., (2013) find that current evidence indicates that, generally, increases in mountain pine and spruce beetles do not increase fire risks (particular active crown fires) in lodgepole pine and spruce forests in the Rocky Mountains of the Central U.S. However, other scientists disagree with their methods and dispute their conclusions (Page et al., 2014).

[13] Higher temperatures and other climatic changes will alter the geographic range of suitable habitat for many plant species. As a consequence, plants will either shift their location over time to remain within this range or perish. These shifts occur through increased tree mortality, which increases the volume of dead wood, and thus, fire risks (IPCC, 2014; Brown et al., 2014). However, these vegetation shifts have a variety of other effects, such as changing the flammability of the vegetation, which may act to exacerbate or counteract the increased fire risk from dead vegetation.

[14] These practices make crown fires more likely, which are much more likely to lead to tree mortality (McKelvey et al., 1996).

[15] Specifically, "In savannas, faster growth rates under higher CO_2 can allow woody plants to grow tall enough between successive fires to escape the flames...[Furthermore], the increased growth rate of C3 photosynthetic system trees relative to C4 grasses under...rising CO_2 could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses (IPCC, 2014, Chapter 4)."

[16] Different factors drive the wildfires in the Western United States depending on the specific region. For example, researchers characterize the wetter Rocky Mountain areas as *temperature limited* because of the general finding that these wetter areas experience increased fire risks when maximum temperatures exceed 23 degrees Celsius. However, California is categorized as *precipitation limited* because of the increased risk of fire from above average precipitation in the previous year (NRC, 2011).

[17] Similarly, Spracklen et al. (2009) predict a 54% increase in area burned by 2050 for the Western United States.

[18] A large wildfire is often defined as wildfire consisting of 1,000 acres or more (Cleetus and Mulik, 2014). From the anthropomorphic view, these large wildfires are often characterized as catastrophic. From an ecological standpoint, large wildfires may be necessary to return many ecosystems back to a sustainable ecological condition characterized by a more stable fire regime.

[19] Logging increases fire risks by: increasing the portion of fire-intolerant species (e.g., species that are more likely to burn and die from wildfires); exposing the forest to wind and sun; increasing the number of ignition sources, including flammable materials like slash piles; and introducing pests, pathogens, and invasive species (Gorte et al., 2013; IPCC, 2014; Padmanaba and Sheil, 2014).

[20] Scientists increasingly view smaller, more regularly occurring wildfires as an essential part of nature and ecosystems; some plants and animals require fires for survival. Furthermore, fire suppression increases the likelihood of large, intense fires that can wreak havoc on ecosystems, creating permanent damage.

[21] Much of the health literature relating to wildfires relies on dose-response functions for urban air pollution to determine the health effects of wildfires. As a consequence, some of the listed health effects above may be overstated, while others are understated. Reviewing this literature, Kochi et al. (2010a) concludes that wildfire has a less severe effect on mortality and cardiovascular-related morbidity as compared to the urban pollution studies, but has a more significant effect on respiratory-related morbidity. However, these results are preliminary, and more research is necessary.

[22] In Australia and New Zealand, increased fire risks threaten human health directly and via decreased air quality, which will affect individuals with asthma (IPCC, 2014). The 2009 Australian bushfire season resulted in 173 direct deaths from fire, while smoke also increased mortality and morbidity (IPCC, 2014).

[23] Specifically, the IPCC (2014, Chapter 4) states that "More severe burning consumes soil organic matter to greater depth, often to mineral soil, providing conditions that favour recruitment of deciduous species that in some regions of the North American boreal forest replace what was previously evergreen conifer forest."

[24] Black carbon can also have some atmospheric benefits. It has a stabilizing effect on the atmosphere at low and medium levels (USDA, 2013).

[25] Specifically, Chakrabarty et al., (2014) state that they "estimate that SAs contribute, per unit optical depth, up to 35% less atmospheric warming than freshly-emitted (Df ≈ 1.8) aggregates, and ≈90% more warming than the volume-equivalent spherical soot particles simulated in climate models."

[26] Non-market goods are goods and services that human welfare depends on, but which are not bought and sold in the marketplace. Non-use value, which is a subset of non-market damages, is the value that humans place on something, usually the environment, even if they will not consume it. While you may never see a blue whale, a polar bear, or a tiger, you are likely willing to pay some money for their survival. This is non-use value.

[27] The marginal cost of wildfire is the cost of an additional acre burned, while the average cost of wildfire is the mean cost of current wildfires. Given that climate change is expected to increase the area burned from wildfires with respect to its current levels, marginal cost is the more appropriate estimate of wildfire costs due to climate change. Generally in climate economics, it is assumed that damages are increasing in the unit of interest, e.g., global average surface temperature and sea level rise. If this is true for wildfires, i.e., that the cost of wildfire damage increases in area burned, using the average cost of wildfire to approximate the marginal cost of wildfire is likely to underestimate the cost of additional wildfires from climate change.

[28] Most of the studies on the effects of forest fires on timber production focus on the U.S. market.

[29] This was equivalent to "roughly 7.1 million m3 of [publicly owned] timber–primarily Douglas fir, ponderosa pine, and western larch" – burning" (Prestemon et al., 2006).

[30] In addition to analyzing the welfare effects on producers and consumers separately, the authors also analyze the effects of the wildfire on two groups of producers: owners of damaged timber and owners of undamaged timber. Without any salvage effort, owners of damaged timber lose from a fire (assuming optimal management), while owners of undamaged timber benefit from the resulting rise in the price of timber. Of course, a significant fire is required to significantly raise price; otherwise, the owners of undamaged timber do not benefit or lose.

[31] Producer and consumer surplus are terms in microeconomic theory that refer to gains from trade and production to each entity. Producer surplus can be thought of as total revenue minus total cost, or profit. Consumer surplus refers to how much consumers would have been willing to pay above what they actually paid, as measured by a demand curve.

[32] While this result initially seems counterintuitive when thinking of private timber companies, which manage their forests to maximize profits, it is sensible given the public ownership of most U.S. timberland. Given that the government manages public forests with other objectives in mind than timber profits, it is easy to see that a fire may increase timber profits by making more timber available. Specifically, if the government manages the forests to equate the marginal benefit (i.e., the price of timber) and the marginal social cost of logging (which includes lost environmental, health, and recreational benefits from forests in addition to the production cost of timber), an increase in the supply of timber from a fire will increase timber company profits given that the marginal social cost of logging is greater than the marginal cost of logging.

[33] Specifically, Reeves and Stringer (2011) state "wildfires can also change the species composition and overall density and structure of woodlands. Structural changes include killing whole trees and changing regeneration. Repeated fire, if intense enough, can also lead to a continued 'resetting' of tree ages in a stand, resulting in a reduction in overall timber volume and value."

[34] Lindenmeyer and Noss (2006) group these damages in three broad types: "(1) altered stand structural complexity; (2) altered ecosystem processes and functions; and (3) altered populations of species and community composition."

[35] In Australia, 83 homes are lost annually to bushfire (Ashe et al., 2009). However, as many of the trends discussed earlier hold in Australia, this number is likely to increase in the future as more individuals move into the urban-wildlife interface.

[36] Cleetus and Mulik (2014, p. 44) cite insurance losses for the ten most expensive fires in Colorado and California. The costs range from $218 million to approximately $2.6 billion, which is equivalent to a range of $144 thousand per 100 acres to $170 million per 100 acres. While these represent the most expensive fires and not the average property loss from fires, it does indicate the potential catastrophic nature of wildfires in more densely populated areas.

[37] Fires increase flood and mudslide incidences by (1) removing protective and water absorbing vegetation, and (2) increasing the amount of debris in stream beds (Cleetus and Mulik, 2014).

[38] There is no fear of double-counting flash flood damages in the SCC because inland flooding is also omitted from the SCC.

[39] In 1998, approximately 500,000 acres burned in Florida, resulting in a damage of $12,200 per 100 acres.

[40] While most studies have found that fires decrease the number of hikers and bikers to an area and that these services eventually return as the forest recuperates (Sánchez et al., 2013), Englin et al. (2008) finds that forest fires increase trips in the medium run and decrease trips in the long run.

[41] In some ecosystems, some level of high-intensity fires may be natural (Lydersen et al., 2014). Thus, in terms of climate change, the costs of catastrophic (large-scale, high-intensity) fires are those associated with increasing the probability of catastrophic fires.

[42] Another problem when estimating the costs of wildfires is that current wildfire costs are the results of the interaction of wildfire and human activity, such as fire suppression. In particular, the current high levels of wildfires are partially the result of decades of fire suppression. Thus, some of the current costs often associated with wildfires should not necessarily be attributed in full to natural wildfire regimes, and instead should be partially defined as a cost of fire suppression. While this issue is not of paramount importance in our application to climate change, it is important in any benefit-cost analysis of fire suppression policies.

[43] Other benefits from wildfires include increased fire-dependent and adapted ecosystems and improved overall ecosystem health (Keane and Karau, 2010).

[44] There is debate surrounding the Rim Fire in that some described it as catastrophic—an ecologist for the U.S. Forestry service described the worst-affected area as "nuked" (Cone, 2013). This statement is somewhat controversial in that not all areas were so dramatically affected and the amount of area severely burned was debated (Gabbert, 2013). Furthermore, some emphasize that even a fire of this severity may have ecological benefits (Hanson, 2014)—though whether ecological benefits exceed costs may depend on the type of ecosystem affected (Keane et al., 2008). Batker et al. (2013) do not consider any benefits from wildfires in their estimates even though they discuss several in their report, including vegetation control. One cost that they include, habitat and biodiversity, could also be considered a benefit. This is because wildfires provides important habitat to many plant and animal species (Hanson, 2014; Keane and Karau, 2010; Smith et al., 2000). Thus, wildfires may provide a variety of benefits, including provision of habitat and supporting biodiversity, as long as they are within their pre-settlement patterns to which ecosystems are adapted (Smith et al., 2000; Keane et al., 2008). Otherwise, as in the case of rapid climate change, they may be costly.

[45] If the ecosystem that provides butterfly habitat is considered as a whole, i.e. where an ecosystem is a dynamic system where each unit of its area may not provide a habitat service all of the time, the ecosystem is still providing the habitat for the butterflies. Specifically, given that habitat still exists for the butterfly and that the burned areas will regenerate, and potentially healthier, it could be argued that the habitat services were not lost from the wildfire. However, the wildfire may still produce a cost to society if humans value the decline in butterfly populations (e.g., via decreased sightings)—it is just not in terms of habitat loss or biodiversity loss.

[46] According to Cleetus and Mulik (2014), an average of eighteen firefighters died per year over the last decade from wildfires.

[47] See Table 1 in Kochi et al. (2013) for a full list of the economic damages they assembled.

[48] There are several general approaches to estimating the economic costs of health damages from wildfires: willingness to pay studies (WTP) capture the total cost of wildfires on health; the cost of illness (COI) approach adds up medical expenditures and lost pay; and the damage function approach estimates dose-response functions and then applies cost estimates per unit of response. The latter method is a mix of WTP and COI in that cost estimates per unit of response are derived using WTP and COI methods. The willingness to pay studies can be further subdivided into: the defensive behavior model, which calculates health costs as the sum of mitigation expenditure and lost days of work (averting), and the contingent valuation method, which develops estimates using interviews in which individuals are asked what they are willing to pay to avoid exposure and its corresponding health impacts. The COI and damage function approaches capture only the direct costs of health impact, while willingness to pay estimates tend to be higher because, unlike the other two methods, they capture the effect of smoke on well-being (discomfort and leisure time lost) and the costs of defensive behavior.

[49] While the inclusion of mortality effects (even small), lost workdays, and restrictive activity days (minor and major restrictions) is key, hospitalization (i.e. admission), respiratory problems, and self-treatment are also important components of total health costs, to a lesser extent.

[50] The latter estimate also includes the value of lost recreation.

[51] While the authors find evidence that health effects can result from fires up to 200 to 300 miles away, they also find that these health costs decrease with distance and fuel load.

[52] This adjustment is rather ad hoc, but can be justified in that Moeltner et al. (2013) captures similar health impacts from wildfires as the first two estimates by Richardson et al. (2013). Assuming that the latter two estimates by Richardson et al. (2013) more fully capture health damages from wildfires and a similar ratio of hospital costs to total health damages from wildfires holds between Richardson et al. (2013) and Moeltner et al. (2013), this adjustment is appropriate. The appropriateness of this adjustment term is further supported by the similarity of the final total cost estimates to those found by Rittmaster et al. (2006).

[53] The study looks at premature mortality, respiratory hospital admissions, cardiac hospital admissions, emergency room visits, restricted activity days, asthma symptom days, bronchitis admissions, and acute respiratory symptoms.

[54] Cleetus and Mulik (2014) cite health damage ranges of $91 to $467 per 100 acres of biomass burned, citing Moeltner et al. (2013), Butry et al. (2001), and Rittmaster et al. (2006). However, Moeltner et al. (2013) and Butry et al. (2001) looked at only the treatment costs of respiratory and cardiovascular illnesses resulting in hospital admissions. While Butry et al. (2001) also includes doctor visits and outpatient treatment in addition to inpatient admissions, the study fails to include all respiratory problems or medication costs.

[55] While aggregate expenditure on prevention and suppression are likely to increase with wildfires, prescribed burning may decrease. Because prescribed burning is only necessitated by aggressive fire suppression (which increases fuel loads) and climate change will make suppression efforts increasingly less successful, the use of prescribed burnings will potentially decline with climate change.

[56] An example of economies of scale would be that as fires become more frequent and more intense, fire departments invest in expensive, but more effective firefighting technologies such as helicopters. While such investments would increase the overall cost of firefighting, they could potentially decrease the cost of fighting fires per acre. De Groot et al. (2013) argue that such cost savings per acre will not be realized under climate change.

[57] These costs include emergency funds, fuel reduction, preparedness, site rehabilitation, and suppression.

[58] In 2013, this amount equaled $1.7 billion (Cletus and Mulik. 2014; NIRC, 2014).

[59] A large wildfire is often defined as wildfire consisting of 1,000 acres or more (Cleetus and Mulik, 2014).

[60] While wildfire suppression expenditures tripled, this was not solely due to an increase in area burned. Figure 9 clearly shows that the average cost of suppression per acre increased less rapidly than total cost (about 40 percent from the 1990s to the 2000s).

[61] In Abt et al. (2008), the authors fit a time trend model for fire expenditure for 10 regions of the United States. For all regions, the time trend variable was positive and significant at the 5 percent level, indicating that real suppression costs are increasing for all regions of the United States.

[62] Estimates of suppression costs differ greatly by fire. According to a recent study by Kochi et al. (2012), suppression costs in Southern California in 2003 were $123,247,243 for 750,043 acres burned; this is a cost of $16,432 per 100 acres. However, Lynch (2004) found an average suppression cost in her case study in Colorado that was much higher, at $52,500 per 100 acres burned with regional variation. Similarly, Dale et al. (2009) find an average suppression cost of $26,200 per 100 acres burned in their survey of six Western fires.

[63] In another example, though not spent completely on suppression, the budget for the California Department of Forestry and Fire Protection is over $1 billion (Cleetus and Mulik, 2014).

[64] Catastrophic fires are defined with respect to economic costs, and may have ecological benefits when they are a normal part of a fire regime. However, if fires occur at intensity levels above which the ecosystem is adapted, damages to ecological services in the medium-run and long-run can also potentially occur.

[65] The distribution of U.S. fire suppression expenditure is skewed to the right (Abt et al, 2008). Due to the uncertainties associated with climate change, this distribution will shift, and is likely to be further skewed to the right and potentially "fat tailed" (Keating and John Handmer, 2013; Holmes et al, 2013). This means that large fires, e.g., catastrophic fires with large suppression costs, will be increasingly more likely under climate change.

[66] Scientists increasingly agree that small, regularly occurring wildfire is essential to the health of many ecosystems. This is particularly true for fire-dependent ecosystems made up of plants and animals that require fires for at least one part of their lifecycle. Not only does fire suppression decrease the number of "healthy fires," at least in the near term, but it also increases the likelihood of large, intense fires in the longer run. These "catastrophic" fires can wreak havoc on ecosystems, leading to permanent damage.

[67] De Groot et al. (2013) specifically refer to the Canadian Wildland Fire Strategy. This is a vision document that aims to move Canada toward an integrated approach for fire management, which includes "mitigation, preparedness, and recovery programs that complement an efficient fire suppression and response system" (CWFS, 2006).

[68] Fankhauser (1995) argues that the mental cost of being a climate refugee is likely to be substantial. While the cost of being a wildfire evacuee is likely to be far below this amount, it will take a psychological toll on evacuees particularly if their home is lost.

[69] With large-scale community adoption of adaptive measures, a "let burn" policy could become politically feasible in the future–this would decrease future suppression expenditures. Such a policy could become more likely with the development of new technologies that greatly decrease the risk of property damage from wildfires.

[70] The U.S. Forestry Service focuses on short-term rehabilitation through the Burned Area Emergency Rehabilitation (BAER) program. This fund focuses on emergency treatment to prevent further property loss, human health consequences, and degradation of natural resources and environmental services (including clean water services).

[71] Many of these damages are relatively insignificant without a major precipitation event (Robichaud, 2009).

[72] See Table 1 in Dale (2009).

[73] Specifically, Lindenmeyer and Noss (2006) state that "Although salvage logging removes wood from burned areas, such practices generally do not help regenerate or save ecosystems, communities, or species…and often have the opposite effect."

[74] In dollar terms, total damages are $354,629 and damages per hectare are $1,697.

[75] The value of the resource before the fire was €661,328 (€3,164 per hectare); this is $892,793 ($1,055,364 per 100 acres), of which 40 percent was attributed to market value, 27 percent to non-market value, and the remaining 33 percent to non-use value. Thus, 40 percent of the resource's value was lost due to fire.

[76] Rahn (2009) includes the value of ecosystem services in his wildfire cost estimates which, as discussed in the previous section, may rely on some wildfire activity for their healthy provision. More importantly, the ecological costs and benefits from a normal fire regime potentially should not be counted, and should be considered as a natural part of any ecosystem. Thus, in a cost-benefit analysis of suppression, these ecological benefits from suppression should be ignored, and, in fact, many of these wildfires costs should instead be attributed to an aggressive suppression regime. However, when considering the costs of climate change, the ecological costs of increased frequency, size, and intensity of wildfires from climate change should be accounted for because these costs arise from fires outside of the natural regime.

[77] Grey literature is papers, books, or reports that are informally published (i.e., printed and/or distributed by a non-commercial publisher), and, often, do not go through a formal peer-review process, as is common in academic journals.

[78] Like Rahn, Zyback et al. (2009) includes ecosystem service losses in his wildfire cost estimates. See the footnote 76 for a discussion on why this potentially problematic for some benefit-cost applications, but not with respect to climate change.

[79] The 2008 California Wildfires burned 1.2 million acres equaling $833,333 to $2,500,000 per 100 acres (http://www.fire.ca.gov/fire_protection/downloads/siege/2008/2008FireSiege_ExecSummary_Timeline.pdf).

[80] The A2 scenario is one of the standard IPCC climate scenarios utilized by climate analysts; see http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=91. The scenario models a future with regionalized economic development characterized by slower economic growth (on a per-capita basis) and technological innovation. Additionally, the A2 scenario is characterized by a lack of global cooperation and a failure of regional governments to focus on environmental protection and social equity. As a consequence, the A2 scenario appears to be the most like a business-as-usual scenario, and is commonly referred to as such (e.g., http://www.fhwa.dot.gov/environment/climate_change/adaptation/publications_and_tools/climate_effects/effects03.cfm). For more on the A2 storyline, see http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=94.

81 Alternatively, Dale (2009) estimates the ratio of suppression cost to total cost to be between 2 and 30. However, we chose the Zybach et al. (2009) ratio (between 10 and 50) for our cost calculates because it more closely overlaps our results of between 4 and 75.

82 This assumes that U.S. federal suppression costs total $1.5 billion (see Figure 8), and that state and local costs total to between $0.5 and $1 billion (Gorte, 2013).

83 Specifically, Spracklen et al. (2009) states, "We regress observed area burned onto observed meteorological fields and fire indices from the Canadian Fire Weather Index system and find that May–October mean temperature and fuel moisture explain 24–57% of the variance in annual area burned in this region. Applying meteorological fields calculated by a general circulation model (GCM) to our regression model, we show that increases in temperature cause annual mean area burned in the western United States to increase by 54% by the 2050s relative to the present day."

84 Specifically, Yue et al. (2013) state "We develop fire prediction models by regressing meteorological variables from the current and previous years together with fire indexes onto observed regional area burned...[, and we] also parameterize daily area burned with temperature, precipitation, and relative humidity... By applying the meteorological fields from 15 climate models to our fire prediction models, we quantify the robustness of our wildfire projections at midcentury. We calculate increases of 24-124% in area burned using regressions and 63-169% with the parameterization." Given that Yue et al. (2013) provides a range, we calculate a 60 percent increase using the central estimates of present and predicted area burned for the Western United States reported in their Table 3, which displays the results from their regression model.

85 According to DICE-2010, global average surface temperature will increase by 2.3°C above pre-industrial levels and 1.5°C above current temperatures by 2050.

86 This is a conservative estimate given that the scientific and economic evidence indicates that wildfire costs increase at an increasing rate in area burned (and, more generally that the costs of climate change increase at an increasing rate in global average surface temperature).

87 For United States GDP for 2050 and 2100, we utilize country-level GDP and downscale projections based on socio-economic projections from the IPCC Special Report on Emissions Scenarios (SRES) for the A2 scenario. These projections were developed by NASA's Socioeconomic Data and Applications Center (SEDAC), hosted at Columbia University's Center for International Earth Science Information Network [NASA, 2002; NASA, 2004].

88 Specifically, De Groot et al. (2013) state that "The results of the de Groot and others (2012b) study, combined with the increasing fire season length in the boreal region found by Flannigan and others (2013) and other studies suggesting that annual area burned could increase 2–5.5 times in boreal North America (Flannigan and others 2005, Balshi et al, 2009)." This prediction differs from the other numbers in that it is more of an educated guess than an estimate from a model.

89 Specifically, Flannigan et al. (2004) state that "area burned was not projected to decrease in any of the ecozones modelled. On average, area burned in Canada is projected to increase by 74–118% by the end of this century in a $3 \times CO_2$ scenario. These estimates do not explicitly take into account any changes in vegetation, ignitions, fire season length, and human activity (fire management and land use activities) that may influence area burned."

90 Specifically Balshi et al. (2009) state that "Relative to the 1991–2000 baseline period..., area burned increases by 5.7 times under the A2 scenario while it increases by 3.5 times under the B2 scenario by the last decade of the 21st century."

91 Specifically, NRC (2011) states that "As the time horizon increases, a further complication arises in projecting wildfires because of the importance of fuel availability and quality (moisture content) for determining the likelihood and size of wildfires. Systematic climate changes will inevitably alter the distribution of the vegetation, and significant changes in the vegetation would greatly affect the potential for wildfires and the wildfire area burned. For example, if climate change further dries already arid grasslands, then the grasslands will wither to deserts and fire will no longer be supported."

92 Globally, grassland and savannah fires account for approximately 80 percent of area burned. While Africa and Australia are the most significant contributors to these types of fires, South Asia and South America are also key contributors (Flannigan et al., 2013).

93 For global GDP for 2050, we utilize country-level GDP and downscale projections based on socio-economic projects from the IPCC Special Report on Emissions Scenarios (SRES) for the A2 scenario. These projections were developed by NASA's Socioeconomic Data and Applications Center (SEDAC) hosted at Columbia University's Center for International Earth Science Information Network [NASA, 2002; NASA, 2004].

94 Frequently, economists assume that developing nations have a lower willingness to pay for non-market goods relative to developed nations. Given that most damage estimates are derived using data from developed nations, traditionally economists adjust current estimates using an adjustment term approximately equal to $(Y(r,t)/Y(0))^E$ where $Y(r,t)$ is the income per capita in region *r* and time period *t*, Y(0) is the income per capita in the current time period for the region that the damage estimate was derived from, and *E* is the income elasticity of demand for that non-market good; the income elasticity of demand captures the percentage change in quantity demanded for a 1 percent increase in income.

95 Benefit transfer is a method for extrapolating benefit and cost estimates from a well-studied location and context to another location and context for which primary estimates are unavailable. This method is a more sophisticated way to further develop extrapolations of U.S. wildfire damages from climate change for other regions.

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