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Wildfire Ignitions: A Review of the Science and Recommendations for Empirical Modeling

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ABSTRACT

Deriving from original work under the National Cohesive Wildland Fire Management Strategy completed in 2011, this report summarizes the state of knowledge regarding the underlying causes and the role of wildfire prevention efforts on all major categories of wildfires, including findings from research that have sought to model wildfire occurrences over fine and broad spatial and temporal scales. The report also describes a conceptual model of wildfire ignitions, which is designed to provide a modeling framework for analysts who seek to better understand wildfire ignition processes or develop statistical models that can predict wildfire occurrences across any spatial or temporal scale.

Keywords: Accidental fire ignition, human-caused fire ignition, incendiary, lightning-caused fire ignition, National Cohesive Wildland Fire Management Strategy.

INTRODUCTION

Wildfires are the result of an ignition source, fuels, and conditions that allow a fire to grow. Ignition sources are commonly divided into natural causes (primarily lightning, but also of geological origin) and human causes, including both accidentally and intentionally ignited fires. Customarily, natural ignitions are assumed not to respond to changes in land management. To address the accidental and intentional ignition sources, land management agencies have a few key management options—wildfire prevention education, fuels management, and law enforcement. Below, we describe how wildfire ignitions are produced in an effort to lay the groundwork for further advances in wildfire production theory and in the empirical modeling of wildfire management intervention. This work was conducted as part of the development of the National Cohesive Wildland Fire Management Strategy (USDA Forest Service 2000), as required by the Federal Land Assistance, Management and Enhancement Act of 2009 (43USC1748b; Title V, Section 503 of PL 111-88).

The National Science and Analysis Team of the National Cohesive Wildland Fire Management Strategy includes several sub-teams charged with exploring in depth a set of concerns and processes associated with fire management. A final report (Lee and others 2011) describes the outcomes of the work by several sub-teams of experts to develop a scientifically based conceptual framework for wildfire management. The Wildfire Ignitions and Prevention sub-team, whose members authored this report, sought to better identify which variables might be used to explain the occurrences of wildfires of natural and human origins. Humans directly or indirectly ignite most wildfires in the United States, and these wildfires more often occur near values at risk (Butry and others 2002). Therefore, one approach to reducing losses and enhancing societal welfare would be to reduce their occurrence. Wildfire occurrence can be reduced through a variety of means, many of which are controlled by land and wildfire managers as well as public policymakers.

In this report, we describe a conceptual model showing how wildfire ignitions are both produced and affected by management. This model thus lays the groundwork for further advances in wildfire production theory and in the incorporation of wildfire management interventions in empirical ignition modeling. Development of tools based on these models could improve the ability of land managers to respond to emerging and ongoing wildfire threats. The conceptual model description involves a brief survey and assessment of the scientific literature and the illustration of the ignition process using a conceptual diagram. The conclusion of the report outlines areas where science is still needed to improve understanding of the processes that control wildfire ignitions. We caution that this report is not focused on modeling of area burned or damages observed from wildfires. Rather, our interest is confined to understanding the relationships between empirically validated and hypothesized causal or explanatory variables and ignitions.

A CONCEPTUAL MODEL OF WILDFIRE IGNITIONS AND PREVENTION

The conceptual model in figure 1 shows the primary linkages among wildfire ignitions with the various biophysical, societal, prevention, and management variables. It also describes the relationship to wildfire impacts, whose reduction is the primary reason for managing wildfire and the justification for the National Cohesive Wildland Fire Management Strategy. Logically, wildfire ignitions are the centerpiece of this model (see the Wildfire Ignitions box) and are separated into three general categories in the conceptual model. Natural ignitions include primarily lightning-caused ignitions. Accidental ignitions are generally human-caused ignitions that were not intentional (including escaped prescribed fires), whereas arson ignitions are those that were generated with malicious intent. Among these three general categories, the occurrence of natural ignitions is largely beyond our control, but the frequency of human-caused ignitions can be altered through prevention efforts.

The boxes connected to the Wildfire ignitions box in the conceptual model indicate the potential pathways by which humans affect ignition frequency or alter the biophysical conditions necessary for successful ignition. Many of the variables listed in these boxes are described in detail in the following sections. However, several variables may affect more than just wildfire ignition patterns. For example, biophysical drivers have a large influence on fuels and fuel moisture conditions, which govern whether an ignition is physically possible. However, these same variables also influence wildfire behavior and spread. Thus, to accurately characterize the patterns of ignitions and the mechanisms influencing the ignitions, it is critical that the individual processes affecting wildfire ignitions and behavior are recognized and incorporated into empirical models.

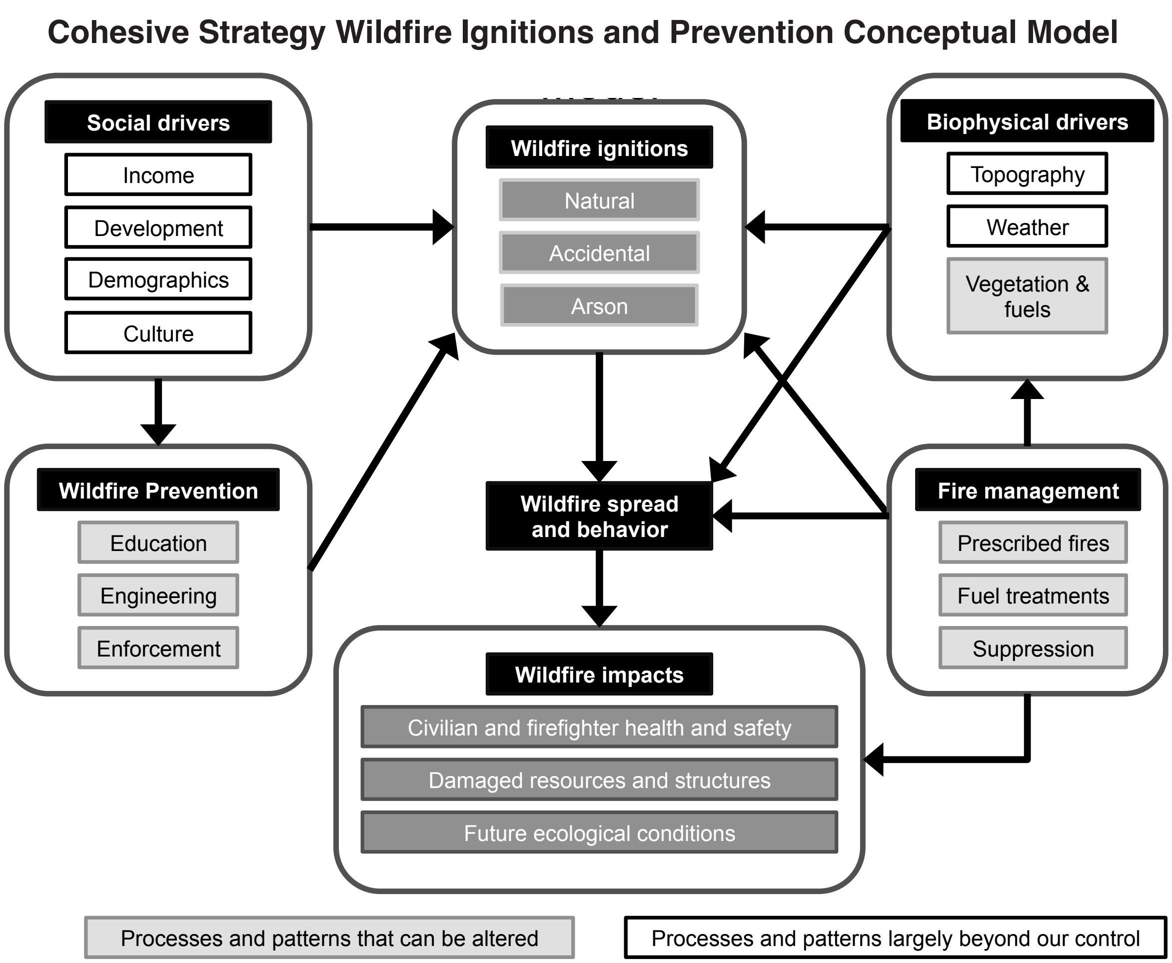

Figure 1—Conceptual model of wildfire ignitions and preventions.

Societal variables are present in the conceptual model as four general categories: (1) income, (2) development, (3) demographics, and (4) culture. These drivers are considered to be largely immutable by actions that land-management agencies can make, even though the drivers may be influenced by more broad-scale local, State, and Federal government policies. Development, whether measured through housing, population, or road density, provides a proxy measure of human use of the landscape, with the idea that more use will result in more ignitions. Income, demographics, and culture may modulate human use of the landscape, including how often and what kinds of work and leisure activities occur in fire prone locations. All four categories of societal variables are likely to influence the amounts, kinds, and effectiveness of alternative prevention activities.

The prevention variables shown in figure 1 (under Wildfire Prevention) are subdivided into three categories: (1) education, (2) engineering, and (3) enforcement. These categories capture three broad approaches to reducing unwanted wildfire ignitions. A fourth approach, not shown in figure 1, administration, is assumed to operate at larger spatial and temporal scales for land and fire management organizations. Administration encompasses how a management organization deploys the three other categories of prevention. This category also includes how agencies invest in prevention productivity enhancement for people involved in the other prevention categories, e.g., training of wildfire prevention and law enforcement personnel and engineering research and development.

The pathways through which management variables affect ignition patterns are not always direct. The primary land management action that directly affects ignition occurrence is prescribed fire, which can produce an unwanted escaped wildfire. Fuel treatments may alter ignition frequencies and spatial patterns by changing the structure and arrangement of fuels on the landscape. Wildfire suppression could be considered an ignition reduction action at fine spatial and temporal scales, e.g., by changing ember transport near an active wildfire, but suppression generally occurs after successful ignition and ultimately alters the area burned by wildfires.

The conceptual model provides a framework and describes the pathways that could guide construction of a probabilistic, empirically based wildfire ignition production function for the National Cohesive Wildland Fire Management Strategy. Although a very simple wildfire ignition production function model could be specified as a random draw from an unconditional ignition distribution based on historical data, science can do better than this. The existing scientific literature, which we review below, documents that the spatial and temporal patterns of wildfire ignitions can be characterized through a wide variety of predictor variables. Incorporation of the relationship between ignitions and these predictors may result in a more accurate, if somewhat more complex, wildfire ignition production function. This more complex function would be more accurate because it recognizes differences across space and over time in the factors that drive wildfire ignitions. The production function also can include variables that can be manipulated by land managers, making it a tool for evaluating economic tradeoffs.

WILDFIRE IGNITIONS PROCESSES AND PREVENTION ACTIVITY EFFECTIVENESS

Wildfire Causes

The U.S. Department of the Interior and the Forest Service, U.S. Department of Agriculture, each have lists of wildfire causes. The names differ slightly but the specific causes of wildfires included in the most aggregated list (General Causes for the Department of the Interior and Statistical Causes for the Forest Service) overlap (table 1). State and local agencies typically have adopted one of the two lists. These lists can be aggregated into nine codes for each agency. (More details are provided in the appendix.)

The first ignition code (1) in both lists is wildfire caused by a natural source—anything natural for the Department of the Interior, and lightning for the Forest Service. Presumably, a wildfire caused by spontaneous combustion or through geological processes would be classed as Miscellaneous by the Forest Service. The numbers and percentages of wildfires of different causes vary widely across the United States and its territories. On lands managed by the Forest Service, the most common wildfire cause is lightning, representing 55.8 percent of wildfires and 74.3 percent of area burned between January 2000 and December 2008 (table 1). On Department of the Interior lands, natural wildfires represented 37.0 percent of all reported wildfires and 81.6 percent of all reported area burned between January 2000 and December 2008.

The second most common wildfire cause in recent years on Department of the Interior lands is incendiary, comprising 15.5 percent of reported ignitions. When the average annual amounts are combined in a tally of Forest Service plus Department of the Interior (table 2), we see that 45.3 percent of reported wildfires and 79.9 percent of area burned is caused by natural sources. Incendiary is the next most common single category (12.4 percent), after miscellaneous and unknown (15.4 percent). This is followed by fire use (6.4 percent), equipment (5.6 percent), juveniles (4.4 percent), smoking (1.7 percent), and railroad (0.5 percent). For area burned, the rankings are similar, although juveniles and smoking are both the source of about 0.3 percent of area burned across the land managed by either the Department of the Interior or the Forest Service. Natural fires take up a larger share of area burned compared to its share of the count. In contrast, human-caused fires tend to be smaller and comprise a smaller share of the total area burned compared to their count. The mixes of ignitions reported in tables 1 and 2 for the Department of the Interior obscure differences across agencies within that Department. For example, human-ignited wildfires are more common on lands administered by the Bureau of Indian Affairs, while lightning fires comprise a larger share of wildfires on lands managed by the National Park Service.

The mixes of ignitions vary widely across landscapes, and more finely disaggregated wildfire statistics bear this out, at least for lands managed by the Forest Service. Table 3 reports the numbers of wildfires by cause for the 9 years covering 2000 through 2008 in the Western and Eastern United States. The table shows that in the national forests of the West, lightning comprised 65 percent of all reported wildfires but accounted for only 11 percent in the East. Likewise, arson fires represented 3 percent of all wildfires in the West but 39 percent, the largest single category, of all wildfires in the East. Although debris burning was the identified cause for only 2 percent of wildfires in the West, this cause represents 17 percent of wildfires reported on national forests of the East.

The summary statistics shown in tables 1, 2, and 3 describe fire activity on most Federal lands, but these statistics are not necessarily representative of fire activity on other government or private lands. For example, and as highlighted in table 3, lightning is a relatively minor cause in many parts of the Eastern United States (Cardille and others 2001, Yaussy and Sutherland 1994). A detailed accounting of these rates was not produced for this report. Further, the summary statistics cover 9 recent years of wildfire activity, which does not allow identification of long-term (multi-decadal) trends in how the frequencies and causes of wildfires may have varied over time. We discuss some of those trends later in this report.

Variables Predicting Wildfire Ignitions

As we describe and cite in the pages that follow, research into the numbers of wildfires of various causes has identified several categories of variables that play an important role in determining when and where wildfire ignitions occur. The major categories include biophysical, societal, and management variables. Biophysical variables generally explain why wildfire ignitions vary across space and time because of temporal and spatial variations in weather and climate, vegetation, geology, and topography. In contrast, societal variables describe how human populations vary across landscapes and the social and cultural context of every location. In empirical research, societal variables are often modeled with proxy variables, that is, variables which correlate with the latent variables that actually cause wildfires; examples would be the population of youths or the percentage of the population in poverty. Management variables are used to quantify the influence of specific actions taken to alter fire occurrence

Table 1—Wildfire cause categories of the U.S. Department of the Interior and the Forest Service, U.S. Department of Agriculture

Department of the Interior general cause number	Department of the Interior general causes	Department of the Interior average annual numbers reported, CY2000–2008	Department of the Interior average annual area burned reported, acres, CY2000–2008	Forest Service statistical cause number	Forest Service statistical causes	Forest Service average annual numbers reported, CY2000–2008	Forest Service average annual area burned reported, acres, CY2000–2008
1	Natural	4,936	4,306,552	1	Lightning	5,937	1,189,684
2	Campfire	444	84,263	4	Campfire	1,520	95,075
3	Smoking	223	14,559	3	Smoking	195	7,828
4	Fire Use	1,112	82,451	5	Debris Burning	426	18,520
5	Incendiary	2,063	206,894	7	Arson	906	62,068
6	Equipment	1,038	173,933	2	Equipment Use	299	72,871
7	Railroad	64	6,076	6	Railroad	54	8,117
8	Juveniles[a]	985	16,471	8	Children [a]	78	3,992
9	Miscellaneous (and unknown)[b]	2,479	386,071	9	Miscellaneous (and unknown) [b]	1,225	143,242

[a] Classification of wildfire starts as the U.S. Department of Agriculture Forest Statistical Cause of "children" requires that the child be 12 years old or younger (National Wildfire Coordinating Group 2005, p. 83); we assume that the same applies to the U.S. Department of the Interior General Cause of juveniles.

[b] The U.S. Department of Agriculture, Forest Service Statistical Cause of Miscellaneous includes fires of unknown origin, and we have added to these wildfires without valid Statistical Cause codes entered into the National Interagency Fire Management Integrated Database (2011); similarly, U.S. Department of the Interior wildfire records without a valid General Cause were added to the Miscellaneous category.

Sources: U.S. Department of the Interior General Causes (National Wildfire Coordinating Group 1998); U.S. Department of Agriculture, Forest Service Statistical Causes are from Forest Service (U.S. Department of Agriculture Forest Service1995). Department of the Interior wildfire data are from the Wildland Fire Management Information database (available from the authors: Jeffrey P. Prestemon, Southern Research Station, P.O. Box 12254, Research Triangle Park, NC, 27709) and the U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service 2011). U.S. Department of Agriculture, Forest Service wildfire data: [National Interagency Fire Management Integrated Database (2011])].

Table 2—Fire causes, reported average annual ignitions, reported average annual area burned, and percentage shares of fires by causes, using combined data from the U.S. Department of the Interior and the Forest Service, U.S. Department of Agriculture, January 2000–December 2008

Cause	Average annual ignitions reported	Average annual area burned reported, acres	Percentage share of reported ignitions	Percentage share of reported area burned
Natural/Lightning	10,874	5,496,235	45.34	79.90
Campfire	1,964	179,338	8.19	2.61
Smoking	418	22,387	1.74	0.33
Fire Use/Debris Burning	1,538	100,971	6.41	1.47
Incendiary/Arson	2,969	268,962	12.38	3.91
Equipment (Use)	1,338	246,804	5.58	3.59
Railroad	117	14,193	0.49	0.21
Juveniles/Children [a]	1,063	20,464	4.43	0.30
Miscellaneous and unknown [b]	3,704	529,313	15.44	7.69

[a] Classification of wildfire starts as the U.S. Department of Agriculture Forest Statistical Cause of "children" requires that the child be 12 years old or younger (National Wildfire Coordinating Group 2005, p. 83); we assume that the same applies to the U.S. Department of the Interior General Cause of juveniles

[b] U.S. Department of Agriculture, Forest Service Statistical Cause of Miscellaneous includes fires of unknown origin, and we have added to these wildfires without valid Statistical Cause codes entered into the National Interagency Fire Management Integrated Database (2011); similarly, Department of the Interior wildfire records without a valid General Cause were added to the Miscellaneous category.

Sources: U.S. Department of the Interior General Causes are from National Wildfire Coordinating Group (1998, p. 17); U.S. Department of Agriculture Forest Service Statistical Causes are from U.S. Department of Agriculture Forest Service (1995). U.S. Department of the Interior wildfire data are from the Wildland Fire Management Information database (available from the authors: Jeffrey P. Prestemon, Southern Research Station, P.O. Box 12254, Research Triangle Park, NC, 27709) and the U.S. Fish and Wildlife Service (2011). U.S. Department of Agriculture, Forest Service wildfire data: National Interagency Fire Management Integrated Database (2011).

Table 3—Average annual fires and percent by cause for 2000–08 for western and eastern regions of the Forest Service, U.S. Department of Agriculture (regions 1-6 and 10, and regions 8 and 9, respectively)

Forest Service Statistical Cause	Western Forest Service Regions (1-6, 10)		Eastern Forest Service Regions (8 and 9)	
	Average annual fires	Percent by cause	Average annual fires	Percent by cause
Lightning	5,255	65	193	11
Campfire	1,116	14	116	7
Smoking	152	2	27	2
Debris Burning	191	2	278	17
Arson	220	3	651	39
Equipment Use	258	3	62	4
Railroad	33	0	24	1
Children [a]	65	1	21	1
Miscellaneous (and unknown) [b]	841	10	311	18

[a] Classification of wildfire starts as U.S. Department of Agriculture Forest Service Statistical Cause of "children" requires that the child be 12 years old or younger (National Wildfire Coordinating Group 2005, p. 83).

[b] The U.S. Department of Agriculture Forest Service Statistical Cause of Miscellaneous includes fires of unknown origin, and we have added to these wildfires without valid Statistical Cause codes entered into the National Interagency Fire Management Integrated Database (2011).

Source: U.S. Department of Agriculture Forest Service Statistical Causes are from U.S. Department of Agriculture Forest Service (1995). Wildfire data: National Interagency Fire Management Integrated Database (2011).

and behavior. In this section, we discuss the categories of variables that researchers have found can explain the ignitions of wildfires of various causes. The categories correspond with the conceptual model that we outline in an earlier section of this report (A Conceptual Model of Wildfire Ignitions and Prevention).

Biophysical variables—At the most basic level, fire is a physical process. Many studies seeking to explain observed ignition patterns over space and time have tried to incorporate predictor variables capturing the essence of that process. For a successful ignition to occur, the presence of fuels with low enough moisture levels to allow the combustion process to begin is required. Assuming fuels are present, moisture content is largely a function of temperature, solar radiation, humidity, and precipitation. In the case of precipitation, the duration of an immediately preceding precipitation event is the most important moisture determinant (Bradshaw and others 1983). Consequently, variables quantifying temperature, radiation, humidity, and precipitation are commonly used in a logistic regression framework to characterize ignition patterns, but often at varying spatial and temporal resolutions. A number of studies have related ignitions to daily weather conditions, fuel moistures, and fire behavior indices, either measured at individual weather stations (Andrews and others 2003, Butry and Prestemon 2005, Finney and others 2011, Haines and others 1983, Martell and others 1987, Preisler and others 2004,) or inferred from satellite imagery (Preisler and others 2009). Other studies have relied on monthly summary statistics of precipitation and temperature or other weather-derived variables (Butry and others 2010a, Donoghue and Main 1985, Preisler and others 2008, Westerling and others 2011) and long-term climate averages (Cardille and others 2001, Parisien and Moritz 2009, Syphard and others 2009) to explain past ignition patterns. For analyses that seek to explain longer term variations in ignition patterns, long-term climate averages are used. Such empirical studies may produce relationships to fuel conditions that are difficult to interpret because the mechanism through which precipitation alters fuel moistures is obscured by the mechanisms that determine climatic influences on vegetation (Neilson 1995). Regardless of the temporal scale used by these studies, the expected relationship is that ignition frequency will be higher under warmer and drier conditions.

Plants vary in their combustibility, and this variation can explain some observed differences in ignition rates across vegetation types. Very few studies have explicitly incorporated spatial variability in moisture patterns that resulted from the combination of different fuels types and weather patterns, but see Preisler and others (2004, 2009) for examples. Instead, most studies have relied on variables that characterize fuel and vegetation types as predictors of wildfire ignitions (Cardille and others 2001, Parisien and Moritz 2009, Syphard and others 2009), particularly for large wildfires (Westerling and others 2011). Vegetation and fuel types seem more likely to be included as predictors when the temporal resolution of the moisture-related predictor variables are monthly or longer. Accounting for spatial variability in vegetation possibly compensates for some of the lost ability to include weather and fuel moisture data in these lower temporal scale studies.

Topographic exposure affects incident solar radiation and drying rates of moisture loss from fuels. Consequently, topographic variables are also commonly included predictors, especially in studies that used monthly weather summaries or long-term climate summaries (Cardille and others 2001, Parisien and Moritz 2009, Syphard and others 2009, Westerling and others 2011). In empirical modeling, inclusion of vegetation types but exclusion of topographic variables, or vice versa, can lead to ambiguity because general vegetation type categories and topographic exposure are correlated. Inclusion of both sets of variables can resolve the ambiguity.

The potential impacts of climate change on ignition patterns are intuitive: if climate shifts are warmer and drier in a location, then conditions will be more favorable for ignitions in that location (Fauria and others 2011, Flannigan and others 2009, Hessl 2011). Little research exists that has attempted to link ignitions to climate or that predicts how climate change may change ignitions, although notable studies do exist (Price and Rind 1994, Westerling and Bryant 2008, Westerling and others 2011). These studies suggest that even though inter-annual variability is high, the climate conditions favoring ignitions and fire spread have become more common in recent decades. The more favorable conditions have led to increased area burned and an increase in the number of large fires. However, when all wildfire ignitions, regardless of fire size, are considered, the total number of ignitions on western national forests appears to be undergoing a long-run decline (National Interagency Fire Management Integrated Database 2011) since at least 1971. Some of this decline may be due to the long-term trends in societal variables (see the next section of this report, Societal Variables), but this decline is also occurring for lightning wildfires, which decreased in numbers on national forests in aggregate by about 15 percent between 1971 and 2010.

The influence of different biophysical variables on ignition patterns may vary with the type of ignition. Of the nine major causes, natural ignitions may be the most influenced by biophysical variables. The predictive factors primarily associated with lightning wildfire ignitions are high frequency of lightning strikes, dry low-level atmospheric conditions, and abundant fuels (Rorig and Ferguson 1999) or particular vegetation types (Calef and others 2008). Short-run forecasts of lightning-ignited wildfires could be made with models based on the existence of unstable atmospheric conditions, which are conducive for lightning, and dry and abundant available fuels. Calef and others point out that a challenge is to understand when lightning occurs without simultaneous precipitation that could prevent successful ignition. Rorig and others (2007) used dew point depression (the difference between the dew point and the ambient air temperature) as one predictor of the probability of dry lightning wildfires in the Pacific Northwest. Wallman and others (2010) further refined the work of Rorig and Ferguson (1999) and Rorig and others (2007), providing new atmospheric instability measures that may enhance the accuracy of dry lightning frequency predictions, especially for California. Over longer time periods, such as seasons or years, and across broad landscapes, lightning (natural) wildfires could be predicted with a combination of historical frequency data and measures of fuel moisture such as the Canadian Fire Weather Index or various Palmer drought indices (Littell and others 2009).

Societal variables—Human-caused ignitions are heavily influenced by biophysical conditions, but a more complete understanding of human-caused ignitions requires the added consideration of how humans interact with their landscapes. Research by Butry and others (2010a, 2010b) and Prestemon and others (2010) found that human-ignited wildfires in Florida depend on weather (fire weather indices, precipitation) in ways expected from theory. Presumably, higher counts of wildfire starts occur when fuel and weather conditions are favorable for fire spread. Butry and Prestemon (2005) also connected arson wildfires ignited on a daily basis in Florida to high values of the Keetch-Byram Drought Index and at annual time scales to an index of the El Niño-Southern Oscillation.

Many studies have identified a number of variables emanating from society that are correlated with, or expected to affect, wildfires of various categories. Society influences the frequencies of wildfires of most causes in multiple ways. Society's influences include altering land cover and fuel types and building roads and other hard surfaces that serve as transportation corridors. Society also generates a subpopulation of individuals that intentionally set or who accidentally ignite wildfires directly through their work and leisure activities. Additionally, society builds a physical infrastructure and operates a large collection of machines that can ignite wildfires accidentally through malfunctions or in the course of regular operation. From a wildfire reporting perspective, more people living on and using landscapes generally leads to a higher likelihood that an accidentally (or even a naturally) ignited wildfire is reported and thus included in a wildfire occurrence database.[1] Scientific efforts to uncover relationships between wildfire and society have received attention for at least the last 50 years. Notable earlier studies include Donoghue and Main (1985). This was a large spatial and temporal scale statistical analysis of annual human-caused wildfires in the Eastern United States. This study quantified how law enforcement and population density, among other variables, were related to human-caused wildfires in 27 eastern States. Donoghue and Main found that law enforcement, as measured by a state's annual number of law enforcement actions, was negatively related to arson wildfire occurrence but had no detectable influence on other human-ignited wildfires.

Earlier studies related multiple hypothesized societal variables to the number of human-caused wildfires on a daily time scale. Three such studies focused on Australia (Gill and others 1987) and Canada (Martell and others 1987, Vega-Garcia and others 1995). These analyses identified systematic influences of weekend days and holidays (Australia) and seasons (Canada) on human-caused wildfire ignitions. Martell and others (1987) estimated separate models for eight cause categories and aggregated their predictions to construct an overall human-fire likelihood prediction model. Martell and others (1987) specifically mentioned that wildfire prevention activities are likely modifiers of the probability of human-caused wildfires, lamenting the lack of good data on wildfire prevention and therefore the inability to evaluate its role. Prestemon and Butry (2005, 2010) and Prestemon and others (2012) similarly documented the regular day-of-week, holiday, and seasonal patterns of human-caused wildfire ignitions in Florida, California, and Spain.

Other research has identified a long list of other societal variables that can be correlated to the frequencies of human-ignited wildfires. Cardille and others (2001) statistically related multi-year totals of counts of wildfires (at least 93 percent of which were human-caused) to unspecified State-specific fixed factors, rail density, road density, distance to non-forest, distances to cities, population density, and land ownership. Broadly, population and road density increased the numbers of fires, while other societal factors had varying influences.

Several studies of human-ignited wildfires emanate from Europe, and these studies could be relevant to wildfire prediction in the United States. Martínez and others (2009) examined 13 years of wildfire data at the (forested) municipality spatial unit in Spain. The authors found that a "risk" index of annual human-caused wildfire ignitions (for

[1]This could happen if some reported fires would have eventually self-extinguished had the fires not been reported.

6,066 municipalities, 1988 to 2000) was related statistically to several variables connected to the agricultural sector but also to agricultural land abandonment (leading to forest regrowth and afforestation) and unemployment. The latter result implies, supporting work by Prestemon and Butry (2005, 2010), that labor market conditions are connected to arson wildfire frequencies (more wildfires in weak labor markets of low wages and high unemployment). Martínez and others (2009) also found that road and railroad density were independent positive contributors to human-caused wildfire likelihoods. Martínez and others also found that the proportion of land in recently declared (since 1980) protected status was positively related to wildfire likelihood, demonstrating the possible importance of disputes by local residents against government entities that have restricted traditional uses of rural lands. This last finding validates earlier work, conducted in the United States (Doolittle and Lightsey 1979), in which similar use restrictions may have been the source of some firesetting by rural southern residents. Whether such land use conflicts today represent a major contributor to incendiary wildfire occurrence in the United States is not certain.

Management variables—Land managers take many actions that are intended to affect wildfire occurrence, spread, and severity, in the interest of minimizing or maximizing or achieving an optimal combination of outputs given costs. Although wildfire prevention encompasses the main set of actions designed to reduce fire starts, fuels management might also influence the likelihood of wildfire ignitions.[2]

Fuels—Fuels quantities, structures, and moisture contents have been shown to influence human-caused wildfires as well as lightning fires in several studies. Dry fuelbeds are needed to enable successful ignition and spread (Littell and others 2009, Prestemon and others 2002, Rorig and Ferguson 1999, Rorig and others 2007). Rorig and Ferguson (1999) indicated that fuel conditions need to be optimal to facilitate lightning wildfire ignitions. Hu and others (2006) found that a particular tree species (black spruce) is related to higher rates of ignitions of certain causes of wildfires in Alaska. It could be that a wildfire ignition is more likely to be reported to authorities when fuels conditions are favorable for spread, and this may be true for wildfires of any cause. When moisture levels are high or fuel levels are low, wildfires are more likely to be self-contained or extinguished by nearby people (potentially including the people responsible) and thus possibly go unreported.

While fuels themselves (structure, quantity, moisture content) might be connected to ignition success, there is so far limited understanding of the role that fuels management plays in wildfire ignition processes. Butry and Prestemon (2010a) and Prestemon and Butry (2010) found an inverse statistical relationship between some human-ignited wildfires and the total area of authorized hazard-reduction prescribed burn permits in Florida. The relationship to fuels reduction treatments and the probability of ignition success is as yet unproved. But one possible explanation for the statistical connection is that burn permit requirements for prescribed fire are an effective form of wildfire prevention, reducing the likelihood of accidental fires of several causes. (We provide more detail on the burn permit connection to wildfire in the next section of this report.)

Prevention—There has been scant research published in the refereed literature on the effects of wildfire prevention efforts. This is in spite of widespread acceptance that prevention efforts are worthwhile. In its “Wildfire Prevention Strategies” publication, the National Wildfire Coordinating Group (1998) defines wildfire prevention to consist of administrative, education, enforcement, and engineering activities. As indicated in a previous section of this report (A Conceptual Model of Wildfire Ignitions and Prevention), the administration portion of wildfire prevention could be classified as long-term efforts to reduce unwanted wildfire, including such activities as planning, development of early warning systems, and training of wildfire prevention personnel. Education includes 26 activities, ranging from public service announcements, development of wildfire safety programs directed at homeowners, character appearances (e.g., Smokey Bear), development and distribution of printed materials, bilingual programs, parades and fairs, school programs, and signage. Engineering consists of eight activities, ranging from the establishment of building and land use codes and standards, improvement of campfire facilities, spot-checks of utilities and other kinds of inspections, and hazardous fuel reduction. Enforcement is broken into seven activities, including fire investigations, fire use restrictions, burn permitting, fire code enforcement actions, and spark arrester compliance checks. As described in the “Wildfire Prevention Strategies” publication, although prevention efforts are not likely to affect natural ignitions, there are certain prevention activities that could reduce the damages emanating from natural wildfires after the fires are ignited (National Wildfire Coordinating Group 1998). Examples of such prevention strategies are fuels reduction and the implementation and enforcement of building codes that mandate fire resistant building materials.

Statistical analyses that seek to quantify the effects of prevention are hampered by a lack of accurate and complete reporting of prevention activities. They are also hindered by

[2] While combustible fuels are required for a fire to start, there is limited statistical evidence that alterations of those fuels significantly affect wildfire ignition probabilities. The only study we are aware of is Butry and others (2010a). There is statistical evidence that fuels manipulations affect wildfire extent and intensity (Mercer and others 2007). Wildfire extent and intensity are not the focus of this report.

analytical (statistical) problems that might arise due to high numbers of potential variables that could influence ignitions. Fire management agencies have not collected and archived consistent data on wildfire prevention activities over long time spans and large spatial scales.

In spite of data limitations, some analysts have successfully quantified statistically some of the effects of wildfire prevention efforts on wildfire occurrences. Butry and others (2010a, 2010b) and Prestemon and others (2010) concentrated on understanding the role of wildfire prevention education (WPE) on some wildfire cause categories in Florida. As we define the term, WPE includes only a subset of the activities outlined in the "Wildfire Prevention Strategies" publication. The Florida studies classified wildfire causes into four major categories, only one of which was presumed to be affected by WPE efforts of wildfire mitigation specialists in Florida from 2002 to 2007. The statistical models related the occurrence of wildfires caused by the aggregate of camping, debris burning, children, and smoking wildfires to eight categories of WPE: media (public service announcements appearing in radio, TV, newspaper), home visits, presentations to schools and the general public, brochures distributed, hazard assessments, and law enforcement (measured by police per capita). Researchers found that WPE in current and 6 previous months had an inverse relationship with the counts of these wildfires, after controlling for other factors. Researchers noted that timing of the education efforts mattered, that effectiveness varied by WPE category, and that public service announcements, presentations, brochures, and hazard assessments were the most effective at reducing wildfires. The effectiveness of many kinds of WPE was higher when done just prior to and during the main wildfire season.

Some recent efforts at understanding human-caused wildfires have focused on incendiary wildfires and the effect of law enforcement, which can be considered a prevention activity (particularly when done by the land management agency). Prestemon and Butry (2005, 2010) found that law enforcement, as measured by sworn law enforcement officers per capita, was negatively related to arson wildfires in Florida and California. Prestemon and others (2012) showed that intentional firesetting arrests can be highly effective at reducing intentional wildfire occurrence. Donoghue and Main (1985) found that law enforcement efforts were inversely related to arson wildfires in the Eastern United States.

Discussions with wildfire managers from various agencies indicate that burn permitting systems can facilitate education and enforcement, two main types of wildfire prevention outlined in the publication "Wildfire Prevention Strategies." In Florida, the burn permit system allows the State a chance to engage the fire user, providing instruction and information on how to reduce the likelihood of escapes and an opportunity to discuss laws and regulations with respect to fire use. Anecdotal evidence provided by wildfire managers,[3] fire prevention officials, and fire investigators suggests that burn permits are probably most effective when accompanied by sufficient permit enforcement resources.

Although several wildfire prevention actions have been found to be effective means of reducing unwanted human-ignited wildfires, studies are limited in spatial and temporal scope. Studies are also limited in not yet identifying how the full suite of wildfire prevention efforts could alter wildfire activity across the full range of spatial and temporal scales.

Spatial and Temporal Ignition Patterns and Trends

Wildfire ignitions of various causes tend to be clustered in space and time and have been observed in the United States to be undergoing long-term trends. The clustering has been linked in the research to the presence of fuels, humans, and their infrastructure, and it might also be connected to varying levels of wildfire prevention efforts, including law enforcement. Short-term trends can also be explained by human deviance, such as serial firesetting behavior by particular individuals in concentrated locations over short (multi-day) and long temporal scales. Long-term trends in wildfire occurrences may be attributable to climate-related changes in fuel moisture conditions but also to more gradual changes in society. Gradual changes that might be connected to wildfire occurrence include the frequency of outdoor activities, rates and mixes of wildfire prevention efforts, the size of the active population of arsonists, land use patterns, the smoking rate, technology, and laws and regulations. Improved wildfire investigation capacities may have also contributed to some of the observed long-term changes in the mix of wildfires by cause.

Clustering in space and time—Scientists have evaluated clustering patterns from at least three analytical perspectives. One perspective characterizes observed short-term clustering of ignition points in space and time. A second perspective seeks to understand why ignition densities (number of fires reported per unit area) vary across space. A third perspective measures how spatial clusters of wildfire ignitions gradually change over time.

Butry and Prestemon (2005) and Prestemon and Butry (2005) focused in particular on the short-term clustering

[3] In this report, we consider "wildland fire" and "wildfire" to be equivalent concepts, as we do the terms "wildfire managers" and "wildland fire managers."

of arson fires in space and time and linked it to repeat offending. The arson clustering, found at Census Tract and county levels at the daily time scale in Florida during the 1990s and 2000s, was not explained by the biophysical, management, or societal variables included in the models but instead was an independent explainer of occurrences. The clustering in space and time was attributed to serial and/or copycat firesetting. Prestemon and Butry (2010) also identified temporal clustering of arson fires in national forests of southern California during the 1990s and 2000s. Prestemon and others (2012) detected similar spatio-temporal clustering of intentional wildfires in Galicia, Spain. The authors exploited this property of spatio-temporal clustering to design forecast models that could predict the dates and locations of intentional wildfire outbreaks in coming days.

Many studies have related spatial clusters of human-ignited wildfires to hypothesized causal or correlated variables. Calef and others (2008) indicated that distance to road or human settlements are good predictors of human-ignited wildfires in Alaska, with generally higher probabilities close to roads. Yang and others (2007) determined that wildfires of lightning, arson, and other human causes were highly clustered in space in the Missouri Ozarks when evaluated from a multi-year average perspective (33 years). The analysts attributed the clustering to stable relationships to elevation, slope, distance to road, and distance to town. Thomas and others (2011) found that annual counts of arson wildfires in Michigan were spatially clustered and related their differential occurrence across the landscape to many variables, biophysical (average annual precipitation and temperature and land use patterns) and societal (crime rates, law enforcement, population levels, building vacancy rates). Chas-Amil and others (2010) discovered that intentional and negligent wildfires in Galicia, Spain, were clustered spatially by subcauses (motivations) according to dominant land use practices.

Recent research has found that human population densities were positively correlated with the number of human-caused fires in California (Syphard and others 2007) and in Mediterranean ecosystems worldwide (Syphard and others 2009). In both of these cited studies, the relationship identified was nonlinear: the highest wildfire frequencies were found in locations of intermediate population densities. This nonlinearity could be the result of the combination of at least two factors: the first factor is fuel connectivity, which is lowest in high population locations; the second factor is the number of potential wildfire ignition events, which may be highest in high population locations. Moving away from populated regions, potential ignition events decrease in frequency while connectivity increases, producing the inverse-U shape observed. This finding is consistent with that of Donoghue and Main (1985), but found in a different set of ecosystems.

Several studies have found that human-ignited wildfires conform to intra-annual patterns that can be linked to seasonal variations in fuel and weather conditions. Martell and others (1987) and Vega-Garcia and others (1995) measured higher rates of human-ignited wildfires during the main fire season in Canada. Prestemon and Butry (2005, 2010) found that arson wildfires in Florida and California followed patterns connected to the fire season (though slightly shifted to earlier months of the fire season in Florida), while Prestemon and others (2012) identified similar regular patterns in Galicia, Spain.

Genton and others (2006) and Hering and others (2009) examined long-term changes in clustering by wildfire cause (Forest Service Statistical Causes for some human causes and lightning) in northeastern Florida. Genton and others found long-term spatial clustering and linked it to spatially stable long-term lightning clustering and societal variables. Hering and others (2009) reexamined the Genton and others (2006) methods and concluded that there was weak evidence of spatio-temporal clustering for selected years. That work separately modeled arson, lightning, and aggregate accidental wildfires, without specific examination of other wildfire causes (except railroad).

In summary, evidence exists that human-caused wildfires do cluster spatially around places frequented by people and machines and with higher levels of fuel connectivity, which can be explained by variables describing infrastructure and land use. Moreover, spatial clustering has been linked to topographic position. Research has also demonstrated that human-caused wildfires of some causes, especially incendiary, often cluster spatially and temporally, which could be explained by serial and copycat behavior by arsonists. Finally, in short time frames, human-caused wildfires cluster in regular, predictable patterns associated with work, leisure, and the time of year.

Long-term spatial and temporal trends—Data on wildfires reveal that some causes of wildfire are occurring less frequently in the United States. Some, but not all of these trends could be connected to broad societal trends that lie outside the scope of manager influence. Among the societal trends that we touch on in this report—by no means an exhaustive list—are a possible decline in normative (culturally acceptable) firesetting, a reduction in the smoking rate, improved fire prevention technology, altered rates of law enforcement presence, and increasing severities of criminal sanctions.

The frequency of wildfire in the United States, particularly wildfire ignited by humans, has changed vastly over many centuries. Gamst (1974) and Pyne (1995) described deep-rooted cultures of intentional firesetting across many parts of the United States and around the World, in the United States linked to the practices especially of Native American

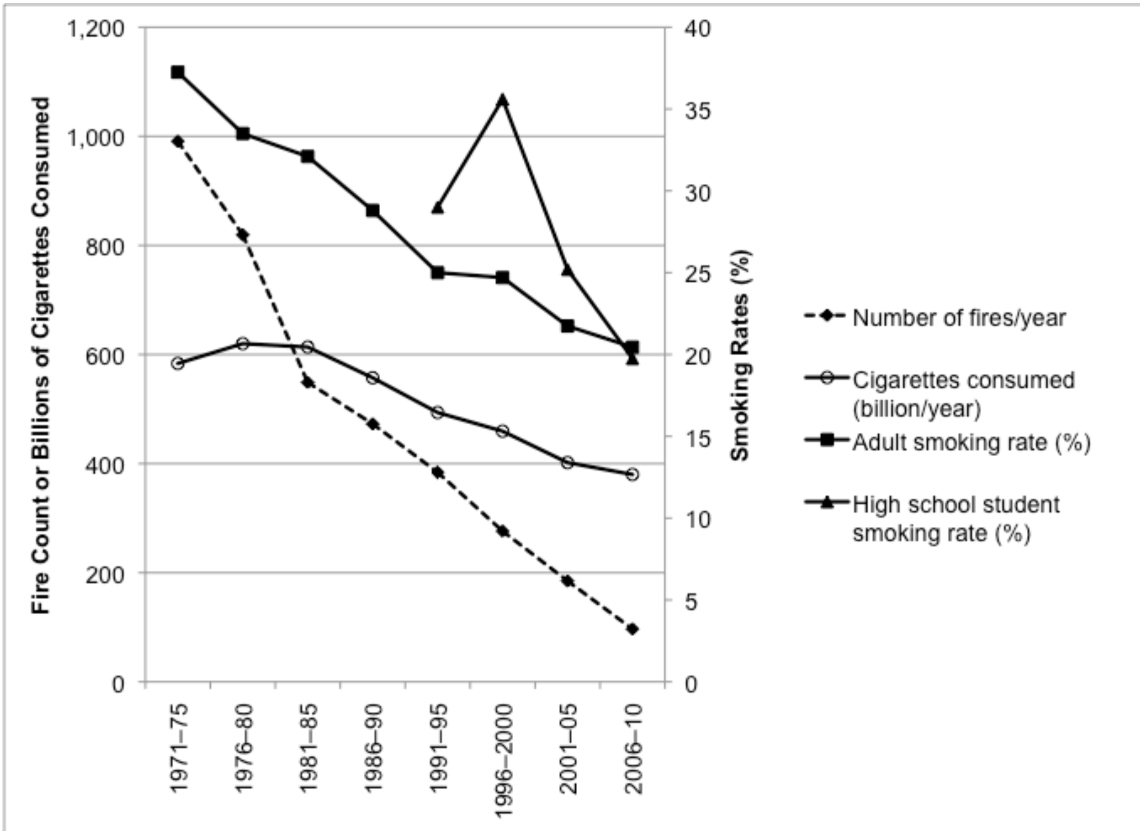

Figure 2—Average annual count of wildfires caused by smoking on national forests, total cigarettes consumed annually nationwide, and smoking rates of adults and high school students in the United States. Sources: U.S. Centers for Disease Control (2011) and the National Interagency Fire Management Integrated Database (2011).

Indian cultures. Anderson (1996) discussed how fire was widely used in North America in indigenous cultures before widespread European settlement.

In more recent decades, the frequency of wildfire in the United States may be undergoing long-term trends related to cultural changes. Doolittle and Lightsey (1979) and Kuhlken (1999) described regular burning of forests as a cultural practice in the Southern United States that was still active in the mid-20th century. According to surveys reported by Doolittle and Lightsey (1979), many intentional wildfires were set with motivations similar to indigenous cultures. These fires were also set to allow easier and more abundant grazing opportunities for range livestock, reduce the numbers of pests and snakes, and enhance hunting opportunities. With the creation of national forests and the emergence of large scale timber plantations in the Southeastern United States, some wildfires were ignited out of protest and revenge against governmental and large landowner restrictions of traditional (open-access) uses of forests, including limiting cultural fire use. Doolittle (1978) hypothesized that the observed reductions in incendiarism in the Southern United States in the 1960s and 1970s was at least partially linked to increased use of prescribed fire by land management agencies and other landowners. Doolittle's finding implies that the people involved in traditional firesetting felt less need to ignite illegal fires as long as someone was burning. Other authors (Chas-Amil and others 2010, Molina 1997) outlined similar cultural firesetting in Galicia, Spain, but also noted significant components of motivations of protest, revenge, vandalism, and thrill-seeking in recent years. We are aware of no empirical research that has statistically measured the amounts or trends of current cultural firesetting occurring over the past half-century (today classified as incendiary) in the United States. However, it is possible that the prevalence of such firesetting is declining, which could explain some of the long-term decline in incendiary wildfires in some parts of the country.

An example of a wildfire cause that appears to be trending downward because of changing human behavior is one associated with smoking materials. On Forest Service protected acres, the number of smoking-caused wildfires declined from 991 per year in the first half of the 1970s to 97 per year in the second half of the 2000s—a 90 percent drop. (We note that Department of the Interior data from at least some agencies within that Department are not reliable enough before 2000 to identify valid time trends.) The share of the number of these wildfires among all wildfire causes fell from 7.8 percent to 1.3 percent during the same time span (National Fire Incident Management Integrated Database 2011) (fig. 2). One possible explanation for the observed trend in the number of smoking-caused wildfires—though not examined in any study of wildfires as far as we know—could be the falling rate of tobacco use. The U.S. Centers for Disease Control (2011) reports that the smoking rate among U.S. adults fell from 42.4 percent in 1965 to 20.6 percent in 2009. Between 1965 and 2006, the numbers of cigarettes consumed in the United States fell from 529 billion to 380 billion per year. Smoking rates among high school students fell from 27.5 percent in 1995 to 19.5 percent in 2009 (fig. 2).

Clouding this hypothesized but logical connection between smoking and smoking-caused wildfires, however, is a possible change in the reliability of wildfire cause classifications. Improved wildfire investigation capabilities, partially enabled by the advent of new training programs, e.g., FI-210, Wildland Fire Origin and Cause Determination[4] may have led to a reduced rate of misclassification of wildfires as smoking-caused. It is not clear how improved wildfire investigation capacities may be altering the mixes of other wildfire causes. Until an in-depth study is done that definitively connects the reductions in national rates of smoking, enhanced wildfire investigation, and lower numbers of smoking-caused wildfires, the effects of these two phenomena remain as hypotheses to be tested.

Research, development, and upkeep of certain technologies may also be causing some of the most recent declines in reported accidental wildfire occurrences (Pottharst and Mar 1981). Technology might lie behind some of the most recent declines in the numbers of reported smoking-caused wildfires on U.S. Federal lands. In 2004, a relatively recently introduced smoking technology for so-called "fire safe," or banded cigarettes, was mandated statewide in New York. The mandatory use of the technology spread quickly nationwide. As of July 1, 2011, banded cigarettes are the only cigarettes allowed for sale in every State and the District of Columbia (Coalition for Fire-Safe Cigarettes 2011a).[5] Although cigarettes (rather than smoking materials generally—such as discarded but lighted matches—any of which can ignite a fire) are unlikely to ignite a wildfire, the lower danger associated with banded cigarettes may lead to continued declines in the number of smoking-caused wildfires in the United States. As of today, however, the link between banded cigarettes and wildfire occurrence is an untested hypothesis.

Another example of a technology affecting wildfire ignitions comes from the railroad cause category. On national forests of the United States, the number of such wildfires per year declined by 92 percent between the first half of the 1970s (417 per year) to the late 2000s (32 per year), while the share of railroad wildfires among all wildfires fell from 3.3 percent to 0.4 percent over the same time span (National Fire Incident Management Integrated Database 2011). This negative trend is not apparently clearly linked to rail traffic volumes. Data compiled by the Congressional Budget Office (2006) show that Class 1 rail freight traffic doubled between 1970 and 2003, from about 800 billion ton-miles to over 1,600 billion ton-miles. A more obvious link to the decline in railroad wildfires may be changing technology and the rate of compliance to its required use. The National Wildfire Coordinating Group (NWCG) reported that an NWCG Fire Equipment Working Team was established in 1986 to develop a Spark Arrester Guide targeted at railroad operators (National Wildfire Coordinating Group 2000). The current guide contains Appropriate Standards that can be recommended to regulatory agencies at all governmental levels, which can be used by fire managers, indeed wildfire prevention personnel in any government agency. Likewise, the Forest Service and other Federal land management agencies, per U.S. Code of Federal Regulations 36 CFR 261.52(j), have required the use of spark arresters on all machinery operated on Federal lands. One can surmise, and some evidence has been offered (Pottharst and Mar 1981), that the rapid decline in the number of railroad wildfires can be connected at least partially to the increased use of spark arresters as the rail industry has modernized, an improvement in the quality of spark arresters, and perhaps as well to an increase in the rate of compliance to the U.S. Code of Federal Regulations. (Whether the increased compliance with the U.S. Code of Federal Regulations is also responsible for the declines in the numbers of other kinds of human-caused wildfires on Federal lands is worthy of additional research.) We also conjecture that, because railroad wildfires can also be caused by overheated brake shoes and sparks emitted by rail grinders, better maintenance of rail cars, more frequent replacement of brakes with newer technologies, and more attention to vegetation management along tracks in more recent years (fuel reduction, fire retardant application) might explain some of the decline in railroad wildfires (Forrester 1978, Pottharst and Mar 1981).

Our final example of a wildfire cause that is influenced by broad trends in society is incendiary wildfires. Prestemon and Butry (2010) reported that an index of arson wildfire

[4] Offered by the National Wildlife Coordinating Group. Additional information is available at www.nwcg.gov.
[5] Banded cigarettes contain multiple concentric rings of special (less porous) paper within the length of a cigarette that facilitate self-extinguishing of the cigarette when left unattended or discarded but incompletely smoked (Coalition for Fire-Safe Cigarettes 2011b). This technology was originally intended to help reduce the number of structure fires. The technology is not fail-safe, but it has been judged effective at reducing morbidity and mortality in structure fires (Miller and Levy 2000).

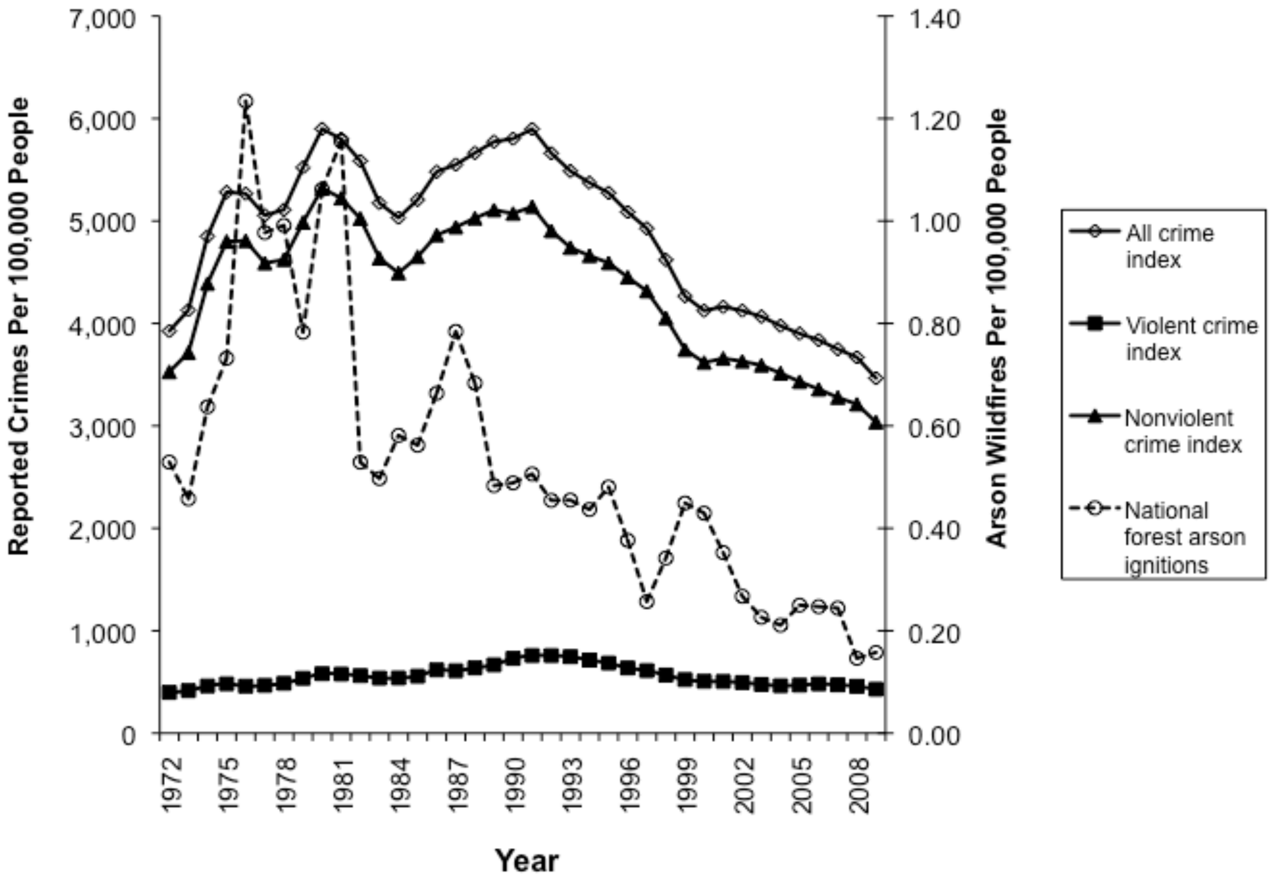

Figure 3—Reported arson wildfires on national forests, fires per 100,000 residents of the United States, and the nationwide total crime index for all index crimes, violent index crimes (murder and manslaughter, forcible sexual offenses, aggravated assault, and robbery), and nonviolent property crimes (including burglary, larceny/theft, and motor vehicle theft but excluding all targets of arson) in the United States, 1972—2009. Sources: National Interagency Fire Management Integrated Database (2011) and the Federal Bureau of Investigation (2012).

frequencies on national forests closely followed changes in the rate of all crimes (and especially property crimes) reported in the United States. The most recent data indicate that the trends identified by Prestemon and Butry (2010), who had data through 2005, continued through 2009 (fig. 3). The primary implication of the Prestemon and Butry (2010) study and other research is that arson wildfire trends continue to be negative and that societal-level factors seem to be influencing arson rates in the same way that the factors are influencing rates of other major categories of crime. Prestemon and Butry (2010), although finding no significant effect of a proxy of the prison sentence length on arson wildfire counts in Florida, speculated that part of the negative trend in arson wildfire frequencies observed nationwide could be attributable to generally longer prison sentences handed down in the 1980s and 1990s compared to earlier (Bonczar 2011, Greenfield 1995). Stambaugh and Styron (2003) indicate that there are now greater efforts to identify and apprehend firefighter arsonists than in previous years, so this could also explain some of the negative trends observed. It should be mentioned, however, that land management agencies typically contain wildfire investigation and law enforcement capacities. Enhanced wildfire investigation capacity can lead to better evidence gathering. Coupled with agency law enforcement, better evidence can lead to successful arrests and prosecutions. So enhanced and more widespread use of wildfire investigation training programs—e.g., FI-210, Wildland Fire Origin and Cause Determination and FI-310, Wildland Fire Investigation: Case Development[6]—in recent years may also explain some of the downward trend in reported incendiary wildfires on Federal lands. Increased fire investigation capacity and training, we contend, may be an effective long-term measure to reduce rates of incendiary and some other human-caused fires.

Implications of spatial and temporal patterns and trends—To summarize this section, research shows that wildfires of all causes undergo seasonal variations linked to fuel conditions and human activities. Human-ignited

[6] Offered by the National Wildlife Coordinating Group. Additional information is available at www.nwcg.gov.

wildfires demonstrate seasonalities that might be slightly different than the seasonality observed for natural wildfires, mainly because natural (especially lightning caused) wildfires require specific conditions that do not always correspond with fuel receptivity toward wildfire ignitions. Human-ignited (especially incendiary) wildfires may have regular variations within a week (especially weekend effects) that correspond with work and leisure activities, and these can be exploited for predictive purposes. Many wildfire ignition types have been shown to be clustered in space and time. Spatial clustering exists over large (multi-kilometer) spatial scales and over long (interannual) and short (daily) time scales. Spatial clustering is linked to human population density, typically in an inverse-U fashion from low to high density, an observed pattern that could be used for prediction, once long-run trends are factored in. Temporal clustering on a daily time scale has been shown to occur especially with incendiary wildfires, and much of this has been attributed to serial firesetting. This sort of temporal and spatio-temporal clustering could be useful for making short-run wildfire forecasts in specific locations of the landscape.

Recent research, although limited in temporal and spatial scope, shows that human caused wildfires are apparently undergoing long-run negative trends in the United States, when viewed over time spans of years or decades. Limited data prevents analysis of these trends on Department of the Interior administered lands or other ownerships. These temporal trends have not been broadly and carefully examined, nor have their underlying causes been identified with confidence. Trends have been quantified for a limited number of small regions—notably, Florida, California, and Michigan. The multi-decadal negative trends in wildfires of many causes on national forests in most of the United States are in contrast to the multi-decadal positive trends in area burned for all wildfires in aggregate in the Western United States that have been identified by other authors.

RECOMMENDATIONS FOR MODELING OF WILDFIRE IGNITIONS AND PREVENTION

Table 4 lists many of the major drivers of wildfire ignitions, based on the literature. While neither the literature nor the list of drivers is complete, the table shows a subset of the variables that could be employed to predict the occurrence of wildfires by causes. This listing could also be used by analysts who seek to understand wildfire ignition processes in their own studies, including testing for the influence of these predictor or driver variables.

The range of studies discussed in the previous section and indicated in table 4 vary in their focus, from fine to large spatial scales and from daily to annual temporal scales. Model development for predictive or for conducting scientific studies based on table 4 should include only the variables relevant at these different spatial and temporal scales.

The following specific recommendations are derived in part from this listing:

1. Most statistical studies quantifying fine scale spatial and temporal patterns of wildfire ignitions have used a logistic regression or similar technique. Any modeling approach with a binary (fire/no fire) or count specification would be appropriate. These could include regression trees or support vector machines. Point-process models that capture the clustered pattern of ignitions and incorporate additional predictor variables may also be appropriate. Count models (Poisson and its variants) should be used to model ignition processes at slightly larger spatial and temporal scales, particularly when wildfire occurrences exceed 1 in any temporal-spatial unit of observation.

2. The historical coverage, completeness of coverage within covered timeframes, cause attribution accuracy, and spatial accuracy of the fire start location vary greatly across agencies of local, State, and Federal governments. In developing models that are applicable to particular locations or agencies, we recommend that analysts begin with at least a minimally reliable dataset. Even flawed, it might allow for a first approximation that could be built on or coupled with other datasets in developing a reliable prediction model.

3. If the analyst seeks to explain and predict the occurrence of multiple causes of wildfire, the modeling needs to recognize the potential differences of wildfire ignition production across causes. This means, developing separate models for natural wildfires, accidental wildfires, and arson wildfires. Separation of the accidental wildfire category into its component individual causes (campfire, smoking, fire use, equipment, railroad, and perhaps juveniles) would allow an analyst to identify differential effects of wildfire prevention activities across these individual causes. We do not recommend modeling all wildfire ignitions as an aggregate across all causes.

4. Biophysical variables that are reported daily and that capture weather and fuel moisture conditions should be included (an example is energy release component, or ERC). At larger spatial and temporal scales, such as months or years, counts or occurrences of wildfire ignitions can be related to drought (e.g., Palmer drought indices), forest types, and measures of topography.

Table 4—Probable statistical explanatory variables or drivers of wildfire ignitions, by cause category at short and long temporal scales

Cause	Fire weather indices	Drought indices	Precipitation, relative humidity, maximum temperature	Police density	Distance to road or town	Elevation or slope	Arrests	Wildfires in previous days	Burn permits required	Spark arresters required	Wildfires in previous years	Wildfires nearby in space	Weekends	Holidays	Wildfire prevention	Time trend	Human populations/density	Economic conditions	Labor market conditions
Natural/Lightning	X	X	X		X	X					X								
Campfire	X	X	X	X	X	X					X			X	X		X		
Smoking	X	X	X	X	X	X					X		X	X	X	X	X		
Fire Use/Debris Burning	X	X	X	X	X	X	X		X		X		X	X	X		X		
Incendiary/Arson	X	X	X	X	X	X	X	X			X	X	X	X		X	X	X	X
Equipment (Use)	X	X	X	X	X	X				X	X		X	X			X		
Railroad	X	X	X	X		X				X	X					X			
Juveniles/Children [a]	X	X	X	X	X	X	X				X		X	X	X		X		
Miscellaneous	X	X	X	X	X	X			X	X	X		X	X			X		

[a] Classification of wildfire starts as U.S. Department of Agriculture Forest Service Statistical Cause of "children" requires that the child be 12 years old or younger (National Wildfire Coordinating Group 2005, p. 83).

5. To make statistical models most useful for policy development and assessment of management tradeoffs, societal, prevention, and management variables should measure or be proxy measures of things that can be intentionally manipulated by managers. Until greater information is available about actual, on-the-ground wildfire prevention activities by fire managers, agency budgets for wildfire prevention or numbers of wildfire mitigation specialists operating in particular locations on the landscape could be used as proxy variables that capture their effects. Information about law enforcement densities or success rates could also be used, where available, to better predict occurrence of many human-ignited wildfires, especially incendiary. This can also help law enforcement organizations understand the potential effects of changes in enforcement and surveillance.

6. Models of human-ignited wildfire occurrences at fine temporal scales should recognize weekends, holidays, and intra-annual seasonality.

7. To account for the effects of fire prevention, there are various hierarchies of data that could be used to develop predictive models. At the most aggregate level, budgets for fire prevention (e.g., spending per unit of managed area, or spending per historical reported human-caused fire starts, or spending per unit of forest visitors or per unit of local population) could be used as an index for overall prevention effort. Breaking out prevention into its three main subcategories would perhaps provide additional model accuracy. For law enforcement, data on the numbers of full-time-equivalent law enforcement officers per unit area or per number of historical fire starts or per unit of the local population could be tried. For education, the number of full-time-equivalent fire prevention education specialists per unit of forest or per unit of local population, could be attempted. Still better, counts or spending on individual fire prevention education activities (e.g., numbers of individuals contacted, brochures distributed, public service announcements issued) would be still better. For engineering, measures could include the existence of a fire burn permit system (perhaps most affecting fire use wildfires), regulations requiring spark arrestors (equipment and vehicle and railroad fires), actions by railroads to reduce trackside fuels (railroad fires), or requirements for campfires (campfire rings available or required, for campfire escapes), could be introduced in a model.

8. Models that seek to predict or understand wildfire ignitions from a long-term (multiannual) perspective should include time trend variables. Explicit inclusion of known trending variables that have been determined to be or have been hypothesized to be causal would be a further refinement. Included among the potential long-term trending variables could be explicit indicators of climate change, measures of tobacco use, spark arrestor use or legal compliance rates, and societal variables that have been shown to explain crime trends.

9. Models of wildfire ignitions should include topographic and vegetation type variables, if possible.

10. Models of fire use/debris burn wildfires should include, if possible, information about burn permitting and government-issued burn bans. Potentially useful

variables include an indicator of whether burn permits are required or voluntary and counts of burn permits issued. In cases where burn permits are required, such models could also include measures of law enforcement. If burn bans occur in the geographical location of inference, information on when the burn ban has occurred could prove useful.

11. When analysts seek to develop forward-looking (forecast) models, variables that measure the causes of fire clustering in space and time can help improve accuracy. These models could also be specified by including time-lagged counts or occurrences in the same or nearby spatial unit of inference.

12. When developing predictive models of smoking, railroad, and incendiary wildfire occurrences, the associated statistical equations could include time trends that capture gradual trajectories of their occurrences. When analysts lack reliable data on the trending variables hypothesized or found through scientific studies to affect these kinds of wildfires, time trend variables can help improve the reliability of estimated statistical models.

13. Daily information on fire weather, ground-level fuel dryness, precipitation, relative humidity, day of the week, holidays, and recent wildfire activity in nearby areas may be needed to develop fine temporal and fine spatial scale predictive models of wildfire ignitions of any cause category. For modeling natural/lightning wildfires, additional variables to include besides those quantifying weather and fuel dryness would be variables quantifying atmospheric instability and the occurrence of thunderstorms. For models using daily data on wildfires that span only a year or two, relatively slowly changing variables shown to have an influence on human-caused fires in a long-run sense, such as population levels and law enforcement efforts, are not likely to be important. But when the span of the daily models exceeds a few years, these slowly changing variables should be accounted for. Their inclusion is required because they might change average expected numbers or likelihoods of the ignitions.

14. Models of wildfire occurrences estimated statistically using data spanning many years but specified at daily, monthly, or annual time scales have many potential driving variables. These include measures of drought (e.g., Palmer drought indices), human population, recent months' and planned levels of wildfire prevention efforts, existence of burn permit requirements (and their interaction with law enforcement efforts), labor market conditions, aggregate law enforcement success rates (e.g., arrests), aggregate fuels levels and structures (including information about fuels management activities and previous levels of wildfires), and time trends or other measures of broad societal trends.

15. In developing predictive models of wildfire ignitions using data spanning large spatial scales, specifications should include variables that have been shown in scientific studies to affect aggregate human and natural wildfire occurrences. Variables include road, rail, or trail distances or densities; measures of topography; distances to cities or towns; population densities; and an indicator of fixed traditional practices that may favor firesetting for a variety of reasons, not necessarily malicious.

CONCLUSIONS

Scientists and wildfire managers nationwide and around the world seek to identify the underlying causes as well as the appropriate predictors for wildfire ignitions. Our report documents that wildfires of different causes behave differently in response to various categories of biophysical, societal, and management (including law enforcement) variables. While individual fires are partially randomly distributed in space and time, systematic variation exists over small and large spatial scales and across short and long temporal scales. The effects of the underlying driving variables are observed in a straightforward manner by examining occurrence maps and time series plots of occurrence counts. Development of statistical models that can predict the variations across space and time, however, is a more challenging endeavor that has nevertheless yielded some advances in our understanding of wildfire ignition processes. Research has found that forecasting may aid in tactical responses to incendiary wildfires, including by land managers and law enforcement personnel.

Yet much more needs to be done to expand our understanding of how wildfire ignitions are affected by society and management. Specifically, more research is needed into the effects of wildfire prevention, and new scientific studies could be targeted at specific land ownership categories or regions of the United States. We know little about how efforts to manage fuels affect ignition patterns. We need to understand with confidence the reasons behind observed long-run trends in ignitions of individual categories—e.g., reduced numbers of incendiary and smoking materials related fires—and why ignitions in most categories of natural and anthropogenic wildfires are trending downward in many parts of the United States.

New science should focus on identifying the mechanisms underlying the "cause behind the cause" when it comes to certain kinds of accidentally ignited fires, such as children or debris burn escapes. For example, what are the variables that explain why a debris burn escapes control of the burner? What variables explain why a campfire becomes a wildfire? This enhanced understanding could help in the development of more effective wildfire prevention activities carried out by land management agencies. Finally, in the field of criminology, some analysts have advanced our understanding of how to make near-term forecasts of "hotspots" of certain crime activities at relatively restricted spatial extents and short timeframes. But scientists have not advanced much in the development of similar hotspotting tools for wildfires. Such tools could be developed for many causes of wildfires, especially those ignited by people. Wildfire hotspot models could be used by managers and law enforcement, as well as Agency decisionmakers seeking to allocate scarce resources to achieve overall gains in societal well-being.

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APPENDIX: DEFINITIONS AND DISCUSSION OF THE CAUSES OF WILDFIRE

The U.S. Department of the Interior and the Forest Service, U.S. Department of Agriculture, have lists of specific wildfire causes covering all wildfires that occur on Federal lands under their jurisdiction. The lists can be consolidated into nine codes for each agency. For the Department of the Interior, all specific causes are aggregated up to nine "General" causes; for the Forest Service, the specific causes are aggregated up to nine "Statistical" causes (table 1). State and local agencies typically have adopted one or the other of the two shown. The first listed code (1) for both the Department of the Interior and the Forest Service is wildfire caused by a natural source—anything natural for the Department of the Interior, and lightning for the Forest Service. Presumably, a wildfire caused by spontaneous combustion or through geological processes would be classed as Miscellaneous by the Forest Service. Donoghue (1982) described the history of Forest Service wildfire cause classification, including delineation of the three classification schemes required for all Forest Service wildfires: Statistical Cause, General Cause, and Specific Cause. In this report, to the extent possible, we rely on the Statistical Cause categories of the Forest Service (USDA Forest Service 1995) and the General Cause categories of Department of the Interior (National Wildfire Coordinating Group 1998), as indicated in table 1. In the text discussion below, we refer to the General Causes of the Department of the Interior when referring to wildfires on all ownerships or when referring only to wildfires on Department of the Interior managed lands. When referring to wildfire data from lands where the wildfires were classified under the Forest Service Statistical cause, we use the Forest Service's nine categories.

There are recognized shortcomings of the Department of the Interior General Cause and the Forest Service Statistical Cause classification schemes. These shortcomings are important when analysts need to relate wildfire ignition frequencies to prevention efforts and other variables expected to affect occurrences (e.g., weather, fuels, and technology). Shortcomings include the unavailability for fire reporters of an "unknown" wildfire cause category, misclassification of wildfires thought to be of a known General or Statistical Cause, the lumping of many and diverse wildfire causes into the Miscellaneous category, and the heterogeneity of the origins of many kinds of wildfires classified within cause categories. Donoghue (1982) determined that many wildfires reported previous to 1982 whose origins were truly unknown were instead classified as smoking, incendiary, or miscellaneous.

Another shortcoming of the current classification schemes relates to wildfires ignited by youths. Young minors (under 13 years old) who ignite wildfires for whatever reason have their wildfires classified as juveniles or children. When such wildfires are summarized under their General Cause (by the Department of the Interior) or Statistical Cause (by the Forest Service), the campfires that escaped the care of a minor, wildfires ignited by a juvenile playing with fireworks, and wildfires ignited by juveniles for the sake of vandalism are all nonetheless classified as juveniles wildfires. The problem for analysts or mitigation specialists examining the data on juveniles wildfires would be an inability to tailor research on the effects of prevention education and then, based on that research, design specific prevention programs that would be effective at reducing juveniles wildfires.

A similar limitation of the cause classification relates to the diversity of mechanisms underlying ignitions in many accidental and intentional wildfire ignitions. Fire use wildfires may be ignited by several possible specific mechanisms, including the burning of timber slash or the burning of trash piles. Incendiary wildfires comprise wildfires started for a variety of motivations, including revenge, economic gain, thrill-seeking, and vandalism (Stambaugh and Styron 2003). Equipment wildfires can be started from electric shorts, engine overheating, ignition of fine fuels beneath a hot engine, exhaust particles, etc. Miscellaneous fires contain such diverse causes as fireworks, vehicle accidents, live fire from weapons, and the spread of fire from burning buildings, among many others. From a modeling standpoint, heterogeneity of sources or motivations within Statistical or General Cause categories makes estimation of statistically consistent and unbiased parameters from observational data challenging.

Another limitation for conducting scientific studies and developing predictive models of wildfire occurrences is varying data reliability. For example, data on wildfires that we address in this report are for wildfires that are recorded in government databases, although many wildfires likely go unreported for a variety of reasons. No minimum size thresholds are required for being recorded, only that the recording agency is informed of the occurrence of the wildfire, regardless of whether the wildfire self-extinguishes. An unknown number of wildfires self-extinguish or are extinguished by nearby persons but go unrecorded by any agency (Baker and Ehle 2001, Collins and Stephens 2007).

Prestemon, Jeffrey P.; Hawbaker, Todd J.; Bowden, Michael [and others]. 2013. Wildfire Ignitions: A Review of the Science and Recommendations for Empirical Modeling. Gen. Tech. Rep. SRS-171. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station, 20 p.

Deriving from original work under the National Cohesive Wildland Fire Management Strategy completed in 2011, this report summarizes the state of knowledge regarding the underlying causes and the role of wildfire prevention efforts on all major categories of wildfires, including findings from research that have sought to model wildfire occurrences over fine and broad spatial and temporal scales. The report also describes a conceptual model of wildfire ignitions, which is designed to provide a modeling framework for analysts who seek to better understand wildfire ignition processes or develop statistical models that can predict wildfire occurrences across any spatial or temporal scale.

Keywords: Accidental fire ignition, human-caused fire ignition, incendiary, lightning-caused fire ignition, National Cohesive Wildland Fire Management Strategy.