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Investigation of the decline in reported smoking-caused wildfires in the USA from 2000 to 2011

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Abstract. The number of smoking-caused wildfires has been falling nationwide. In national forests in 2011, smoking-caused wildfires represented only 10% of their 1980 level. No other cause of wildfire has experienced this level of decline. For 12 states, we evaluate the rate of smoking-caused wildfires and find it is a function of weather, other ignitions, the number of adult smokers, the presence of improved wildfire cause-determination methods, and whether a state required the sale of less fire-prone cigarettes. We find the decline in adult smoking rates has led to a reduction of smoking-caused fires by 9%. The finding that less fire-prone cigarettes appear successful at limiting wildfire starts – by 23% – is a likely unintended benefit of a technology aimed at reducing fire fatalities in residences. We also find that the improvements in wildfire cause determination have resulted in a reduction in smoking-classified fires by 48%. Although improved wildfire cause-determination methods do not necessarily reduce the number of wildfires, they ensure that the causes of wildfire are accurately tracked. Accurate wildfire cause determination can, however, result in targeting wildfire-prevention programs to specific fire-cause categories, which can lead to a reduction in the overall number of wildfires.

Additional keywords: economics, fire-safe cigarettes, fire standard compliant, prevention, wildfire investigation, wildland–urban interface.

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Introduction

The interaction between human activity and the natural environment has varied over time; however, in recent years the population of the USA has increasingly opted to live in suburban areas (Hobbs and Stoops, 2002). This trend has resulted in a 52% increase in the wildland–urban interface (WUI) between 1970 and 2000 (Theobald and Romme 2007). This is the area where 'humans and their development meet or intermix with wildland fuel' (Federal Register 2001). Additionally, recreation activities in the wildland appear to be increasing. For example, visitations to USDA Forest Service lands increased 50.6% between 1986 and 1996 (USDA Forest Service 2008). Occasionally, the human activity that occurs in the WUI and other natural environments results in wildland fires that damage property and cause injuries. One source of ignition for these fires is cigarettes (technically, a cause category of 'smoking'). Frequently, smoking materials, including cigarettes, are deposited into wildland areas before they have been fully extinguished; thus, occasionally these materials ignite dry brush, grass or other natural vegetation, producing a wildland fire.

Compared to 1980, the number of wildfires reported within the USDA Forest Service's National Interagency Fire Management Integrated Database (NIFMID) was lower in 2011 for all statistical causes – lightning, equipment use, smoking, campfire, debris burning, railroad, arson and children – except miscellaneous causes. Fig. 1 depicts wildfire ignition trends from 1980 to 2011 for all human causes. Although lower in 2011, several causes exhibit no distinct pattern of decline (e.g. campfires). However, the pattern of smoking-caused wildfire displays a clear pattern of steady decline (arson trends downward, too, but is marred with a few saw-toothed spikes). In 2011, smoking-caused wildfires fell to 10% of their 1980 level. Of all human-caused wildfire, including miscellaneous causes, smoking-caused wildfires comprised 10% in 1980. By 2011, this percentage had dropped to 2%. The smoking-caused wildfire decline may not be particularly surprising, given that data also show a large decline in structure fires due to smoking materials (Hall 2012).

Since 1980, cigarette smoking by adults has fallen steadily from a rate of 33%, to 19% in 2011, whereas smoking by high

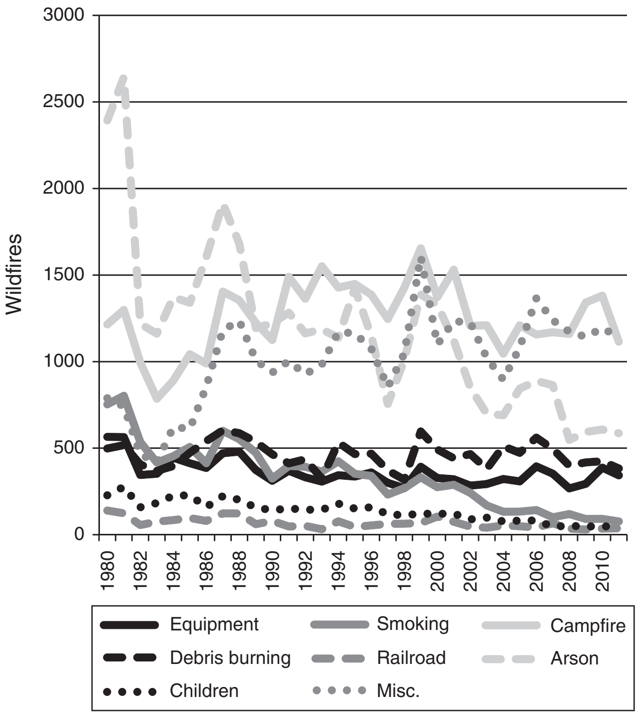

Fig. 1. Number of wildfires reported to National Interagency Fire Management Integrated Database 1980–2011.

school students – tracked since 1991 – peaked in 1997 to 36%, but fell to 18% in 2011 (Center for Disease Control 2013). Based on municipal fire department data, all fires caused from smoking materials are down 73% (1980 to 2010; Hall 2012), so we pose the hypothesis that the decline in cigarette smokers partly explains the fall in smoking-caused wildfires.

It has long been established that cigarettes and other lighted tobacco products are a leading cause of fire deaths in residences. As early as 1929, there were calls for self-extinguishing cigarettes; however, it was not until the 1970s that a grassroots campaign was started and in the 1980s and 1990s federal and state legislative efforts were underway. 'Less fire-prone' (LFP) cigarettes are made with a wrapping paper that contains regularly spaced bands.[A] At a band, the air flow to the burning tobacco is reduced, and (some of the time) the cigarette goes out. Starting in 2004, New York became the first state to require LFP cigarettes. By 2012, all 50 states and the District of Columbia had such a requirement (National Fire Protection Association 2013). The National Fire Protection Association (NFPA) reported that fatalities due to cigarette-caused fires dropped by 21% from 2003 to 2010, and were expected to drop to 30% overall (Hall 2012).

Wildland fires ignited by smoking materials are the result of an individual discarding a cigarette or other smoking material adjacent to natural vegetation and then failing to extinguish the material before discarding it. It is unclear how often this occurs; however, tobacco products account for 38% of pieces of roadway litter (Keep America Beautiful, Inc. 2009), and studies further show that cigarette butts are littered 65% of the time (Keep America Beautiful, Inc. 2010). In 2008 there were ~2444 cigarette butts per mile of roadway and a total of 18.6×10^9 total cigarette butts along roadways in the US (Keep America Beautiful, Inc. 2009, 2010). These butts represented a potential ignition source for wildland fires. Although the LFP cigarette requirement may be motivated by a desire to limit structure fire fatalities, we hypothesise that a spill-over effect of this technology is to reduce the number of wildfire ignitions. Unfortunately, there has been little research conducted on wildfires that are ignited by cigarettes and even less research linking LFP cigarettes and wildland fire ignitions.

A third reason for the decline in smoking-caused wildfires might also be connected to an increase in the number of formally trained wildfire cause investigators. Since 1980, the National Wildfire Coordinating Group (NWCG) and the Federal Law Enforcement Training Center (FLETC) have offered courses that train individuals in basic and advanced wildfire investigation techniques. Included in the training have been USDA Forest Service law enforcement personnel and firefighters with wildfire investigative responsibilities. The original FLETC course *Wildfire origin and cause determination* (P-151) was replaced by course FI-210 of the same name (piloted from 2003 and officially released in 2005; M. Heath, Fire FLETC, pers. comm., 7 August 2013). It is estimated that 130 individuals per year have attended FI-210 and that this exposure has led to improved wildfire cause investigation, hence more accurate wildfire cause attribution. Another course, FI-310 (*Wildland fire investigation: case development*), was added in 2011 (it had been taught by FLETC since *c.* 2007).

Much of the previous literature examining the occurrence of human-caused wildfires, which explicitly consider those caused by smoking materials, focuses on understanding patterns in broad-scale spatial and temporal trends (e.g. Grala and Cooke 2010; Miranda *et al.* 2012; Sun and Tolver 2012), although smoking-caused wildfires tend to garner little discussion. However, it is clear that in addition to biophysical conditions, proxies for human activity, such as population, housing and road density are important drivers of human-caused wildfire ignitions (Syphard *et al.* 2007; Miranda *et al.* 2012). This analysis seeks to understand the root causes of the decline in reported smoking material wildfire. Specifically, we evaluate the role of (1) the decline in the number of adult cigarette smokers; (2) the advent of self-extinguishing LFP cigarettes (or fire standards compliant cigarettes) designed to reduce the number of cigarette-caused fire fatalities; and (3) the use of improved wildfire cause-determination methods (i.e. training provided through courses FI-210 and FI-310).

Methods

Empirical model

In this analysis, we examined the number (count) of wildfires ignited by smoking materials by state by month in years 2000–11. A zero-inflated negative binomial (ZINB) model was used because of the number of observations (state–months) without any smoking-caused wildfires (83%). The ZINB model

[A]These cigarettes are also known as 'fire-safe cigarettes' and 'fire-standard-compliant cigarettes'.

allows for a statistical hurdle process to affect the number of wildfires in each state–month. Specifically, the ZINB model allows for a count process to be (1) always zero or (2) zero or sometimes a positive integer, by using a different set of covariates to explain the two states. The equations for the model are:

$$\Pr(Y_i = 0) = P + (1 - P)\left(\frac{\theta}{\theta + \lambda_i}\right)^{\theta} \tag{1}$$

$$\Pr(Y_i = y_i) = \frac{(1 - P)\Gamma(\theta + y_i)}{y!\Gamma(\theta)}\left(\frac{\lambda_i}{\theta + \lambda_i}\right)^{y_i}\left(\frac{\theta}{\theta + \lambda_i}\right)^{\theta}, \quad y_i = 1, 2, \ldots \tag{2}$$

where Y is the count of smoking-caused wildfires; i indexes the observations (state–month–year combinations); θ is a shape parameter; $P = \Pr(s_i = 0)$ and s is a binary variable indicating the state (0 if wildfires caused by smoking never occur [state 1]; 1 otherwise); $\lambda_i = e^{\beta' \mathbf{x}_i}$, which is the conditional mean number of smoking-caused wildfires per period, and is a function of covariates $\mathbf{x}$ and parameters β. In this analysis, we assume, as is standard with the ZINB model, that the probability of state 1 can be estimated as a function of covariates $\mathbf{z}$ ('zero-inflation factors') and parameters γ, such that $\Pr(s_i = 0) = F(\mathbf{z}_i, \gamma)$.

In this analysis, the probability of state 1 was estimated using the logit specification, so that $F(\mathbf{z}_i, \gamma) = (1 + e^{\gamma' \mathbf{z}_i})^{-1}$. Using Stata 12 (StataCorp 2011), we maximised the following log-likelihood function with respect to the parameters of the ZINB model (θ, γ, β):

$$\begin{aligned}\ln L = \sum_{i=1}^{N} &(1 - s_i)\ln[F(z_i, \gamma) + \{1 - F(z_i, \gamma)\}(1 + \theta^{-1}e^{\beta' x_i})^{-\theta}] \\ &+ s_i[\ln\{1 - F(z_i, \gamma)\} + \ln\Gamma(\theta + y_i) - \ln\Gamma(y_i + 1) \\ &- \ln\Gamma(\theta) - \theta\ln(1 + \theta^{-1}e^{\beta' x_i}) - y_i\ln\{1 + \theta e^{-\beta' x_i}\}]\end{aligned} \tag{3}$$

where Γ denotes the Gamma distribution.

Data

Monthly data from January 2000 to December 2011 were assembled for the aggregate of all of the national forests and national grasslands (only) located within each state for 12 states: Alaska, California, Illinois, Kentucky, Minnesota, Montana, Oklahoma, Oregon, Pennsylvania, Texas, Utah and Vermont. Fig. 1 depicts all wildfire ignitions reported to the NIFMID between 1980 and 2011, and Fig. 2 presents the same data for the 12 states studied in this analysis. The states were chosen because they had a LFP cigarette regulation by 2009.[B] Fig. 3 provides the number of forests and grasslands by state. Fig. 4 shows the location of the forests and grasslands by state.

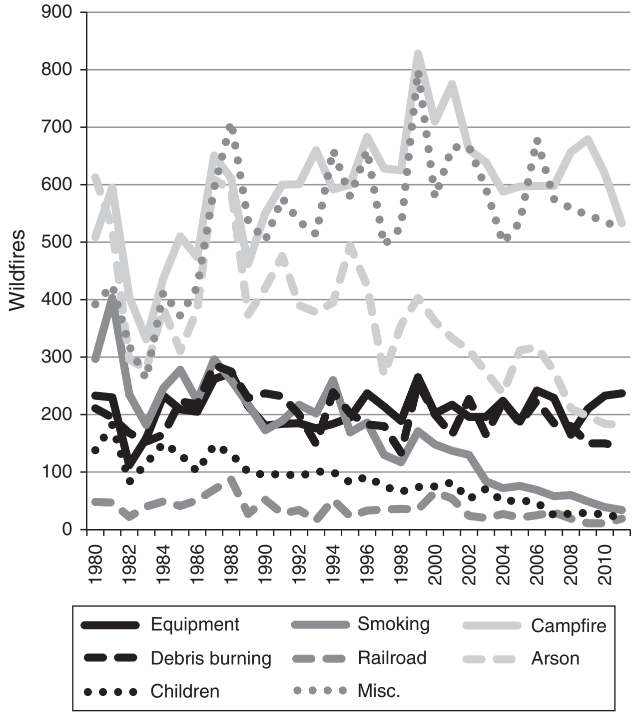

Fig. 2. Number of wildfires reported to National Interagency Fire Management Integrated Database 1980–2011 for the 12 states included in this analysis.

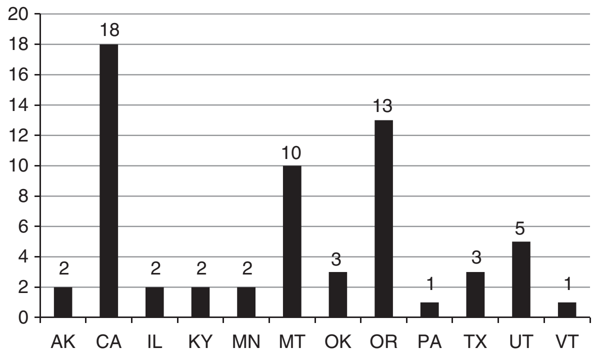

Fig. 3. Number of National Forests and Grasslands by state.

The number of wildfires caused by smoking [SFIRE] was regressed, using a state-wide ZINB model, on a set of covariates:

- a binary variable (LFP) indicating whether the sale of LFP cigarettes was mandated by the state (Table 1 provides the month when each state's regulations came into effect)[C];

[B]The analysis was restricted to states that had a regulation by 1 January 2009 because some cigarette manufacturers began voluntarily producing only LFP cigarettes for all states by the end of 2009 (USA Today 2009). Thus, prior to states requiring the use of LFP cigarettes in 2010 and 2011, some of the cigarettes sold within these states would have met the requirement.

[C]There is reason to assume that the sale and use of non-compliant cigarettes continued beyond the enactment dates shown in Table 1. First, states varied in their 'sell-through' period, which allowed vendors to sell non-compliant cigarettes already in stock. Second, cigarette smuggling occurred between unregulated, low-tax states and regulated, higher tax states. Third, forest visitors that originated from an unregulated state may have brought non-compliant cigarettes.

Fig. 4. States included in analysis are shown in white, with their national forest and grasslands in dark grey (states not included are masked in light grey).

Table 1. Date of less fire-prone cigarette regulation by state (first full month)

State	Month of regulation
Alaska	August 2008
California	January 2007
Illinois	January 2008
Kentucky	April 2008
Minnesota	December 2008
Montana	May 2008
Oklahoma	January 2009
Oregon	July 2007
Pennsylvania	January 2009
Texas	January 2009
Utah	July 2008
Vermont	May 2006

- a binary variable (NWCG) indicating whether National Wildfire Coordinating Group courses FI-210 or FI-310 were in existence;
- the number (millions) of adult smokers (SMOKERS), as reported by the Center for Disease Control's Behavioural Risk Factor Surveillance System[D];
- the number (millions) of state-wide average annual visits to national forest and grasslands (VISITS), as reported by the USDA Forest Service's National Visitor Use Monitoring Program (Round 2 estimates)[E];
- the number of non-lightning, non-smoking-caused wildfire ignitions – that is, the number of other human-caused ignitions – lagged 1 month (HUMAN1) to avoid simultaneity;
- number of forest–days (number of days in the month with reported weather data multiplied by the number of forests in the analysis) in the month (DAYS);
- number of forest–days with a maximum temperature equal to or greater than 90°F (32°C) (TEMP90);
- number of forest–days with maximum wind speed $\geq$15 miles per hour (6.7 m s^{-1}) (WIND15);
- number of forest–days with 10-h fuel moisture (a time-lag measure of moisture in dead forest fuels between 1/4 to 1 inch, 0.635–2.54 cm, in diameter) $<$14% (FUEL14);
- number of forest–days with minimum relative humidity $<$22% (RH22);
- number of forest–days with any precipitation (PRECIP);
- size of total national forest and national grassland (millions of acres) (FOREST);
- total state-wide population (millions) (POP) (based on the 2000 census); and
- binary variables indicating high (HSEASON) and low fire season (LSEASON) applicable to the national forests and grasslands of the state, which varied across states. High fire seasons were months with $\geq$10% or more of the average annual wildfire ignitions. Low fire seasons were months with $\leq$1% of the average annual wildfire ignitions.

[D]Data on youth cigarette use were not used because of the large number of missing observations over the study period.

[E]Round 2 estimates were conducted from 2005 to 2009 and resulted in one set of estimates for each national forest and national grassland. Thus, in our analysis, the number of visits varies by state but not over time.

Table 2. Descriptive statistics (*n* = 1592)

Variable	Mean	s.d.	Minimum	Maximum
SFIRE	0.60	1.910	0	18.00
HUMAN	14.66	32.15	0	249.00
LFP	0.32	0.47	0	1.00
NWCG	0.76	0.43	0	1.00
MOS_NWCG* (HUMAN1/VISITS)	89.61	250.20	0	4473.00
SMOKERS	1.28	1.26	0.08	4.34
VISITS	7.18	9.50	0.35	35.18
(SMOKERS/ADULTS)* VISITS	1.22	1.43	0.06	6.05
TEMP90	19.62	46.02	0	362.00
WIND15	5.61	7.02	0	37.00
FUEL14	159.20	172.20	1	619.00
RH22	53.82	93.15	0	500.00
PRECIP	43.54	56.67	0	396.00
DAYS	161.60	172.90	1	619.00
HSEASON	0.34	0.47	0	1.00
LSEASON	0.22	0.41	0	1.00
POP	9.29	10.56	0.61	37.25
FOREST	8.51	8.73	0.73	24.36

Wildfire (SFIRE and HUMAN1) and weather (TEMP90, WIND15, FUEL14, RH22 and PRECIP) variables were assembled from NIFMID. The (lagged) number of non-lightning, non-smoking-caused wildfire ignitions (HUMAN1) was included to account for unobserved factors related to the ignition process that vary across time and states. The weather factors were chosen to best describe the weather conditions needed to support ignition from smoking materials. National forest and grasslands were matched to the nearest reporting weather station based on Euclidean distance between their centroids. The forest weather data, measured in number of days meeting some threshold (see above), were aggregated to produce state-wide numbers. The *Wildfire origin & cause determination handbook* indicates that cigarettes generally do not result in ignition unless relative humidity is <22% and fine dead fuel moisture is <14% (NWCG 2005, p. 70). Although a better indicator of fine fuel moisture than the 10-h moisture index, 1-h fuel moisture was not available,[F] and the measures are correlated over time. The wind and temperature thresholds were based on expert judgment (S. Scranton, Bureau of Indian Affairs, National Interagency Fire Center, pers. comm., 17 January 2013). Our chosen threshold was also comparable to published estimates of wind speeds above which cigarettes fail to ignite vegetation litter: Xanthopoulos *et al.* (2006) shows that at wind speeds $>8\,\mathrm{m\,s^{-1}}$ (17.9 miles per hour), the probability of ignition in dead grass from a discarded cigarette is zero; and Satoh *et al.* 2003 found cigarettes could not ignite dried Japanese oak leaves (*Quereus acutissma*) in winds of $\geq 4\,\mathrm{m\,s^{-1}}$ (9 miles per hour).

Table 2 presents descriptive statistics of the variables used in estimation. Of the 1728 possible observations, 127 had missing weather station data. A total of 1601 observations were available for estimation; however, the use of a 1-month lagged value for human-caused wildfires (HUMAN1) reduced the final number of observations to 1592. Fig. 5 shows the total number of smoking-caused wildfires by state.

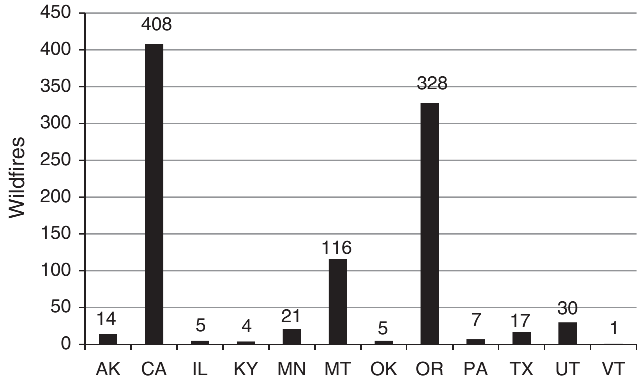

Fig. 5. Numbers of wildfires in National Forests and Grasslands caused by smoking materials from 2000–2011, by state.

Improved cause-determination methods could have two opposite effects on the reported number of smoking-caused wildfires: smoking-caused wildfires are better determined, so the reported number increases (i.e. historical under-attribution existed before better training), or other causes are better determined in the presence of smoking material, in which case the number of smoking-caused wildfires decreases (i.e. historical over-attribution existed). We have no *a priori* expectation for the net effect.

We considered two ways to control for improved cause-determination methods. The first was to use a simple binary variable (NWCG), equal to 0 before January 2003 and 1 subsequently. The second way was to use a duration variable to account for time since January 2003 (in months) (MOS_NWCG) interacted with the ratio of lagged human-caused wildfires to the number of forest visits (HUMAN1/VISITS). (The VISITS variable does not vary over time.) This latter specification allows the effect of improved cause-determination methods to increase over time – as exposure to the new guidance and experience grows – while controlling for the amount of recent investigation activity.

In addition, two alternative specifications were considered for smoking behaviour. The first was using the number of adult smokers (SMOKERS), while controlling for the number of forest visits (VISITS) (both variables entering the model separately). A second measure assumed the proportion of adults that smoke is the same for forest visitors, as is their smoking consumption – thus, the proportion of adults that smoke (SMOKERS/ADULTS) was multiplied by visits (VISITS).

Given two possible specifications of the smoker and cause-determination variables, three smoking models are estimated, which vary with respect to the smoker, visitation and improved determination method variables: Model 1 includes SMOKERS,

[F]Two anonymous reviewers suggested a lower 10-h fuel moisture threshold than the 14%. Based on their guidance we evaluated all the statistical models (presented below) using five alternative thresholds, ranging from 7 to 11%. For every combination, there was no change in the results (e.g., the log-likelihood remained the same).

Table 3. Results of the zero-inflated negative binomial regression of smoking-caused wildfires, including two alternative specifications, and human-caused wildfires (not including smoking)
Note: significant are ***, at 1% level; **, at 5% level; *, at 10% level

	SMODEL1		SMODEL2		SMODEL3		HMODEL	
MAIN PORTION	IRR	SE	IRR	SE	IRR	SE	IRR	SE
Intercept	0.1552***	0.0486	0.2965***	0.0805	0.1184***	0.0375	1.6250***	0.2047
LFP	0.7714**	0.0924	0.7868**	0.0961	0.7958*	0.1113	0.9438	0.0658
NWCG	0.5212***	0.0560	0.5623***	0.0609			0.9094	0.0658
MOS_NWCG*(HUMAN1/VISITS)					0.9992**	0.0004		
SMOKERS	1.6186**	0.3225			2.3543***	0.4719	0.9071	0.1285
VISITS	0.9055**	0.0370			0.9516	0.0383	0.9551***	0.0140
(SMOKERS/ADULTS)*VISITS			1.2156	0.1507				
TEMP90	0.9998	0.0008	0.9999	0.0007	0.9994	0.0008	0.9984**	0.0008
WIND15	0.9870	0.0083	0.9816**	0.0081	0.9943	0.0086	1.0158***	0.0045
FUEL14	0.9915	0.0070	0.9922	0.0066	0.9895	0.0071	0.9697***	0.0049
RH22	1.0031***	0.0011	1.0027***	0.0010	1.0026**	0.0011	1.0020**	0.0010
PRECIP	0.9963**	0.0018	0.9961**	0.0018	0.9944***	0.0018	0.9954***	0.0012
DAYS	1.0162**	0.0071	1.0123*	0.0067	1.0173**	0.0073	1.0387***	0.0054
HSEASON	1.6620***	0.2032	1.6799***	0.1996	1.7420***	0.2199	3.0692***	0.2028
POP	0.9462*	0.0302	0.9376***	0.0080	0.8854***	0.0273	1.0149	0.0190
FOREST	1.0733***	0.0187	1.0309**	0.0160	1.0696***	0.0190	1.0176***	0.0067
INFLATE PORTION	Coeff.	SE	Coeff.	SE	Coeff.	SE	Coeff.	SE
Intercept	−0.6482	0.6333	−0.5715	0.5737	−0.2800	0.5553	−2.0716***	0.3727
HUMAN1	−0.0790***	0.0316	−0.0583***	0.0165	−0.0899***	0.0257		
POP	−0.0810	0.1072	−0.0638**	0.0263	−0.0732	0.1042	−0.0039	0.1374
PRECIP/DAYS	5.6488***	1.4883	6.3357***	1.3004	5.3010***	1.3407	5.3053***	0.8105
LSEASON	2.8956***	0.7348	3.4865***	0.8258	2.7255***	0.6678	3.8503***	0.3625
SMOKERS	0.4612	0.7579			0.3318	0.7369	−0.7921	0.8867
VISITS	−0.0144	0.0487			−0.0020	0.0441	−0.4236***	0.0540
(SMOKERS/ADULTS)*VISITS			−0.1318	0.2458				
SMOKE1							−0.9290	0.5761

VISITS and NWCG; Model 2 includes (SMOKERS/ADULT × VISITS) and NWCG; Model 3 includes SMOKERS, VISITS and (MOS_NWCG × HUMAN1/VISITS). In addition, the non-zero count portion of the ZINB model includes LFP, TEMP90, WIND15, FUEL14, RH22, PRECIP, DAYS, HSEASON, FOREST and POP. The zero-inflation portion of the model (**z**) includes HUMAN1, POP, PRECIP normalised by DAYS and LSEASON. The variables for the zero-inflation portion of the model account for a hurdle process, so these variables were selected to describe times when the likelihood of any ignition is low. It is expected that months with a higher proportion of days with rain (RAIN/DAYS) or of low wildfire activity (HUMAN1, LSEASON) are correlated with zero probability of smoking-caused wildfires. Population is included to account for any unobserved factors correlated with population size.

To evaluate the potential for spurious correlations between the count of smoking-caused wildfires and LFP cigarettes, improved wildfire cause-determination methods and smokers, a fourth (control) model is estimated that replaces the count of smoking-caused wildfires with the count of all human-caused wildfires, not including smoking (HUMAN).

Results

Model output for all four models is summarised in Table 3, which reports for each model the incident rate ratios (IRR) of each covariate in the main (count) model, coefficients of each covariate in the inflation model, standard errors for each IRR or coefficient, along with their *z*-scores and significance. Of the three smoking-caused wildfire models, SMODEL1 had the lowest Akaike Information Criterion (AIC) (1639), hence is the preferred model and is the focus of the findings and discussion below. The AICs for SMODEL2 and SMODEL3 were 1645 and 1671.

For SMODEL1, the likelihood ratio Chi-square statistic was 428.67, which, with 13 degrees of freedom, is significant at the 1% level. A Vuong test (Vuong 1989), with a null hypothesis of no zero inflation, was rejected at the 1% level ($z = 5.79$); thus, the ZINB specification was preferred over a standard negative binomial model. A likelihood ratio test, with a null hypothesis of $\theta = 0$, was rejected at the 5% level ($\chi^2 = 7.79$), which justifies the application of a ZINB specification over its zero-inflated Poisson counterpart.

Count model

LFP cigarettes were correlated with a reduction in smoking-caused wildfires. States with such regulations were estimated to have 23% fewer smoking-caused wildfires than states without. This should be viewed as a lower bound estimate, as we assume non-compliant cigarettes were sold after the enactment date, which would result in a downward bias of the LFP IRR .

Improved wildfire cause determination (NWCG) was correlated with fewer smoking-caused reported wildfires, implying that several wildfires were incorrectly classified as being caused by smoking materials (SFIRE) in the past. The improved cause-determination methods are expected to have reduced SFIRE by 48% (i.e. 48% of classified smoking-caused wildfires were actually ignited by other causal agents).

The number of adult smokers (SMOKERS) in a state was correlated with higher SFIRE. The results show that for an additional 1×10^6 smokers, SFIRE increases by a factor of 1.62, meaning a decline in smokers is expected to reduce the number of smoking-caused wildfires. Estimated average annual forest visits (VISITS) with the number of smokers held constant were negatively correlated with smoking-caused wildfires. This indicates that popular national forests tend to have fewer wildfires caused by smoking materials than those less frequented.

The weather variables RH22 and PRECIP were correlated with SFIRE, as expected. The weather variables TEMP90, WIND15 and FUEL14 were not correlated with SFIRE. High temperature may raise the likelihood of a cigarette ignition; however, at extreme levels it may decrease daily forest use (we considered a TEMP90 $\times$ VISITS interaction, but found no evidence of an effect on SFIRE, perhaps because of the time-invariant nature of the VISITS variable). Furthermore, although higher winds increase the likelihood of an ignition, they also may make it more difficult for a cigarette to ignite wildland fuels. However, this is dependent on whether or not the cigarette's placement is sheltered from the higher winds. Higher winds tend to disperse the heat from cigarettes, reducing their potential as a competent ignition source. The lack of significance of FUEL14 may indicate that the 1-h fuel moisture is a better descriptor of fine fuel conditions than is 10-h fuel moisture; this may also imply that fine fuels are a key factor in smoking ignitions, perhaps in contrast to some other kinds of ignitions.

Forest–days per month (DAYS) and the size of forestlands (FOREST) were positively correlated with smoking fires. Essentially these variables account for 'opportunity' in time and space. Population (POP) was negatively correlated; however, the number of adult smokers was already accounted for. It is likely that POP is picking up unobserved cross-sectional or time-series effects. Finally, months of high wildfire activity (HSEASON) were positively related to smoking wildfires, such that we see an increase in these fires by 66% over low and moderate months.

Inflate model

The zero-inflation model controls for observations (state–month combinations) that have 'too many' months of no reported SFIRE (i.e. would never have SFIRE), as compared to a traditional negative binomial count model. The coefficients shown in Table 3 provide a measure of correlation between the covariate and the probability that the count of SFIRE is zero. The number of lagged human ignitions (HUMAN1) was significant and negatively related to the probability of no SFIRE (as expected). The proportion of days with precipitation (PRECIP/DAYS) and the indicator variable for low fire season (LSEASON) were positively correlated with the probability of no SFIRE (as expected).

Control (human) model

Notable differences between the human-caused (HMODEL) and smoking-caused models (SMODEL1) included the lack of correlation exhibited between human-caused ignitions and LFP cigarettes, number of smokers and the improvement in wildfire cause determination. We would expect that if LFP and NWCG are capturing the effect of less fire-prone cigarettes and number of smokers, these variables would be significant in the SMODEL1, but not in HMODEL. With improved wildfire cause-determination methods, and given the relatively small number of smoking-caused wildfires excluded from the HMODEL, we would expect the net effect to be approximately zero, which is what we find.

In addition, we found that for the human-caused model, temperature, wind speed and fuel moisture were significantly correlated with the number of wildfires. The average number of visits was also negatively correlated with the number of wildfires, which was unexpected, but again, likely suggesting that a higher number of wildfires occur in less popular forests, all else being equal. However, visits were negatively correlated with the probability of no wildfire, meaning a (non-smoking) human-caused wildfire is more likely to occur in popular forests.

Discussion

Based on the ZINB model, the numbers of avoided smoking fires due to fire-safe cigarettes (LFP), improved cause-determination methods (NWCG), and changes in the number of adult smokers were estimated over the study period. For LFP and NWCG, the expected SFIRE of those observations with LFP or NWCG in effect (i.e. the indicator variable equals one) was compared to the expected number of wildfires had LFP or NWCG not been in effect (i.e. the indicator variable equals zero). Given that adult smoking rates have been falling over time, the number of avoided smoking fires due to changes in SMOKERS was estimated by comparing the actual ignition rates with those expected had the numbers of adult smokers been held constant to that at the beginning of the study period.[G]

To make meaningful comparisons between the effects of LFP, NWCG and SMOKERS on the number of smoking-caused wildfire ignitions, the comparisons were made over the same subset of observations (i.e. for only those state–month combinations with a cigarette requirement in effect). Thus, the total effect of improved cause determination and reduction in adult smokers will be smaller than if we had examined their effect over the entire sample. The interest here is to place into perspective the effect that LFP cigarettes have had on SFIRE.

Out of 1592 state–months examined, 32% had a fire-safe cigarette regulation in effect. It is estimated that the regulation

[G]If actual decline in smoking by forest visits is greater (less) than that of the general public, then the effect shown in this analysis will overestimate (underestimate) the actual effect because given data limitations, we assume the change in smoking rates of forest visitors is the same as those of the general public.

Table 4. Statistics on hectares burned and firefighting costs by cause type aggregated over the 12 study states (see text) from 2000 to 2011 (2012 US dollars)

Cause	Ignitions	Hectares burned	Firefighting cost	Average hectares burned	Average firefighting cost
Lightning	26 207	2 333 635	$2 479 878 138	89.0	$94 626.56
Equipment use	2539	275 355	$336 299 391	108.5	$132 453.48
Smoking	956	8060	$21 985 273	8.4	$22 997.15
Campfire	7654	339 402	$346 444 774	44.3	$45 263.23
Debris burning	2196	89 746	$122 682 528	40.9	$55 866.36
Railroad	326	28 729	$54 891 863	88.1	$168 379.95
Arson	3197	260 627	$453 041 885	81.5	$141 708.44
Children	557	26 110	$26 233 423	46.9	$47 097.71
Miscellaneous	6955	773 805	$1 022 089 371	111.3	$146 957.49

avoided 67 smoking fires (23% reduction) – one avoided wildfire every eight state–months. By comparison, the change (net reduction) in adult smoking rates is expected to have avoided 23 smoking fires (9% reduction). Improvement in wildfire cause determination appears to have resulted in 207 ‘smoking-caused wildfires’ to be correctly classified as something other than a smoking-caused wildfire (48% reduction). Although improved wildfire cause-determination methods do not necessarily reduce the number of wildfires, they ensure that the causes of wildfire are accurately tracked. Accurate wildfire cause determination can, however, result in targeting wildfire-prevention programs to specific fire-cause categories, which can lead to a reduction in the overall number of wildfires.

Table 4 provides statistics on hectares burned and firefighting cost by each wildfire cause for the 12 states (in aggregate) used in the analysis. For smoking-caused wildfires, the average area burned was 8.4 ha and the average firefighting cost was US $23 000 per wildfire. Avoiding 67 fires due to LFP regulations resulted in firefighting savings of $1.5 million. Using $3465 as the price of net value change per hectare (following Prestemon *et al.* 2010, adjusted to 2012 dollars and based on an average wildfire, irrespective of cause), then the total net value change was $2 million. Thus, 67 avoided smoking-caused wildfires translates into a cost and loss avoidance of $3.5 million – or $52 000 per wildfire. If this relationship represents future scenarios, it is expected that for the 12 states included in the analysis, LFP cigarettes will result in a cost and loss savings of $1 million per year for the national forests and grasslands of these 12 states.

We contend that these benefits are accruing nationwide, not just in the national forests and grasslands of the states analysed in this study. Avoided costs and losses, therefore, are likely to be several times higher than the $1 million figure identified here for the studied Forest Service managed units. In 2012, the 12 states included in this analysis represented 47% of all national forest plus national grassland area (USDA Forest Service 2013), whereas USDA Forest Service forest lands accounted for only 25% of all forestland in the US (National Atlas 2013). Private forests accounted for 67% of all forest area (National Atlas 2013) and 89% of the WUI (Theobald and Romme 2007).

Conclusions

This analysis evaluated possible reasons for the decline in reported smoking-caused wildfires. Three factors hypothesised to be at least partially responsible include (1) the decline in the number of adult cigarette smokers; (2) the advent of LFP cigarettes and (3) the use of improved wildfire cause-determination methods. Each of these factors was found to be statistically linked to the number of smoking-caused wildfires, and at the same time, not correlated with the number of other human-caused wildfires. In addition, population increases and changes in weather patterns (relative humidity and wind speed) were found to explain the monthly number of smoking wildfire ignitions, whereas monthly precipitation rates and unobserved factors related to the ignition success of other human-caused wildfires were found to play a role in determining the presence or absence of monthly smoking-caused wildfires.

Reduced smoking rates in the population have led to lower overall rates of wildfires in national forests. LFP cigarettes have resulted in economic benefits that go beyond those intended – to save lives and properties from smoking-caused structure fires, mainly in residences. For the national forests in the 12 states that we evaluated, LFP cigarettes avoided costs and losses of $1 million per year. Improved wildfire cause-determination methods means that earlier fires were misclassified at a high rate, with nearly half of so-called ‘smoking’ fires actually having other causes. This implies the actual numbers of smoking-caused fires were originally overestimated suggesting that wildfire ignition by a cigarette may be more difficult than once believed. Although improved wildfire cause-determination methods do not necessarily reduce the number of wildfires, they ensure that the causes of wildfire are accurately tracked. Accurate wildfire cause determination can, however, result in targeting wildfire-prevention programs to specific fire-cause categories, which can lead to a reduction in the overall number of wildfires. These effects should not be ignored when analysts seek to assess the overall net benefits of reduced smoking on human welfare. Although smoking-caused wildfires constitute a small proportion of all human-caused wildfires, both in terms of ignitions and area burned, their downward trend is clear. LFP cigarettes and the decline in adult smoking rates suggest that technologies and changes in human behaviour can significantly influence unwanted fire starts.

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