CSIRO PUBLISHING

www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2005, **14**, 213–222

Forest fire causes and extent on United States Forest Service lands

Scott L. Stephens

Division of Ecosystem Science, Department of Environmental Science, Policy, and Management,
University of California, Berkeley, CA 94720-3114, USA. Telephone: +1 510 642 7304;
email: stephens@nature.berkeley.edu

Abstract. Nationally, the causes and extent of fire on lands administrated by the United States Forest Service varied significantly from 1940 to 2000, with California experiencing the largest relative annual burned areas. The south-east and California experienced the largest relative area burned by fires from human ignitions. No significant differences were detected in the relative area burned by lightning in California, the upper and central Rocky Mountains, and the south-west, which all experienced the highest levels. The north-west and Rocky Mountains have experienced significant increases in the relative total area burned; the north-east, south-east, California, and coastal Alaska all remained unchanged. The northern Rocky Mountains, south-west, and north-east have all experienced significant increases in the amount of area burned by lightning without significant increases in lightning ignitions. Increasing fuel hazards in these areas probably contributed to the increasing area burned by lightning fires; changing climate could have also contributed to the increase in wildfire area from 1940 to 2000. To be effective across the diverse forest types and conditions in the USA, fire policy should better recognize and respond to the diversity of US forests and how they have burned in the past. This analysis determined that there is high geographical diversity on wildfire occurrence and causes. Local input is therefore important in designing diverse, ground-based solutions to address fire management challenges in the United States.

Additional keywords: fire policy; fire statistics; fire suppression; forest policy; wildfire.

Introduction

In 1891, Congress authorized President Harrison to establish forest reserves, later to be known as United States National Forests (Pinchot 1907; Pyne 1982). Gifford Pinchot became the first Chief of the agency that would manage the preserves, and under his direction, a national forest fire policy was initiated (Pyne 1982; Stephens and Ruth 2005). The exclusion of forest fires dominated early United States Forest Service (USFS) forest policy. The second and third USFS Chiefs (Henry Graves and William Greeley) strongly supported and expanded the policy of fire exclusion during their tenures (Graves 1910; Greeley 1951).

The first national education campaign specifically designed to influence USA public behaviour regarding forest fire began when the USFS created the Cooperative Forest Fire Prevention Program in 1942 (USDA 1995*a*). This program encouraged citizens nationwide to make a personal effort to prevent forest fires. This campaign was modified 3 years later (1945) to produce the national 'Smokey Bear' campaign that is still in existence. Earlier public education campaigns to eliminate forest fire in the south-eastern USA occurred but they were limited in their duration and spatial extent.

The policy of fire exclusion was vigorously debated in the south-eastern USA (Schiff 1962; Pyne 1982; Biswell 1989) because the use of fire was culturally accepted in this area (Shea 1940; Komarek 1962; Schiff 1962). Further, several large wildfires in this region reinforced the need to consider policies that used prescribed burning to reduce fuel hazards (Stephens and Ruth 2005). Passage of the federal Clarke–McNary Act in 1924 tied federal appropriations to the state first adopting fire suppression and this law effectively created a national fire exclusion policy.

Research initiated in the south-eastern (Chapman 1926; Komarek 1962) and western USA (Weaver 1943; Cooper 1960; Biswell 1961) began to identify landscape conditions that could be attributed to fire exclusion. For the first time, significant changes in the structure, composition, and fuel loads were documented in forests that primarily experienced frequent, low to moderate intensity fire regimes. The implications of these investigations were profound but not used by contemporary policy (Stephens and Ruth 2005). The very policy of fire exclusion that had been adopted decades earlier was actually producing forests with high fire hazards, and some of these forests were being burned by high severity wildfire.

10.1071/WF04006 1049-8001/05/030213

Shortly after World War II, fire suppression was enhanced by the use of surplus military equipment (Rowland 1946; Pyne 1982). The addition of fixed-wing aircraft in the late 1930s allowed for more efficient fire detection (Motl 1941; Towne 1941; Trygg 1948) and personnel were delivered to fires by parachute for the first time (USDA 1946). Helicopters were added to the USFS fire suppression network in the 1940s (Godwin 1946; Jefferson 1947).

While the extent and causes of USA forest fires are commonly discussed and debated by the public, politicians, scientists, and land managers, no large-scale statistical analyses are available to provide quantitative support for these forums. Federal agencies such as the USFS have developed new national fire policies that assumed increasing annual area burned by wildfires. However, the statistical analyses that accompany these initiatives are limited (USDA 1995*b*; NWCG 2001).

Further, existing federal fire policies frequently do not differentiate between geographical areas or forest types in the USA and this can produce unwanted effects. Forest type is one of the most significant and most misunderstood elements of the decision about where to implement specific fire management policies (Brown *et al*. 2004; Stephens and Ruth 2005).

Some forest types, such as ponderosa pine (*Pinus ponderosa* Laws.), Jeffrey pine (*Pinus jeffreyi* Grev. & Balf), and mixed conifer, have been negatively impacted by fire exclusion (e.g. higher fuel loads and hazards, increases in shade-tolerant species), but others, such as Rocky Mountain lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.), are adapted to infrequent, stand replacement fires and fire exclusion has probably produced limited impacts to these ecosystems (Romme and Knight 1981; Turner and Romme 1994; Veblen *et al*. 1994; Christensen *et al*. 1998). An analysis that incorporates the different geographic regions of the USA and further identifies the most common types of ignitions, and if the area burned by wildfire has changed, could assist in the creation of regional-specific fire policies.

The objectives of this paper are to determine if causes and extent of wildfires on USFS lands have changed from 1940 to 2000. The second objective is to determine if there are significant geographic differences in wildfire patterns across the USA.

Materials and methods

Analysis of USFS forest fire statistics can be used to assess how forest fire is distributed in the USA and if the number of ignitions or area burned have changed over time. The USFS manages a large forested land base (over 69 000 000 ha) located throughout the USA (Table 1; Fig. 1); the National Park Service and Bureau of Land Management also manage forested lands but at a much smaller spatial scale. The USFS has been collecting annual data on the number of fires by cause and the amount of area burned by cause beginning early in the 20th century.

Forest fire cause and extent data analysed in this work were obtained from the annual USFS forest fire reports (USDA 1940–2000). These reports list the total number of fires by cause, total amount of area burned by cause, and total area protected. Beginning in the early 1940s, USFS forest fire statistics were recorded using machine tabulations from punch cards; before this period the recording methodology was less standardized (Mitchell 1947). The addition of aerial resources to fire suppression shortly after

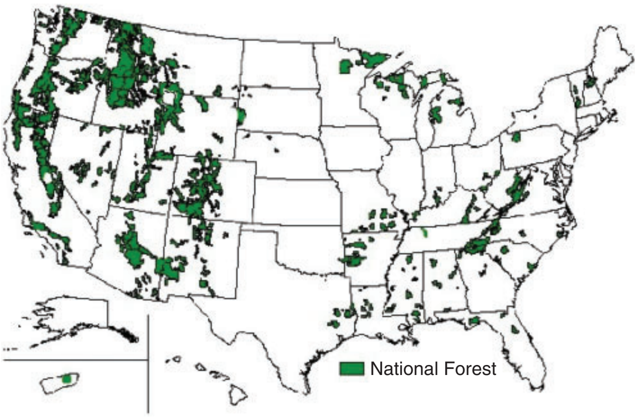

Fig. 1. Locations of the USDA National Forests in the USA.

Table 1. States included in each of the USDA Forest Service regions

Forest Service region	Forest Service region name	States included in USFS region
1	Northern	Montana, northern Idaho, South Dakota, north-eastern Washington
2	Rocky Mountain	Colorado, east and central Wyoming, South Dakota
3	South-western	Arizona, New Mexico
4	Intermountain	Nevada, Utah, southern and central Idaho, western Wyoming, east-central California
5	Pacific South-west	California
6	Pacific North-west	Oregon, Washington
8	Southern	Kentucky, Virginia, North Carolina, South Carolina, Georgia, Alabama, Mississippi, Texas, Arkansas, Florida, Oklahoma, Louisiana
9	Eastern	Minnesota, Wisconsin, Michigan, Missouri, Illinois, Indiana, Ohio, West Virginia, Pennsylvania, New York, New Hampshire, Vermont
10	Alaska	Alaska (southern and central coastal areas only)

World War II increased fire detection efficiency and accuracy (USDA 1960). Adoption of a standard recording methodology for fire statistics in the early 1940s coupled with an increased awareness of the importance of the annual fire reports increased their accuracy (Mitchell 1947).

Collectively, the addition of aerial resources and adoption of a standard recording methodology for fire statistics resulted in higher accuracy in the USFS data beginning in about 1940. This information was used to select the beginning year of this analysis at 1940. Even with improvements in technology and increased agency awareness, there probably are some inaccuracies in the USFS data after 1940. Nevertheless, these data represent the largest, most comprehensive source of forest fire information in the USA.

The USFS data are collected primarily from forested areas. Other vegetation types such as grasslands, shrublands and deserts are not well represented in the USFS data. Major forest types that occur throughout the continental USA (lower 48 states) are well represented (Fig. 1). Data from Alaska are from the Tongass and Chugach National Forests located in south-eastern and south central Alaska respectively. The Tongass and Chugach National Forests are dominated by high-precipitation coastal forests. The Chugach, however, does include some areas of inland boreal and subalpine forests.

The data analysed in the study do not include fires on privately held lands or those managed by other state or federal agencies. Fire occurrence data exist for many of these areas; however, the management agencies responsible for these lands have used a variety of recording methodologies and there has been limited effort to coordinate data collection and dissemination. No other US agency has such a large, well-distributed forest fire database as the USFS.

The forests managed by the USFS are separated into regions (Table 1; Fig. 1). The amount of land managed by each region has changed over the decades, and each region has a different total land base. With different-sized and changing land bases, six normalized metrics were calculated for all regions: (1) annual ha burned for every 400 000 ha protected (relative burned area); (2) annual number of fires for every 400 000 ha protected (relative total fires); (3) annual ha burned by lightning fires for every 400 000 ha protected (relative lightning area); (4) annual number of lightning fires for every 400 000 ha protected (relative lightning fires); (5) annual ha burned from human-caused fires for every 400 000 ha protected (relative human area); and (6) annual number of human-caused fires for every 400 000 ha protected (relative human fires). Relative burned area is the sum of relative lightning area and relative human area; relative total fires is the sum of relative lightning fires and relative human fires. USFS regions vary in size from about 3 to 12 million ha with smaller regions in the east and larger regions in the western USA. A base area of 400 000 ha was selected because this has been used in other analyses (Pyne 1997), it is also about 1 000 000 acres and several US land management agencies have used this land base when reporting fire statistics.

The 54 time series (six normalized metrics from nine USFS regions) exhibited right-skewed frequency distributions. An example of the common distribution pattern is given in Fig. 2 for California's total hectares burned for every 400 000 ha protected (relative burned area). The distributions commonly include many years with a small or moderate number of ignitions or ha burned and a few years with large events. The values of relative burned area, relative lightning area, and relative lightning fires from the north-eastern USA and Alaska are frequently small (less than 1) or zero. All series expressed heteroscedasticity and were $\log_{10}(x + 1)$ transformed to stabilize the variance and to convert the skewed distributions into symmetrical distributions (Fig. 3) (Zar 1999).

For both the ANOVA and linear regression analyses, it is noted that serial dependence is present in the data, which could occur due to the time required for areas burned in previous years to accumulate enough fuel to reburn. Serial dependence could also be produced from multi-year droughts

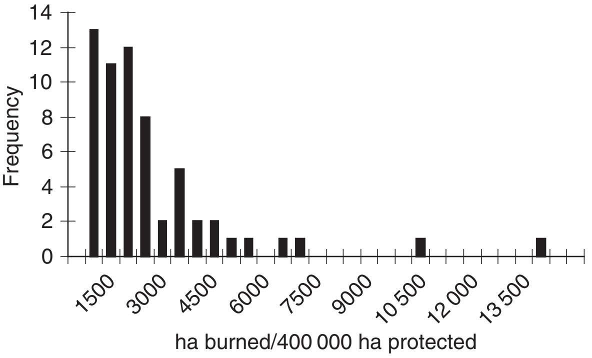

Fig. 2. USDA Forest Service Region 5 (California) total hectares burned for every 400 000 ha protected from 1940 to 2000.

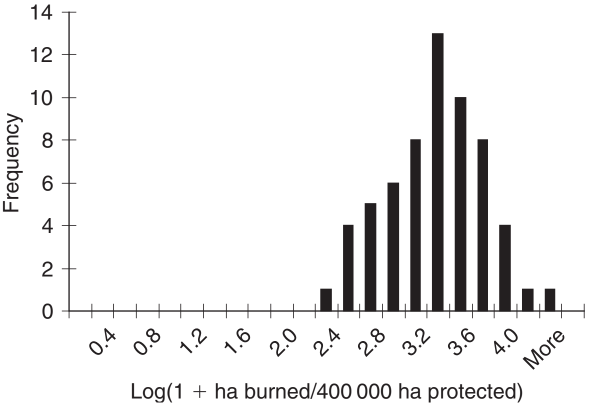

Fig. 3. Transformation (log + 1) of USDA Forest Service Region 5 (California) total hectares burned for every 400 000 ha protected from 1940 to 2000.

Table 2. Homogeneity of variance test P values for time-series data by fire variable and USFS region
Tests were performed on log-transformed differenced data

Region	All types		Lightning		Human	
	Ha burned	No. fires	Ha burned	No. fires	Ha burned	No. fires
1	0.014[A]	0.562	0.002[A]	0.285	0.012[A]	0.099
2	0.275	0.631	0.799	0.074	0.688	0.003[A]
3	0.495	0.227	0.323	0.724	0.367	0.057
4	0.028[A]	0.610	0.135	0.637	0.100	0.399
5	0.001[A]	0.431	0.067	0.250	0.094	0.771
6	0.038[A]	0.174	0.020[A]	0.913	0.250	0.132
8	0.268	0.268	0.479	0.059	0.513	0.296
9	0.278	0.212	0.110	0.621	0.360	0.257
10	0.480	0.931	–	–	0.014[A]	0.830

[A] Series that were not stationary ($P < 0.05$).

that could increase the area burned for several successive years. Analysis of the 54 metrics indicated that significant autocorrelations existed at lags less than 3 years, with most of the metrics having significant autocorrelations with a lag of 1 year. To reduce serial dependence, 5-year averages were calculated for each variable over the 61-year record (12 data points). This condensed dataset was used in the analyses described below.

An analysis of variance was performed on the transformed, 5-year averaged data by USFS region to determine if significant differences ($P < 0.05$) existed in relative burned area, relative total fires, relative lightning area, relative lightning fires, relative human area, and relative human fires from 1940 to 2000 (12 data points for each variable). If significant differences were detected, a Tukey Multiple Comparison Test was performed to determine if there were significant differences in relative burned area, relative total fires, relative lightning area, relative lightning fires, relative human area, and relative human fires between USFS regions.

To determine if relative burned area, relative total fires, relative lightning area, relative lightning fires, relative human area, and relative human fires significantly ($P < 0.05$) changed (increased, decreased, no difference) from 1940 to 2000, a linear regression analysis was performed on the transformed, 5-year averaged data by USFS region (12 data points for each variable). The independent variable in the regression analysis was the midpoint year of the average 5-year range, and the dependent variable was the corresponding transformed 5-year averages of relative burned area, relative total fires, relative lightning area, relative lightning fires, relative human area, and relative human fires. Others have used the log-transform in the regression analysis of skewed USFS annual area burned data (McKenzie *et al.* 2004).

Time series analysis was also performed to determine if trends occurred in burned area, total fires, lightning area, lightning fires, human area, and human fires from 1940 to 2000 (61 years of data for each variable). Time series analysis is primarily used to forecast economic conditions into the future but can also be used to determine if a trend is present in archived data.

Autoregressive moving average (ARMA) models were fitted to the USFS fire statistics time-series data using the techniques of Box and Jenkins (1976). An ARMA (p,q) model has autoregressive factors (AR) up to order p and moving average (MA) factors up to order q. The general form of an ARMA (p,q) model is:

$$z_t = \Phi_1 z_{t-1} + \Phi_2 z_{t-2} + \cdots + \Phi_p z_{t-p} + \delta + u_t - \theta_1 u_{t-1} - \cdots - \theta_q u_{t-q}, \quad (1)$$

where z_t = stationary series (number of fires or number of ha burned by cause) ($t = 1, \ldots, T$); Φ_i = parameters of the autoregressive factors ($i = 1, \ldots, p$); θ_k = parameters of the moving average factors ($k = 1, \ldots, q$); δ = constant; and u_t = white noise (a sequence of identically and independently distributed random disturbances with mean zero and variance σ^2).

The data consisted of two sample types (annual number of ha burned and annual number of fires) from three ignition source types (human, lightning, and all ignitions). Fire statistics data included all nine USFS regions from 1940 to 2000.

Stationarity is one assumption of time-series modeling where the data series has a constant mean (no trend) and homogeneous variance. Examination of the transformed time-series plots revealed trends (changes in slope) in all of the series. The 54 time series were tested for stationarity using homogeneity of variance test. If the transformed series was found to have heteroscedasticity, the series was differenced by computing the difference between every two successive values in a series (Box and Jenkins 1976). The differenced series were then retested for homogeneous variance.

Nine series from regions 1, 2, 4, 5, 6, and 10 were not stationary ($P < 0.05$) after one differencing pass (Table 2). These required further transformations increasing the complexity and were considered beyond the scope of time series modeling for this paper. Therefore, they were excluded from the ARMA model identification stage of the analysis.

Table 3. Averages of ha burned for every 400 000 ha protected (relative burned area), number of fires for every 400 000 ha protected (relative total fires), ha burned by lightning fires for every 400 000 ha protected (relative lightning area), number of lightning fires for every 400 000 ha protected (relative lightning fires), ha burned from human-caused fires for every 400 000 ha protected (relative human area), and number of human-caused fires for every 400 000 ha protected (relative human fires) from 1940 to 2000 for each USFS region

	United States Forest Service region								
	1	2	3	4	5	6	8	9	10
Burned area	560.09^{c}	298.52^{c}	709.46^{bc}	762.06^{bc}	1895.40^{a}	509.80^{c}	1233.71^{ab}	339.83^{c}	4.21^{d}
Total fires	38.70^{c}	23.06^{d}	94.03^{a}	26.45^{d}	69.23^{ab}	57.40^{b}	108.71^{a}	42.12^{c}	1.08^{e}
Lightning area	387.11^{a}	135.28^{ab}	439.73^{a}	589.05^{a}	688.99^{a}	401.88^{ab}	77.12^{ab}	11.84^{c}	0.01^{d}
Lightning fires	32.16^{b}	14.11^{d}	73.10^{a}	19.71^{c}	42.81^{b}	37.79^{b}	12.65^{d}	2.17^{e}	0.03^{f}
Human area	172.98^{c}	163.23^{c}	269.73^{bc}	173.01^{c}	1206.41^{a}	107.92^{c}	1156.51^{a}	327.99^{b}	4.20^{d}
Human fires	6.54^{e}	8.95^{e}	20.94^{d}	6.73^{e}	26.42^{cd}	19.61^{d}	96.07^{a}	39.95^{b}	1.05^{f}

$^{a-f}$Mean values in a row followed by the same letter are not significantly different ($P < 0.05$).

The identification stage of Box-Jenkins time-series modeling utilizes the autocorrelation function (ACF) and partial autocorrelation function (PACF) of each data series. These functions can be displayed in graphical form and aid in determining the number of autoregressive (AR) and moving average (MA) parameters to be included in the ARMA model (Box and Jenkins 1976).

Often the autocorrelation function and partial autocorrelation function did give a clear indication as to the appropriate model for the series. In such cases ARMA diagnostic techniques (Hoff 1983; Pankratz 1983) may also be applied to the models to determine the most parsimonious model. One such technique, Akaike's information criterion (AIC) (Akaike 1971, 1974) was used in this analysis. When using this criterion, the model with the smallest AIC is presumed to be the best model. Five models were estimated for each series (ARMA (p,q), with $(p,q) \in \{(1,0), (2,0), (0,1), (0,2), (1,1)\}$).

If the time series model contained only MA components and was created from data that was differenced once, then the output constant in the time series analysis is the linear trend slope of the original series (Box and Jenkins 1976). Similar to the regression analysis, this analysis was used to identify if burned area, total fires, lightning area, lightning fires, human area, and human fires changed from 1940 to 2000.

Results

Analysis of variance

USFS lands in south-eastern and south central Alaska (Region 10) have experienced the significantly lowest relative burned areas and relative number of ignitions in all categories (Table 3). California (Region 5) has experienced the significantly highest relative burned areas; the south-east (Region 8) follows California in relative area burned. The forests in the northern Rocky Mountains (Regions 1 and 2), the north-west (Region 6), and the north-east (Region 9) all had similar relative burned areas that were approximately one-third to one-fourth of California's (Table 3).

The south-west (Region 3) and south-east (Region 8) regions experienced the highest relative total number of fires, followed by California (Region 5). The north-east (Region 9) and the upper Rocky Mountains (Region 1) experienced a similar number of fires. The north-central Rocky Mountains (Regions 2 and 4) experienced the least number of ignitions in the continental US.

There is a great amount of variability in the relative area burned by lightning fires from 1940 to 2000 within each region. No significant difference in the relative area burned by lightning was detected in California (Region 5), the central Rocky Mountains (Region 4), the south-west (Region 3), and the upper Rocky Mountains (Region 1). The north-east (Region 9) had the lowest amount of relative area burned by lightning in the continental US.

The largest human-caused burned areas (relative) occurred in California (Region 5) and the south-east (Region 8) (Table 3); the north-east (Region 9) and the south-west (Region 3) are in the next most significant group. The northern Rocky Mountains (Regions 1 and 2) and the north-west (Region 6) have experienced similar human-caused burned areas (relative), which are the lowest recorded in the continental USA.

The south-east (Region 8) experienced the highest number of human-caused fires (relative), followed by the north-east (Region 9) with slightly less than half of the south-east (Table 3). California (Region 5) follows the north-east (Region 9) in the number of human-caused fires (relative). The northern and central Rocky Mountains (Regions 1, 2, and 4) have experienced the lowest number of human-caused fires (relative) in continental USA.

Regression analysis

The relative area burned by wildfire in the north-west (Region 6) and Rocky Mountains (Regions 1–4) significantly increased from 1940 to 2000; the relative area burned in the north-east (Region 9), south-east (Region 8), California (Region 5), and Alaska (Region 10) did not significantly change (Table 4).

Table 4. Change in the 5-year averages of ha burned for every 400 000 ha protected (relative burned area), number of fires for every 400 000 ha protected (relative total fires), ha burned by lightning fires for every 400 000 ha protected (relative lightning area), number of lightning fires for every 400 000 ha protected (relative lightning fires), ha burned from human-caused fires for every 400 000 ha protected (relative human area), and number of human-caused fires for every 400 000 ha protected (relative human fires) from 1940 to 2000 for each USFS region

+ significantly increased; − significantly decreased at $P < 0.05$; n.s. not significant. Values in parentheses are the P statistic

	United States Forest Service region								
	1	2	3	4	5	6	8	9	10
Burned area change	+ (0.0141)	+ (0.0073)	+ (0.0142)	+ (0.0086)	n.s.	+ (0.0216)	n.s.	n.s.	n.s.
Total fires change	n.s.	+ (0.0237)	n.s.	+ (0.0006)	+ (0.0045)	+ (0.0280)	− (0.0079)	− (0.0003)	n.s.
Lightning area change	+ (0.0499)	n.s.	+ (0.0093)	+ (0.0053)	n.s.	n.s.	n.s.	+ (0.0084)	n.s.
Lightning fires change	n.s.	+ (0.0214)	n.s.	+ (0.0015)	n.s.	n.s.	− (0.0048)	n.s.	n.s.
Human area change	+ (0.0084)	+ (0.0069)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Human fires change	+ (0.0012)	+ (0.0453)	+ (0.0000)	+ (0.0018)	+ (0.0000)	+ (0.0074)	− (0.0131)	− (0.0003)	n.s.

The total number of fires (relative) in the Pacific coastal region (Regions 5 and 6) and the central Rocky Mountains (Regions 2 and 4) significantly increased from 1940 to 2000. The eastern USA (Regions 8 and 9) are the only areas that have experienced a significant decrease in the number of fires (relative) over the same period (Table 4).

The relative area burned by lightning has significantly increased from 1940 to 2000 in the north-east (Region 9), the south-west (Region 3), upper Rocky Mountains (Region 1), and the central Rocky mountains (Region 4) (Table 4). The central Rocky Mountains (Regions 2 and 4) are the only area that experienced a significant increase in the relative number of lightning fires from 1940 to 2000; the south-east (Region 8) is the only area where the relative number of lightning fires have significantly decreased over the same period (Table 4).

The relative area burned by human-caused fires from 1940 to 2000 has significantly increased only in the northern Rocky Mountains (Regions 1 and 2); in all other regions there was no significant change (Table 4). The western USA (Regions 1–6) has experienced a significant increase in human-caused fires (relative) with the exception of Alaska (Region 10). Significant decreases in the number of human-caused fires (relative) have occurred in the eastern USA (Regions 8 and 9) (Table 4).

Time series analysis

For 44 of the 54 time series in this analysis, the transformation and one regular differencing was sufficient to produce a stationary series (Table 2) that was modeled using Box-Jenkins ARMA modeling techniques (Box and Jenkins 1976). The majority of the series modeled (70%) were fitted with a first-order AR or MA parameters (Tables 5, 6). Thirteen series (30%) required either a 2AR or 2MA parameter model. Tables 5 and 6 summarize the model type chosen with parameter and constant estimates for the six different fire variables for each region.

In the context of the fire statistics data, the interpretation of an AR process is that the number of fires and area burned for any given year is a linear combination of previous year's number of fires or area burned plus random error of the current year. An MA process is interpreted as a combination of current and past disturbances for any given year. A first-order MA process model was the most common type fitted to the data analysed in this work.

Regression and time series analysis agreed on the change (increasing, decreasing, no change) of the fire metrics from 1940 to 2000 in 72% of cases where a comparison is possible (time series model contained only first-order MA components and was created from data that were differenced once). The agreement was stronger in the western USA (Regions 1–6, 80% agreement); in the eastern USA the agreement was lower (Regions 8 and 9, 50% agreement). In all cases where the two methods did not agree, the regression analysis indicated that a significant change occurred (+ or −) whereas the time series analysis revealed no trend over the same period.

Discussion

The amount of USFS forests that burned (relative) in the western USA significantly increased from 1940 to 2000 with the exception of Alaska and California (Regions 5 and 10, both experienced no change) (Tables 4–6). The relative total number of ignitions significantly increased in California but this did not produce a significant increase in relative area burned (Tables 4–6). California's initial attack system has been effective in preventing the burned area from increasing; no other area of the USA had significant increases in ignitions without a corresponding increase in relative area burned. Increased human-caused ignitions in California are probably the result of the state's increasing population and recreational use of wildlands. The increase in human-caused ignitions will probably continue into the future as California's population continues to grow and recreation demand increases.

In contrast to the western USA, the relative total area burned in the south-east (Region 8) did not change from 1940 to 2000, possibly as the result of decreasing lightning- and human-caused ignitions (Table 4), combined with the nation's largest prescribed fire program. In the mid-1990s, the USFS

Table 5. ARMA model parameter estimates for USFS fire statistics time series data for Regions 1–5 from 1940 to 2000
AR, autoregressive; MA, moving average; NA, time series model parameters could not be estimated

Region	Variable	ARMA model	Parameter estimates	Constant
1	Human: number ha burned	NA	–	–
	Human: number of fires	2AR	−0.604, −0.463	0.001
	Lightning: number ha burned	NA	–	–
	Lightning: number of fires	1AR	−0.649	−0.007
	All types: number ha burned	NA	–	–
	All types: number of fires	1MA	0.738	−0.004
2	Human: number ha burned	2AR	−0.560, −0.306	0.064
	Human: number of fires	NA	–	–
	Lightning: number ha burned	1MA	0.911	0.001
	Lightning: number of fires	1MA	0.799	0.003
	All types: number ha burned	1MA	0.978	0.025
	All types: number of fires	1MA	0.870	0.003
3	Human: number ha burned	1MA	0.872	0.031
	Human: number of fires	1MA	0.786	0.007
	Lightning: number ha burned	1MA	0.984	0.024
	Lightning: number of fires	1MA	0.703	0.000
	All types: number ha burned	1MA	0.838	0.027
	All types: number of fires	1AR	−0.438	0.001
4	Human: number ha burned	1MA	0.823	0.001
	Human: number of fires	1AR	−0.616	0.001
	Lightning: number ha burned	1AR	−0.698	0.045
	Lightning: number of fires	1MA	0.684	0.002
	All types: number ha burned	NA	–	–
	All types: number of fires	1MA	0.630	0.001
5	Human: number ha burned	1AR	−0.578	0.007
	Human: number of fires	1MA	0.578	0.005
	Lightning: number ha burned	1AR	−0.659	−0.018
	Lightning: number of fires	1MA	0.849	0.001
	All types: number ha burned	NA	–	–
	All types: number of fires	1MA	0.807	0.003

in the south-east (Region 8) prescribed burned ~200 000 ha annually (Schuster *et al.* 1997) and this was a greater area of prescribed burning than the rest of the USA combined. The south-east also has the nation's largest private prescribed fire program. The south-east continues to lead the nation in the amount of area burned using prescribed fire (GAO 2003).

USFS lands in California (Region 5) have experienced the highest amount of relative area burned from 1940 to 2000. The majority of the ignitions in California's National Forests during this period were from lightning (60%) (Table 3). Fires in other areas of California such as private wildlands surrounding Los Angeles and San Francisco are dominated by human-caused fires. Lightning-caused fires in coastal California (including the areas surrounding Los Angeles and San Francisco) are rare because of limited topography but information from these areas was not included in this analysis because they are not managed by the USFS.

The regions that experienced the highest number of lightning-caused fires (relative) are the south-west (Region 3), the Pacific coastal region (Regions 5 and 6), and upper Rocky Mountains (Region 1) (Table 3). The majority of these areas have also experienced a significant increase in the relative area burned by fire from 1940 to 2000 (Tables 4–6). Lightning strikes are stochastic, making it difficult for fire managers to forecast areas of higher ignition potential. Strategically placed area treatments (SPLATs) (Finney 2001) may be an effective strategy in reducing the areas burned in areas dominated by lightning fires (Stephens and Ruth 2005). SPLATs are a system of overlapping area fuel treatments designed to minimize the area burned by high intensity head-fires in diverse terrain.

The number of human-caused fires (relative) was largest in the south-east (Region 8), followed by the north-east (Region 9), and then California (Region 5) (Table 3). Human-caused fires commonly occur near transportation corridors (highways, roads, trails), campgrounds, and urban areas, making it possible for fire managers to forecast areas of higher ignition potential (Stephens and Ruth 2005). Defensible fuel profile zones (DFPZ) placed near areas of high human-caused ignitions can be used to decrease the probability of large, high-severity fires by improving suppression efficiency (Kalabokidis and Omi 1998; Agee *et al.* 2000). DFPZs are linear landscape elements approximately 0.5–1.0 km wide, typically constructed along roads to break up fuel continuity

Table 6. ARMA model parameter estimates for USFS fire statistics time series data for Regions 6–10 from 1940 to 2000
Information from Region 7 (Grasslands) not analysed in this study. AR, autoregressive; MA, moving average; NA, time series model parameters could not be estimated

Region	Variable	ARMA model	Parameter estimates	Constant
6	Human: number ha burned	1MA	0.870	−0.001
	Human: number of fires	1MA	0.436	0.004
	Lightning: number ha burned	NA	–	–
	Lightning: number of fires	1MA	0.881	−0.005
	All types: number ha burned	NA	–	–
	All types: number of fires	1MA	0.756	0.002
8	Human: number ha burned	1MA	0.591	−0.001
	Human: number of fires	1MA	0.575	−0.006
	Lightning: number ha burned	1MA	0.864	0.010
	Lightning: number of fires	1AR	−0.479	−0.001
	All types: number ha burned	2MA	0.438, 0.258	0.000
	All types: number of fires	1MA	0.588	−0.005
9	Human: number ha burned	1MA	0.740	−0.007
	Human: number of fires	2MA	0.289, 0.419	−0.013
	Lightning: number ha burned	2AR	−0.634, −0.399	0.027
	Lightning: number of fires	2AR	−0.336, −0.359	0.001
	All types: number ha burned	1MA	0.749	−0.008
	All types: number of fires	2MA	0.286, 0.431	−0.013
10	Human: number ha burned	NA	–	–
	Human: number of fires	2MA	0.355, 0.519	−0.001
	Lightning: number ha burned	NA	–	–
	Lightning: number of fires	NA	–	–
	All types: number ha burned	2MA	0.389, 0.408	−0.004
	All types: number of fires	2AR	−0.381, −0.264	−0.075

and provide a defensible zone for fire-suppression forces. DFPZs will be effective in reducing losses in the urban–wildland intermix only if they are used in combination with combustion-resistant homes that have defensible space from wildland and domestic vegetation (Stephens and Ruth 2005).

The amount of area burned (relative) by wildfire from 1940 to 2000 has significantly increased in many areas of the USA (Tables 4–6). The northern Rocky Mountains (Region 1), the south-west (Region 3), and north-east (Region 9) have all experienced significant increases in the amount of area burned by lightning without significant increases in lightning ignitions (Tables 3–6). Increasing fuel hazards from 1940 to 2000 could have contributed to the increasing area burned by lightning fires in these areas. Changing climate during this period could have also contributed to the increase in wildfire area (McKenzie *et al*. 2004).

Even with large, well-funded institutions dedicated to fire suppression, the area burned by forest fires from 1940 to 2000 has increased in many areas of the USA (Tables 4–6). Some management activities can reduce the severity of wildfires in some forests (Martin *et al*. 1989; van Wagtendonk 1996; Weatherspoon and Skinner 1996; Stephens 1998; Moore *et al*. 1999; Pollet and Omi 2002; Stephens and Moghaddas 2005*a*, 2005*b*), but some forest types, such as Rocky Mountain lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.), are adapted to and require periodic high-severity, stand-replacement fires (Romme and Knight 1981; Turner and Romme 1994; Veblen *et al*. 1994; Christensen *et al*. 1998). To produce effective fire management strategies it is critical to differentiate USA forests based on their respective fire regimes and past ignition sources.

The south-east has the nation's largest prescribed fire program and this has probably contributed to the insignificant change in relative area burned by forest fire from 1940 to 2000 (Table 4). No other area in the USA burning large areas (relative burned area >500) has achieved this result (Tables 3–6). The south-east should continue to implement the nation's largest prescribed fire program. Changing state populations in the south-east USA may hinder utilization of fire because most of the new residents are coming from regions where there is lower cultural acceptance of fire (USDA 2002). Public outreach that explains the benefits (ecological, economic, and social) of prescribed fire to new residents should be expanded to maintain the nation's highest cultural acceptance of burning.

Conclusions

Even with a large infrastructure dedicated to fire suppression, the majority of western forests managed by the USFS have experienced a significant increase in relative area burned from 1940 to 2000. A long-term commitment from the US Administration, Congress, Governors, land management agencies, and the public, is required to begin to reduce hazards and decrease the annual area burned by uncharacteristically severe wildfire.

To be effective across the diverse forest types and conditions in the USA, fire policy should better recognize and respond to the diversity of US forests and how they have burned in the past (Tables 3, 4). The federal fire policy of 1995 (USDA 1995*b*) recognized fire as a critical ecosystem process that must be reintroduced to restore forested ecosystems. The National Fire Plan (USDA–USDI 2000) was created 5 years later because, if hazardous fuels are not reduced, the number of severe wildland fires and their associated costs will continue to increase. The National Fire Plan and the Ten-year Comprehensive Strategy recognized that many fuels management decisions should be made at local level. This analysis determined that there is high geographical diversity on wildfire occurrence and causes, further reinforcing a need for diverse, locally based solutions to USA fire management problems.

Acknowledgements

I thank Emily Moghaddas, Neil Sugihara and Jason Moghaddas for reviewing an earlier version of this manuscript. I especially thank Danny Fry for his statistical analysis. Marian Villasenor and Penny Sternberg provided the recent USFS fire occurrence. I thank Greg Biging for statistical advice on this project.

References

Agee JK, Bahro B, Finney MA, Omi PN, Sapsis DB, Skinner CN, Wagtendonk JW, Weatherspoon CP (2000) The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management* **127**, 55–66. doi:10.1016/S0378-1127(99)00116-4

Akaike H (1971) Information theory and an extension of the maximum likelihood principle. In '2nd international symposium on information theory. Institute of Statistical Mathematics, Research Memorandum No. 46'. (Eds BN Petrov, F Csaki) pp. 267–281. (Akademiai Kiade: Budapest)

Akaike H (1974) A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **79**, 716–723.

Biswell HH (1961) The big trees and fire. *National Parks and Conservation Magazine* **35**, 11–14.

Biswell HH (1989) 'Prescribed burning in California wildland vegetation management.' (University of California Press: Berkeley) 255 pp.

Box GEP, Jenkins GM (1976) 'Time series analysis: Forecasting and control.' (Holden-Day: San Francisco)

Brown RT, Agee JK, Franklin JF (2004) Forest restoration and fire: principles in the context of place. *Conservation Biology* **18**, 903–912. doi:10.1111/J.1523-1739.2004.521_1.X

Chapman HH (1926) 'Factors determining natural regeneration of longleaf pine on cut-over lands in the LaSalle Parish, Louisiana.' Bulletin number 16. (Yale School of Forestry: New Haven, CT)

Christensen NL, Agee JK, Brussard PF, Hughes J, Knight DH, *et al.* (1998) Interpreting the Yellowstone fires of 1988. *Bioscience* **39**, 678–685.

Cooper CF (1960) Changes in vegetation structure and growth of southwestern pine forests since white settlement. *Ecological Monographs* **30**, 129–164.

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* **47**, 219–228.

GAO (2003) 'Forest service fuels reduction.' Report GAO-03-689R. (US General Accounting Office: Washington, DC) 43 pp.

Godwin DP (1946) Helicopters hopes for fire control. *Fire Control Notes* **7**, 16–21.

Graves HS (1910) 'Protection of forests from fire.' US Forest Service Bulletin 82. (Washington, DC) 48 pp.

Greeley WB (1951) 'Forests and men.' (Doubleday Publishing: Garden City, NY)

Hoff JC (1983) 'A practical guide to Box-Jenkins forecasting.' (Lifetime Learning Publications: London)

Jefferson FJ (1947) The helicopter—a new factor in fire control. *Fire Control Notes* **9**, 1–9.

Kalabokidis KD, Omi PN (1998) Reduction of fire hazard through thinning residue disposal in the urban interface. *International Journal of Wildland Fire* **8**, 29–35.

Komarek EV (1962) The use of fire: an historical background. In 'Proceedings of the 1st Tall Timbers Fire Ecology Conference'. pp. 7–10. (Tall Timbers Research Station: Tallahassee, FL)

Martin RE, Kauffman JB, Landsberg JD (1989) Use of prescribed fire to reduce wildfire potential. In 'Proceedings of the symposium on fire and watershed management'. (Technical Coordinator NH Berg) USDA Forest Service, Pacific Southwest Forest and Range Experiment Station General Technical Report PSW-109. (Berkeley, CA)

McKenzie D, Gedalof Z, Peterson DL, Mote P (2004) Climate change, wildfire, and conservation. *Conservation Biology* **18**, 890–902. doi:10.1111/J.1523-1739.2004.00492.X

Mitchell JA (1947) Forest fire statistics: their purpose and use. *Fire Control Notes* **8**, 14–17.

Moore MM, Covington WW, Fulé PZ (1999) Reference conditions and ecological restoration: a Southwestern ponderosa pine perspective. *Ecological Applications* **9**, 1266–1277.

Motl LF (1941) Aviation and Wisconsin forest protection. *Fire Control Notes* **5**, 187–189.

NWCG (2001) 'Review and update of the 1995 federal wildland fire management policy.' (National Wildfire Coordinating Group, Interagency Fire Center: Boise, ID)

Pankratz A (1983) 'Forecasting with univariate Box-Jenkins models: Concepts and cases.' (Wiley: New York)

Pinchot G (1907) 'The use of the National Forests.' (USDA Forest Service) 42 pp.

Pollet J, Omi PN (2002) Effect of thinning and prescribed burning on wildfire severity in Ponderosa forests. *International Journal of Wildland Fire* **11**, 1–10. doi:10.1071/WF01045

Pyne SJ (1982) 'Fire in America: a cultural history of wildland and rural fire.' (Princeton University Press: Princeton, NJ) 654 pp.

Pyne SJ (1997) 'America's fires: management on wildlands and forests.' (Forest History Society: Durham, NC) 54 pp.

Romme WH, Knight DL (1981) Fire frequency and subalpine forest succession along a topographic gradient in Wyoming. *Ecology* **62**, 319–326.

Rowland CA (1946) Adapting army equipment to forest fire fighting. *Fire Control Notes* **7**, 6–14.

Schiff AL (1962) 'Fire and water; scientific heresy in the Forest Service.' (Harvard University Press: Cambridge, MA) 225 pp.

Schuster EG, Cleaves DA, Bell EF (1997) 'Analysis of USDA Forest Service fire-related expenditures 1970–1995.' USDA Forest Service, Pacific Southwest Forest and Range Experiment Station Research Report PSW-230-WWW. (Berkeley, CA)

Shea JP (1940) Our pappies burned the woods and set a pattern of human behavior in the southern forests that calls for new methods of fire prevention. *American Forests* **46**, 159–162.

Stephens SL (1998) Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. *Forest Ecology and Management* **105**, 21–34. doi:10.1016/S0378-1127(97)00293-4

Stephens SL, Moghaddas JJ (2005*a*) Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a mixed conifer forest. *Forest Ecology and Management* in press.

Stephens SL, Moghaddas JJ (2005*b*) Silvicultural and reserve impacts on potential fire behavior and forest conservation: 25 years of experience from Sierra nevada mixed conifer forests. *Biological Conservation* in press.

Stephens SL, Ruth LW (2005) Federal forest fire policy in the United States. *Ecological Applications* **15**, 532–542.

Towne CR (1941) Scouting for fire with airplanes in the San Juan. *Fire Control Notes* **5**, 108–109.

Trygg JW (1948) Aerial detection on the superior national forest. *Fire Control Notes* **9**, 12–15.

Turner MG, Romme WH (1994) Landscape dynamics in crown fire ecosystems. *Landscape Ecology* **9**, 59–77. doi:10.1007/BF00135079

USDA (1940–2000) 'Forest fire report (annual).' (USDA Forest Service Department of Fire and Aviation Management: Washington, DC)

USDA (1946) Unit protection by air control. *Fire Control Notes* **7**, 3–5.

USDA (1960) 'Air attack on forest fires.' Agricultural Information Bulletin 229. (USDA Forest Service: Washington, DC) 32 pp.

USDA (1995*a*) 'Smokey Bear, the first fifty years.' USDA Forest Service Publication FS-551.

USDA (1995*b*) 'Course to the future: positioning fire and aviation management.' (USDA Forest Service Department of Fire and Aviation Management: Washington, DC) 19 pp.

USDA (2002) 'Southern forest resource assessment.' USDA Forest Service, Southern Forest and Range Experiment Station General Technical Report SRS-53. (Asheville, NC)

USDA–USDI (2000) 'A report to the President in response to the wildfires of 2000. The National Fire Plan.' Available at http://www.fireplan.gov/ [Verified 12 May 2005]

van Wagtendonk JW (1996) Use of a deterministic fire growth model to test fuel treatments. In 'Sierra Nevada Ecosystem Project, Final Report to Congress, Vol. II, Assessments and scientific basis for management options'. pp. 1155–1166. (University of California, Centers for Water and Wildland Resources: Davis)

Veblen TT, Hadley KS, Nell EM, Kitzberger T, Reid M, Villalba R (1994) Disturbance regime and disturbance interactions in a Rocky Mountain subalpine forest. *Journal of Ecology* **82**, 125–136.

Weatherspoon CP, Skinner CN (1996) Fire silviculture relationships in Sierra Forests. In 'Sierra Nevada Ecosystem Project, Final Report to Congress, Vol. II, Assessments and scientific basis for management options'. pp. 1167–1176. (University of California, Centers for Water and Wildland Resources: Davis)

Weaver H (1943) Fire as an ecological and silvicultural factor in the ponderosa pine region of the Pacific slope. *Journal of Forestry* **41**, 7–15.

Zar JH (1999) 'Biostatistical analysis, 4th edn.' (Prentice Hall: Upper Saddle River, NJ) 663 pp.