Wildland fires: What to blame?

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Abstract: This study investigates the causality relationships among wildland fires, El Niño/Southern Oscillation (ENSO), timber harvest, and urban sprawl in the United States using vector autoregression. Our results indicate that an individual factor may not significantly contribute to wildland fire activity when acting alone, but could trigger fire occurrence when coupled with other factors. ENSO, timber harvest, and urban sprawl are all found to influence wildland fire activity when they are considered jointly. Area burned is more significantly affected by ENSO than the number of wildland fires. The impulse response functions suggest that the impact of an ENSO event on wildland fire activity could last more than a decade before gradually dying out. A unit increase in ENSO anomalies would reduce the number of wildland fires by as much as 8% initially and cause area burned to decrease by 4.7% in the first year and then to increase by 2.5% before returning to the original path. The complex causality interrelationships create challenges for and call for a systematic approach to wildfire fire mitigation and management.

Key Words: Wildland fire activity, Granger causality, vector autoregression, impulse response.

INTRODUCTION

Wildland fires can pose severe threats to property, life, and the environment, engendering far-reaching costs and losses to society (Butry et al. 2001), while playing an important role in the dynamics of forest ecosystems. To alleviate the detrimental impact of wildland fires requires holistic and effective fire management and prevention plans, which rely on our knowledge of factors influencing wildland fire activity. Many factors can contribute to the occurrence of wildland fires. One of the widely recognized causes of wildland fires is probably weather or climatic changes such as El Niño/Southern Oscillation (ENSO). Climatic changes resulting from ENSO events alter vegetation/fuel development and lightning (a major wildland fire ignition source) occurrence, affecting wildland fire risks. Studies have found that ENSO is highly correlated with wildland fires in the U.S. (Simard et al. 1985, Swetnam and Betancourt 1990, Brenner 1991, Chu et al. 2002).

Timber harvest may also affect wildland fire activity. On one hand, timber harvest can play a critical role in mitigating forest fires (Dombeck 2000). Harvest removes biomass/fuels from forestland, reducing fire risks and the intensity of fires if ignited. Harvest also causes the fragmentation of fuel distribution, creating barriers to fire spreading. On the other hand, logging slash and residues may be more susceptible to fire. Meanwhile, machinery operation and human disturbances resulting from harvesting may also increase the probability of fire occurrence. Timber harvest, which affects forest structure, local microclimate, and fuel accumulation, may also increase fire severity (Center for Water and Wildland Resources 1996).

Another factor that has potential impacts on wildland fires is urban sprawl. From 1960 to 1990, urban population density declined by over 30% while the urban population increased by

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Urban sprawl has increased the complexity and severity of wildland fires. Urbanization has led to landscape fragmentation (Alig et al. 1999), increased fire suppression efforts (Irwin 1987), and escalated human interventions with wildland (Plevel 1997). All these potentially affect the intensity and occurrence of wildland fires (Keeley et al. 1999, Monroe 2003).

Other factors have also been linked to wildland fires. Studies on fire behavior have identified that in addition to weather, fuel composition, topography, and moisture are related to fire spread and intensity (Rothermel 1972, Anderson 1982). Forest fire history reveals that anthropogenic change and the degree of stand/fuel development have an influence on wildland fire occurrence (Weisberg and Swanson 2003). Geographic location (latitude) explains most of the variability in human-caused wildland fires in the eastern United States (Donoghue and Main 1985). Fire suppression may lead to fewer, but larger and more intense fires (Rothermel and Philpot 1973). Areas that have been burned would be less likely to be burned again within about a decade (Prestemon et al. 2002). And demographics are found to have no significant impact on wildland fires (Zhai et al. 2003).

These previous studies identified various possible causes of wildland fires based on local or regional case studies. Yet, few studies have explored the subject at the national level. Local and micro-level studies may be insufficient for providing national policy recommendations on large-scale wildland fire prevention and management because many factors affect wildland fire activity and their impacts often vary at different landscape levels. More importantly, these previous studies generally ignore the potential endogeneity of relevant variables, particularly the feedback effects of wildland fires on other variables. The feedback effects between wildland fires and other variables are evident. Wildland fire risks could influence decisions on forest management (Rideout and Omi 1990) and timber harvest (Martell 1980, Reed 1984, Yin and Newman 1996). Wildland fires, which cause carbon emissions to the atmosphere (Carcaillet et al. 2002), may contribute to climate change as well. And wildland fire risks may also affect lifestyle choices including decisions to live in or close to forested areas. Ignorance of the interactions among wildland fires and other factors may introduce biases to the results. Though the correlations between fires and ENSO events showed that ENSO and wildland fires were connected, these studies did not indicate their causality relationships and overlooked the impact of other factors on wildland fires. Furthermore, most of the existing studies look at only the one-time or immediate effects of assumed exogenous variables on wildland fire activity. These effects may not be instantaneous or short-lived, rather may last quite a long period in some cases. For instance, an ENSO event may influence weather patterns for several years. Even a one-time weather change could affect vegetation dynamics for many years to come, leading to potential long-lasting impacts on fuel development and wildland fire activity.

In this article, we seek to address these limitations of previous studies. By drawing upon existing findings on factors influencing wildland fire activity, this study further examines the interrelationships between wildland fires and major factors that potentially interact with wildland fire activity at the national level. Their interrelationships are determined simultaneously and without limiting the directions of causality in the first place. Because many factors may be related to wildland fires, to consider all of them is impossible and may not generate meaningful results due to the limitations of data and analytical tools. Instead, we focus on three major factors: climate/weather (ENSO in particular), timber harvest, and urban sprawl. These factors have been considered to have potential impacts on wildland fire activity as discussed earlier, and they also represent major human and natural driving forces for forest landscape changes over
time, particularly in recent decades. The estimated interrelationships would provide an insight into the causality among wildland fires, ENSO, timber harvest, and urban sprawl. In addition, the impulse responses to an ENSO event are also derived to identify its temporal effect on wildland fire activity.

METHODS

To account for the interrelationships among wildland fires and other variables, vector autoregression (VAR) was used in this study. In a VAR model, relationships among different variables are simultaneously determined (Hamilton 1994, Enders 1995). A VAR analysis usually involves the determination of variables to be included and appropriate lags. As mentioned earlier, four variables are considered in this analysis. The standard form of the VAR model can be expressed as

\[
\ln(F_t) = \alpha_0 + \sum_{p=1}^{\rho} (\alpha_{1p}\ln(F_{t-p}) + \alpha_{2p}\ln(H_{t-p}) + \alpha_{3p}\ln(UPD_{t-p}) + \alpha_{4p}\MEI_{t-p}) + \epsilon_t
\]

\[
\ln(H_t) = \alpha_0 + \sum_{p=1}^{\rho} (\alpha_{1p}\ln(F_{t-p}) + \alpha_{2p}\ln(H_{t-p}) + \alpha_{3p}\ln(UPD_{t-p}) + \alpha_{4p}\MEI_{t-p}) + \epsilon_t
\]

\[
\ln(UPD_t) = \alpha_0 + \sum_{p=1}^{\rho} (\alpha_{1p}\ln(F_{t-p}) + \alpha_{2p}\ln(H_{t-p}) + \alpha_{3p}\ln(UPD_{t-p}) + \alpha_{4p}\MEI_{t-p}) + \epsilon_t
\]

\[
MEI_t = \alpha_0 + \sum_{p=1}^{\rho} (\alpha_{1p}\ln(F_{t-p}) + \alpha_{2p}\ln(H_{t-p}) + \alpha_{3p}\ln(UPD_{t-p}) + \alpha_{4p}\MEI_{t-p}) + \epsilon_t
\]

where

- \( F_t \) = the wildland fire activity at time/year t, measured by the number of wildland fires or area burned (ha);
- \( H_t \) = the amount of timber harvested at time/year t (m³);
- \( UPD_t \) = the urban population density at time/year t (people/km²);
- \( MEI_t \) = the multivariate ENSO index value at time/year t;
- \( \alpha \) = the regression coefficients to be estimated;
- \( \rho \) = the order of the VAR or the lag number; and
- \( \epsilon \) = the disturbance terms.

Here wildland fire activity was measured using two indicators: the number of wildland fires (NF) and area burned (A). As a result, two sets of VAR models were estimated, one examining the number of wildland fires and the other analyzing area burned. The data for the number of wildland fires and area burned annually were derived from the National Interagency Fire Center (2003). The timber harvest represented by the amount of roundwood production was obtained from the FAOSTAT database (FAO 2003). The Multivariate ENSO Index (MEI) was used to measure ENSO events. MEI is based on six main observed variables of ENSO events over the tropical Pacific. These variables include sea-level pressure, zonal and meridional components of the surface wind, sea surface temperature, sea air temperature, and total cloudiness fraction of the sky (Wolter and Timlin 1993). MEI measures both strength and directions of ENSO episodes. Positive MEI values represent the warm ENSO phase (El Niño); negative MEI values indicate the cold ENSO phase (La Niña). The MEI series of May-June was used in the analysis. Using the May-June MEI series rather than the annual average was to avoid the inappropriate cancellation of positive and negative MEI monthly values during some active,
yet irregular ENSO years. The month of May-June was chosen because it was associated with the early to middle stage of the wide-spread regional fire seasons across the country (Edmonds et al. 2000). The MEI data were obtained from the National Oceanic and Atmospheric Administration (NOAA 2003).

The complexity of urban sprawl posed a difficulty in measuring it, especially with a single indicator. However, urban expansion in the U.S. in the past several decades has been characterized by increased urban population and urban land area (US Department of Housing and Urban Development 1999). To incorporate these two important characteristics in the VAR analysis and to choose a measure that has proper meaning, urban population density derived from census data was used as a proxy for urban sprawl. Urban population was calculated based on the annual population estimates (US Census Bureau 2000) and percentage of urban population (US Census Bureau 1993, 2003). Existing data on urban land area (US Census Bureau 1993, 2003, Vesterby and Krupa 2001) were not reported on an annual basis, but in an interval of 4-5 years. Linear interpolations were used to recover the missing data. Urban areas refer the places with a population of 2,500 or more. All the data series cover the period from 1961 to 2000. Except MEI, all other series were transformed to logarithmic values.

Before estimating the VAR models, the stationarity of the data series was analyzed using unit root tests (Dickey and Fuller 1979, 1981) to better understand the data generation process. However, even if a unit root was detected for a series, it was not detrended in the VAR analysis for two reasons. First, detrending may “throw away” information concerning comovements in the data. Second, the purpose of VAR analysis is to determine the interrelationships among the variables, not the parameter estimates. Therefore, there is no need for detrending in a VAR analysis (Sims 1980).

We started with the quadrivariate VAR model of seventh-order lags, the maximum allowable lags\(^1\). A likelihood ratio test statistic\(^2\) suggested by Hamilton (1994) and Enders (1995), which follows a \(\chi^2\) distribution, was used to test the lower order restrictions of the seventh-order VAR. The estimated VAR models then served as the alternative hypothesis for testing Granger causality (Granger 1969, Sims 1972) among wildland fire activity, ENSO, timber harvest, and urban population density. The Granger causality tests determine whether a restriction of excluding a variable in the VAR model is binding at a given significance level. The test statistic for Granger causality is similar to that for determining lag length as stated earlier. To examine the causation within different scopes of interactions among wildland fire activity, ENSO, timber harvest, and urban population density, bivariate and trivariate VARs were also estimated and used for testing causality relationships using the same approach for the quadrivariate VARs. Finally, the impulse response functions of wildland fire activity to ENSO (MEI) were derived from the estimated quadrivariate VAR models. The Choleski decomposition method (Ender 1995) was used in identifying the impulse response functions.

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\(^1\) There are 29 coefficients in each equation of the seventh-order quadrivariate VAR and 33 (40-7) usable observations.

\(^2\) \((T - c)\left(\log|\Sigma_0| - \log|\Sigma_u|\right)\), where \(T\) is the number of usable observations, \(c\) is the number of parameters estimated in each equation of the unrestricted system, and \(|\Sigma_0|\) and \(|\Sigma_u|\) are the determinants of the variance/covariance matrices of the restricted and unrestricted systems, respectively.
RESULTS

Causality relationships

The results of Granger causality tests are presented in Table 1. The tests based on the bivariate VARs indicate that only urban population density Granger-causes the number of wildland fires. In addition, area burned Granger-causes urban population density, suggesting that wildfire risks have influenced decisions on urban sprawl. Urban population density was found to Granger-cause timber harvest and MEI; timber harvest Granger-causes MEI. While the effect of urban sprawl on timber harvest is straightforward because the conversion of forestland to urban uses may increase timber harvest in the short run and decrease it in the long run, there is no known evidence about the effect of urban sprawl and timber harvest on ENSO events. Their impacts may be due to the forward-looking behavior in urbanization and timber harvest with respect to expectations about future ENSO events.

The causality test results based on the trivariate VARs show that more factors have contributed to wildland fire activity. MEI, timber harvest, and urban population density were all found to Granger-cause the number of wildland fires, which in turn Granger-causes MEI, timber harvest, and urban population density. Similarly, MEI, timber harvest, and urban population density Granger-cause area burned while there is no statistical evidence about the effect of the latter on the formers. These results demonstrate more comprehensive and complex causality relationships among the variables considered, and many of these causality relationships cannot be explained by those derived from the bivariate VARs. This implies that a factor/variable alone may not contribute to wildland fire activity, but when it is coupled with other factors it can significantly affect fire activity due to their interactions and joint effects.

The interrelationships among the four variables can be further explained by the causality test results based on the quadrivariate VARs. The number of wildland fires, timber harvest, urban population, and MEI are highly interrelated. The number of wildland fires Granger-causes
Table 1. Granger causality tests based on multivariate VARs.

<table>
<thead>
<tr>
<th>Variable(s) Granger-caused by the variable in the first column</th>
<th>Lag</th>
<th>Number of wildfires $\chi^2$-statistic</th>
<th>Sig.</th>
<th>Area burned $\chi^2$-statistic</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bivariate VARs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>1.520</td>
<td>0.218</td>
<td>0.006</td>
<td>0.938</td>
</tr>
<tr>
<td>NF or A</td>
<td></td>
<td>0.633</td>
<td>0.426</td>
<td>0.837</td>
<td>0.360</td>
</tr>
<tr>
<td><strong>UPD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NF or A</td>
<td>2</td>
<td>9.506</td>
<td>0.002</td>
<td>1.543</td>
<td>0.214</td>
</tr>
<tr>
<td>MEI</td>
<td>1</td>
<td>1.968</td>
<td>0.160</td>
<td>0.665</td>
<td>0.415</td>
</tr>
<tr>
<td>NF or A</td>
<td></td>
<td>0.062</td>
<td>0.804</td>
<td>0.049</td>
<td>0.824</td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>2</td>
<td>1.473</td>
<td>0.225</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MEI</strong></td>
<td>1</td>
<td>3.673</td>
<td>0.055</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UPD</strong></td>
<td>2</td>
<td>16.630</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trivariate VARs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>4.750</td>
<td>0.093</td>
<td>4.289</td>
<td>0.117</td>
</tr>
<tr>
<td>MEI</td>
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<td>2.505</td>
<td>0.286</td>
<td>2.983</td>
<td>0.225</td>
</tr>
<tr>
<td>NF or A</td>
<td></td>
<td>1.420</td>
<td>0.492</td>
<td>0.530</td>
<td>0.767</td>
</tr>
<tr>
<td><strong>UPD</strong></td>
<td>1</td>
<td>8.661</td>
<td>0.013</td>
<td>9.801</td>
<td>0.007</td>
</tr>
<tr>
<td>MEI</td>
<td></td>
<td>6.046</td>
<td>0.049</td>
<td>8.069</td>
<td>0.018</td>
</tr>
<tr>
<td>NF or A</td>
<td></td>
<td>20.614</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>H</strong></td>
<td>1</td>
<td>4.633</td>
<td>0.098</td>
<td>13.421</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>UPD</strong></td>
<td>1</td>
<td>11.560</td>
<td>0.003</td>
<td>0.525</td>
<td>0.769</td>
</tr>
<tr>
<td>NF or A</td>
<td></td>
<td>11.117</td>
<td>0.004</td>
<td>3.419</td>
<td>0.181</td>
</tr>
<tr>
<td><strong>Quadrivariate VARs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>10.831</td>
<td>0.013</td>
<td>16.812</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>UPD</strong></td>
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<td>13.348</td>
<td>0.004</td>
<td>5.620</td>
<td>0.132</td>
</tr>
<tr>
<td>MEI</td>
<td></td>
<td>5.899</td>
<td>0.117</td>
<td>7.986</td>
<td>0.046</td>
</tr>
<tr>
<td>NF or A</td>
<td></td>
<td>9.439</td>
<td>0.024</td>
<td>0.520</td>
<td>0.914</td>
</tr>
</tbody>
</table>

$^\dagger$Probability of $\chi^2$ distribution greater than the test statistic. The bold numbers indicate that the null hypothesis that the variable in the first column does not Granger-cause the variable(s) in the second column is rejected at the conventional significance level. The degrees of freedom (df), the number of restrictions, is 1, 2, and 3 for the bivariate, trivariate, and...
quadrivariate VARs, respectively. Timber harvest, urban population density, and MEI. Timber harvest Granger-causes wildland fires, urban population density, and MEI. Urban population density also Granger-causes wildland fires, timber harvest, and MEI. But, MEI does not Granger-cause the number of wildland fires, timber harvest, and urban population density at the conventional significance levels. This indicates that the number of wildland fires is more significantly affected by timber harvest and urban sprawl than by ENSO events. However, the Granger causality tests based on the second set of the quadrivariate VARs suggest that MEI Granger-causes area burned, timber harvest, and urban population density. This implies that ENSO events contribute significantly to area burned. Overall, timber harvest and urban sprawl affect the number of wildland fires more significantly than ENSO events while ENSO events influence area burned more significantly than timber harvest and urban sprawl. Such results are not surprising. Historical data show that most wildland fires in the U.S. were caused by human or human activities while the largest portion of area burned was due to natural factors such as lightning (Sharpe et al. 1995).

The causality tests based on both sets of quadrivariate VARs indicate that timber harvest Granger-causes wildland fire activity, urban population density, and MEI. Two possible types of interrelationships among them may exist. One type represents the impact of timber harvest on wildland fire activity, urban sprawl, and ENSO. The other suggests the potential forward-looking behavior in timber harvest with the consideration of expected wildland fires, urban sprawls, and ENSO events. The similar argument can also be applied to the explanation of the causality relationship between urban population density and other variables in the VAR model associated with the number of wildland fires. While urban sprawl can affect the number of wildland fires, timber harvest, and ENSO, the causality relationship may also be explained by forward-looking behavior in urbanization in response to anticipated wildland fire risks and ENSO episodes.

Impulse response to ENSO

The impulse responses of wildland fire activity, area burned, timber harvest, and urban population density to MEI are shown in Figure 1. For a unit increase in MEI, the number of wildland fires would fall by about 4.5% from the mean in the same year and continue to decline in the following year to 8% below the mean before bouncing back and converging to the original path. In terms of area burned, a unit increase in MEI would cause area burned to drop by 4.7% in the first year with a slight recovery in the second year and increase by 2.5% above the mean in the third year before gradually returning to the mean. The impulse response functions show that an ENSO event (an increase in MEI) would decrease the number of wildland fires and reduce area burned initially, followed by increased area burned in the third year and afterwards before the impact fades out. Hence, the impact of ENSO events on area burned is not one-directional. This is because weather changes resulting from an ENSO event would affect vegetation dynamics and alter fuel patterns for many years to come. While area burned decreases with the decline in the number of fires at the beginning, as the number of fires tends to return to its original path, the disturbances in fuel patterns caused by an ENSO event may lead to larger areas to be burned when fires are ignited. The impulse response functions also indicate that an ENSO event would have long-lasting impacts on the number of wildland fires and area burned. While the most significant impact would occur during the first few years, its impact would take two decades to die out. Contrary to an El Niño event, a La Niña event would cause more fires, as well as more area burned initially.
CONCLUSIONS

This article investigates the causality of wildland fire activity. The VAR approach allows us to examine the causality relationships among wildland fire activity, timber harvest, urban sprawl, and ENSO without presumably excluding the potential feedback impact between them. Our results provide additional insights into the links among wildland fires, timber harvest, urban sprawl, and ENSO. There exist strong causality relationships among them, and their interrelationships are complex. An individual factor, which alone may not significantly contribute to wildland fires, can trigger wildland fire activity when coupled with other factors. ENSO, timber harvest, and urban sprawl all contribute to wildland fire activity in one way or another when they are considered jointly and simultaneously. The number of wildland fires seems to be more significantly influenced by timber harvest and urban sprawl than by ENSO while area burned is more likely to be affected by ENSO than by timber harvest and urban sprawl. Moreover, an ENSO event has long-lasting impacts on wildland fire activity. Its impact can last two decades before completely fading out.

Such complex relationships demonstrate the difficulty in developing and implementing wildland fire prevention and management strategies and policy. This also highlights the essential importance of incorporating timber harvest, urban development, and climate change in wildland fire policy formulation and implementation in a systematic manner. Accurate forecasts of ENSO events, which could precipitate wildland fire activity, would have values in preventing wildland fires or alleviating their damages. Effective wildland fire management plans should also address the lagged impact of ENSO episodes, particularly because ENSO anomalies could increase wildfire activity later while suppressing wildfire activity initially.
LITERATURE CITED


