Chapter 3. Relating Lightning Data to Fire Occurrence Data

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Why Is Lightning Important?

Lightning disturbance can affect forest health at various scales. Lightning strikes may kill or weaken individual trees. Lightning-damaged trees may in turn function as epicenters of pest outbreaks in forest stands, as is the case with the southern pine beetle and other bark beetles (Rykiel and others 1988). At a landscape scale, lightning greatly influences forest structure and composition by igniting wildfires. Lightning is the leading natural cause of wildfire ignitions worldwide (Vasquez and Moreno 1998) and is the leading overall cause of ignitions in the Western United States (Rorig and Ferguson 1999). Whether lightning-ignited wildfires expand to affect large areas depends on a number of environmental factors, including quantity and moisture content of fire fuels, climate and weather conditions, and fire suppression efforts (Rorig and Ferguson 2002). The relationship among climate, lightning, and fire is not well understood, and this relationship is further complicated by the preponderance of human-caused fires in some regions of the world (Morgan and others 2001, Vasquez and Moreno 1998).

National-scale fire and lightning-density spatial datasets, developed from remotely sensed sources, have recently become available for the United States. By examining the correlation between these datasets, it may be possible to identify regions of the United States where lightning density serves as a predictor of forest fire activity.

Methods

Moderate resolution imaging spectroradiometer (MODIS), mounted on 2 National Aeronautics and Space Administration (NASA) satellites (Aqua and Terra), has 36 spectral bands ranging from 0.4 to 14 μm (thermal infrared) in wavelength. Together, Aqua MODIS and Terra MODIS cover the mid-to-higher latitudes of the globe four times daily (National Aeronautics and Space Administration 2006). The Forest Service, NASA, and the University of Maryland have collaborated to produce daily active fire occurrence data using MODIS thermal infrared bands [see Giglio and others (2003) for a description of the data processing algorithm]. Data on fire occurrences since 2001 are available online from the Forest Service, Remote Sensing Applications Center (RSAC) (2006). The data are delivered as annual point coverages, where each point represents the center of a 1-km^2 cell where a fire was detected in a given year. The MODIS data do not depict the areal extent of fires, and so are best suited to regional- or national-scale assessments of fire pattern.

The NASA Global Hydrology Resource Center created a global map of mean annual lightning activity using data from two satellite-based sensors, the lightning imaging sensor (LIS) and the optical transient detector (OTD). Five years of LIS (1997–2002) and OTD (1995–2000) data were combined to create a raster map of total lightning activity, reported in terms of flash rate density (number of flashes km^{-2} per year) for 0.5-degree grid cells (NASA Global Hydrology Resource Center 2004). Total lightning activity can be divided into two subcategories: intracloud and cloud-to-ground discharges, with only the latter being relevant for fire ignitions. Estimating what proportion of the total lightning activity depicted by the LIS/OTD map consists of cloud-to-ground activity is difficult, as there is some broadscale geographic variation in the intracloud/cloud-to-ground ratio (Boccippio and others 2001). Nonetheless, the overall spatial pattern of the LIS/OTD map is quite similar to maps generated using only cloud-to-ground lightning data from the U.S. National Lightning Detection Network (Zajac and Rutledge 2001), suggesting that it is appropriate for evaluating national-scale trends.

To facilitate comparison of these datasets, the LIS/OTD map was first clipped to the conterminous United States and reprojected from a geographic to an Albers conic equal-area projection. The map's original 0.5-degree cells were resampled to 50 km by 50 km (2500 km2) cells using a nearest neighbor approach. These cells served as the primary sampling units for measuring forest fire occurrence. For each cell, the total number of forest fires (2001–05) was determined by intersecting the MODIS active fire occurrence coverages for each year with a 1-km resolution forest cover map developed by RSAC from MODIS imagery. Only fires that occurred in forested areas depicted by the MODIS forest cover map were counted towards the 5-year total for each 2500-km2 cell. In addition, there were a number of partial cells along U.S. coastlines as well as the United States-Canada and United States-Mexico borders. For each partial cell i, the number of forest fire occurrences was area-adjusted using the formula

$$F'_i = \frac{F_i * 2500}{A_i}$$

where

F'_i = adjusted number of forest fire occurrences for cell *i*

F_i = original number of forest fire occurrences for cell *i*

A_i = actual land area of cell *i* in km^2

Each cell was labeled according to the ecoregion province in which its center point fell.

Spearman's rank-order correlations (Steel and others 1997) were calculated between lightning flash density and the number of forest fires per cell. This nonparametric correlation approach first ranks the data and then applies the standard, i.e., Pearson's, correlation equation to those ranks (SAS Institute 1999). Spearman's correlation coefficients were calculated for cells grouped by ecoregion province (Cleland and others 2005), for all cells in ecoregion provinces of the Eastern United States (N = 1475), and for all cells in ecoregion provinces of the Western United States (N = 1598) (fig. 3.1). Only cells that included some forested area based on the MODIS forest cover map were included in the correlation analyses. To provide perspective on the relative importance of lightning as a predictor, Spearman's rank-order correlations were similarly calculated between human

Figure 3.1—Eastern and Western United States super-regional groups for correlation testing. Gray lines are ecoregion provinces (Cleland and others 2005).

population density (number of individuals km^{-2}) and the number of forest fires per cell. Population density was calculated from U.S. Census 2000 population data mapped at the census block level (Environmental Systems Research Institute 2006).

What Do the Data Show?

The total number of forest fires in each 2500-km^2 cell between 2001 and 2005 (fig. 3.2) ranged from zero to more than 2,800, with heavy fire activity at a few different locations across the Western United States. Lightning flash densities (fig. 3.3) ranged from zero to 59 flashes km^{-2}, with peak lightning activity in Southern Florida. The low level of lightning activity in West Coast States and in Maine follows a consistent pattern that has been noted previously (Huffines and Orville 1999).

The relationship between lightning flash density and forest fire occurrence in the Eastern United States appears to be different from the relationship between lightning flash density and forest fire occurrence in the Western United States. There was a large, significant positive correlation between lightning flash density and forest fire occurrence ($r = 0.59$, $p<0.0001$) in the Eastern United States. In contrast, there was a statistically significant negative correlation between lightning flash density and forest fire occurrence ($r = -0.20$, $p<0.0001$) in the Western United States. This may not be surprising, as lightning activity is low and fire frequency high in many parts of the Western United States.

Nevertheless, when the data were analyzed at a finer spatial scale, lightning and fire occurrence were positively correlated in most individual ecoregion provinces in the United States, including many in the Western United States (fig. 3.4). There were large and statistically significant positive correlations between lightning and fire occurrence in four densely forested provinces covering much of the Southeastern and Mid-Atlantic United States: 231—Southeastern Mixed Forest ($r = 0.46$, $p<0.0001$); 232—Outer Coastal Plain

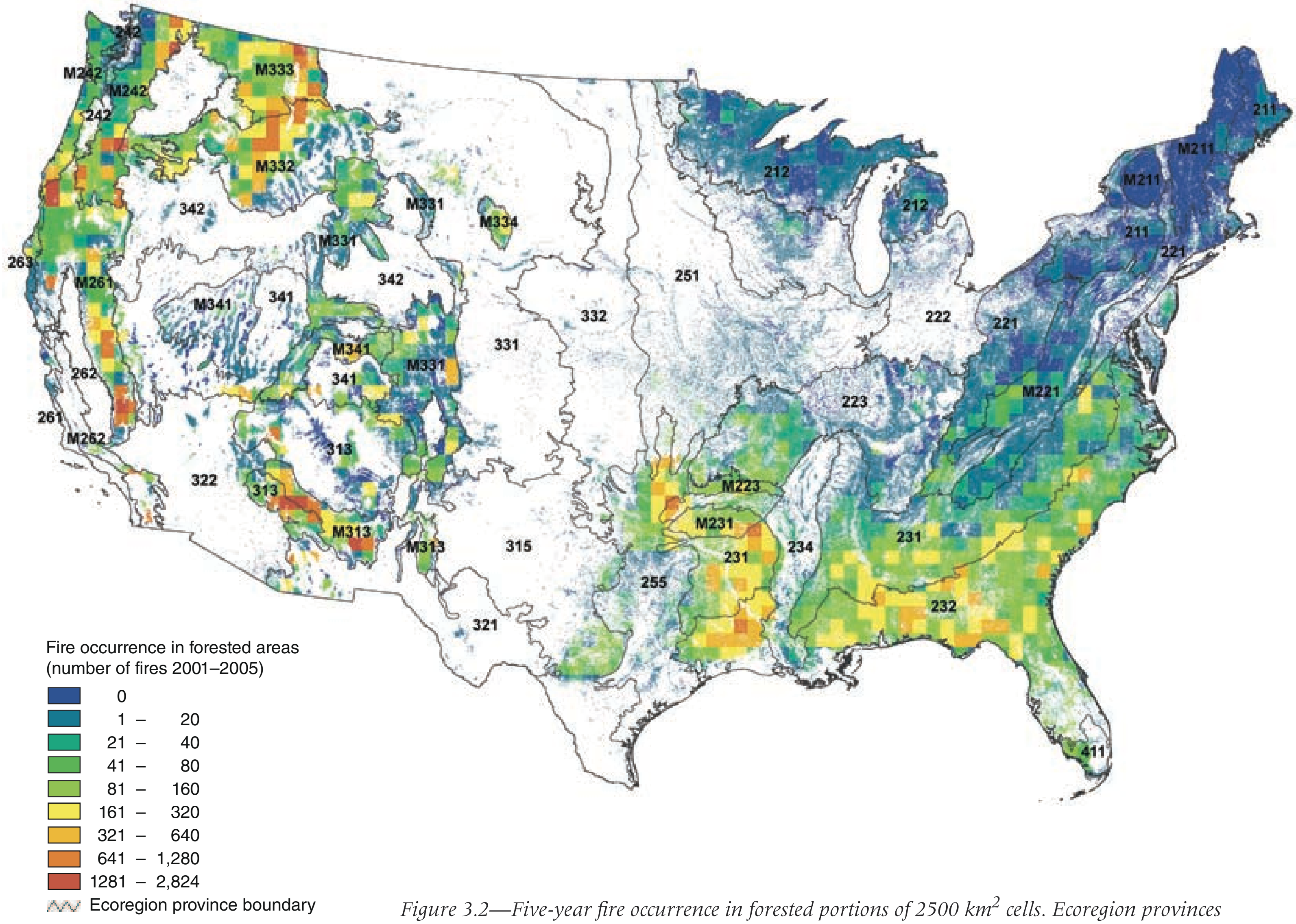

Figure 3.2—Five-year fire occurrence in forested portions of 2500 km^2 cells. Ecoregion provinces (Cleland and others 2005) are shown for reference. Forest cover source was the U.S. Department of Agriculture Forest Service, Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture, Forest Service, Remote Sensing Applications Center)

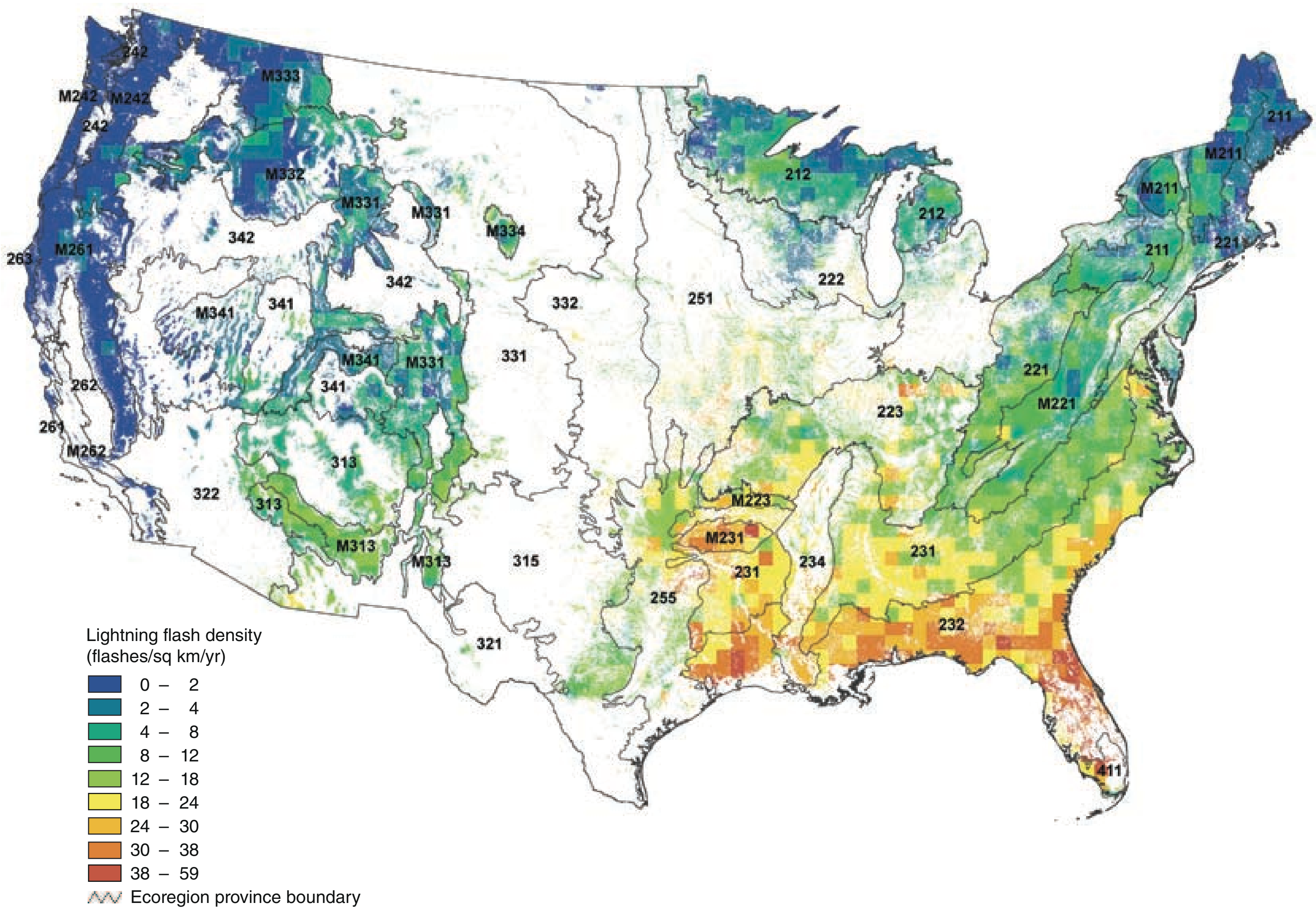

Figure 3.3—Total lightning activity, reported as flash density, for 2500 km^2 cells. Ecoregion provinces (Cleland and others 2005) are shown for reference. Forest cover source was the U.S. Department of Agriculture Forest Service, Remote Sensing Applications Center. [Data source: National Aeronautics and Space Administration Global Hydrology Resource Center]

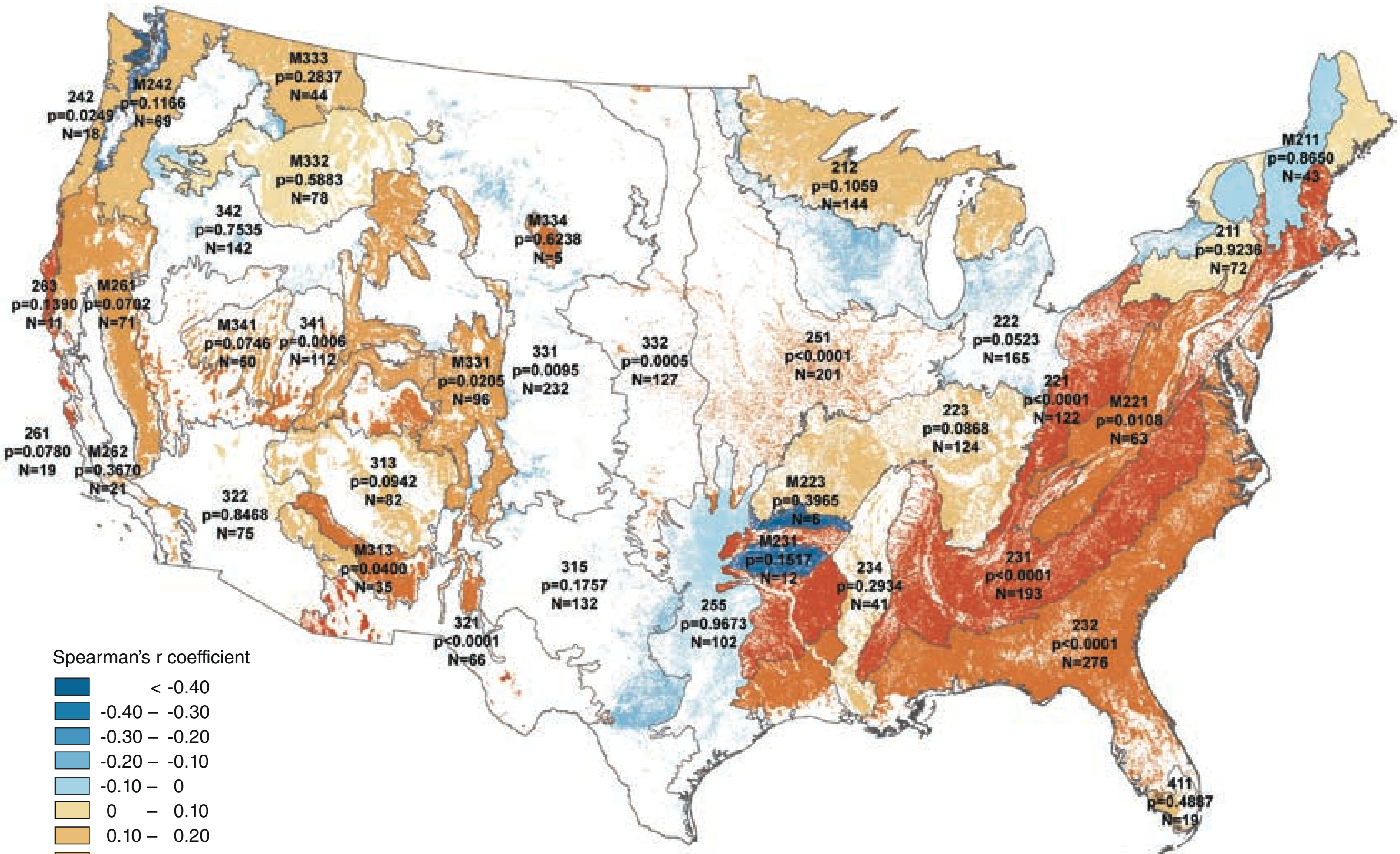

Figure 3.4—Correlation between lightning flash density and forest fire occurrence for ecoregion provinces (Cleland and others 2005). P-value labels indicate statistical significance of correlation. (Province 262—California Dry Steppe omitted because of limited forested area.) [Data sources: U.S. Department of Agriculture Forest Service, Remote Sensing Applications Center, and National Aeronautics and Space Administration Global Hydrology Resource Center]

Mixed Forest ($r = 0.32$, $p<0.0001$); 221—Eastern Broadleaf Forest ($r = 0.42$, $p<0.0001$); and M221—Central Appalachian Broadleaf Forest—Coniferous Forest—Meadow ($r = 0.32$, $p = 0.0108$) (fig. 3.4). The results for the latter two provinces may be influenced by geography. These northsouth oriented provinces extend hundreds of kilometers across a range of lightning densities, but small areas of high lightning density co-occurred with clusters of forest fire activity in their southern portions.

Two mostly forested provinces in the Western United States also exhibited significant positive correlations: M331—Southern Rocky Mountain Steppe—Open Woodland—Coniferous Forest—Alpine Meadow ($r = 0.24$, $p = 0.0205$) and M313—Arizona—New Mexico Mountains Semi-Desert—Open Woodland—Coniferous Forest—Alpine Meadow ($r = 0.35$, $p = 0.04$). Elsewhere, significant positive correlation was not restricted to heavily forested areas. Four patchily forested provinces exhibited strong positive correlations: 251—Prairie Parkland (Temperate) ($r = 0.32$, $p<0.0001$); 332—Great Plains Steppe ($r = 0.30$, $p = 0.0005$); 321—Chihuahuan Semi-Desert ($r = 0.47$, $p<0.0001$); and 341—Intermountain Semi-Desert and Desert ($r = 0.32$, $p = 0.0006$). In these provinces, peak lightning flash density values were relatively low compared to those in provinces in the Southeastern United States, but the locations of those peak values coincided with the provinces' mostly densely forested areas and greatest fire activity.

One sparsely forested province in the Great Lakes Region, 222—Midwest Broadleaf Forest, displayed a small negative correlation with borderline statistical significance ($r = -0.15$, $p = 0.0523$). Province 331—Great Plains—Palouse Dry Steppe also exhibited a small but significant negative correlation ($r = -0.17$, $p = 0.0095$). This province displayed substantial fire activity near the Canadian border, where lightning density was quite low. Ultimately, only one province displayed a large and significant negative correlation between fire and lightning activity, 242—Pacific Lowland Mixed Forest

($r = -0.53$, $p = 0.0249$). This, along with a mix of nonsignificant positive and negative correlations in northern Rocky Mountain Provinces, may support Rorig and Ferguson (2002), who argued that dewpoint depression and atmospheric instability are better predictors of lightning-caused fires than total lightning activity for the Northwestern United States because fires in the region are typically ignited only by “dry lightning” (lightning when there is little or no measurable rainfall).

This preliminary analysis ignored several factors that may affect spatio-temporal patterns of forest fire ignitions. For example, the potential importance of atmospheric and climatic conditions for ignition likelihood has already been noted. Also, forest fuel moisture and condition may vary seasonally, and this may affect the likelihood of fire ignition (Rorig and Ferguson 2002). Moreover, this analysis disregarded fuel type and current fire regime, both of which may vary at multiple spatial scales (Morgan and others 2001, Rorig and Ferguson 2002). Before drawing any conclusions, it is important to consider that in many parts of the Eastern United States, and especially in the Northeast, lightning has historically caused fewer wildland fires than have anthropogenic ignitions (Stephens 2005). However, anthropogenic fires are typically small compared to lightning-caused fires (Larjavaara and others 2005), and are more likely to be extinguished quickly, so the MODIS fire occurrence data are unlikely to depict most of them. Ideally, the forest cover masking process used to filter the occurrence data for this analysis tended to favor larger, lightning-caused fires in sizeable forested areas, but it is currently impossible to determine for any given region what proportion of the remaining MODIS forest fire occurrences are actually lightning-caused. It may also be true that the spatial pattern of human-related fire activity correlates with the spatial pattern of lightning activity. Irrespective of ignition source or other confounding effects, the results suggest that lightning flash density can serve as a useful general predictor of where fires are likely to occur for forested areas in the Eastern United States. However, it may also be advisable to include human population density in any predictive model. Four eastern provinces exhibited sizeable, statistically significant negative correlations between population density and forest fire occurrence: 231—Southeastern Mixed Forest ($r = -0.50$, $p<0.0001$); 232—Outer Coastal Plain Mixed Forest ($r = -0.39$, $p<0.0001$); 221—Eastern Broadleaf Forest ($r = -0.40$, $p<0.0001$); and M221—Central Appalachian Broadleaf Forest—Coniferous Forest—Meadow ($r = -0.33$, $p = 0.0108$). Notably, these same provinces exhibited large positive correlations between lightning flash density and fire occurrence. A succinct explanation of the negative correlations is that forest fires are likely to occur in the most heavily forested areas, where the human population density logically tends to be low. In any case, population density appears to be at least as important as lightning density in explaining forest fire pattern in much of the Eastern United States.

Success of lightning flash density as a predictor appears mixed for the Western United States, although there are certain ecoregion provinces, particularly in the Southwest, where the relationship between lightning and forest fire occurrence appears quite strong. Most western provinces did not exhibit correlations with population density, although three patchily forested ecoregion provinces in the West exhibited significant positive correlations between population density and forest fire occurrence: 332—Great Plains Steppe ($r = 0.34$, $p = 0.0001$); 321—Chihuahuan Semi-Desert ($r = 0.28$, $p<0.0251$); and 341—Intermountain Semi-Desert and Desert ($r = 0.38$, $p<0.0001$). This may be partially explained by the tendency of these provinces to exhibit high population densities in those areas where the limited amount of forest is also concentrated. Nevertheless, given the recent history of drought in several Western U.S. provinces (see chapter 2, "Drought," in this report), timely analyses that apply lightning density as an explanatory variable in conjunction with other relevant factors, e.g., forest fuel spatial pattern, historic fire regime, might provide information that could be used to reduce forest fire risk in these areas in the near future.

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