Relationships of Fire and Precipitation Regimes in Temperate Forests of the Eastern United States

Charles W. Lafon* and Steven M. Quiring

Department of Geography, Texas A&M University, College Station, Texas

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ABSTRACT: Fire affects virtually all terrestrial ecosystems but occurs more commonly in some than in others. This paper investigates how climate, specifically the moisture regime, influences the flammability of different landscapes in the eastern United States. A previous study of spatial differences in fire regimes across the central Appalachian Mountains suggested that intra-annual precipitation variability influences fire occurrence more strongly than does total annual precipitation. The results presented here support that conclusion. The relationship of fire occurrence to moisture regime is also considered for the entire eastern United States. To do so, mean annual wildfire density and mean annual area burned were calculated for 34 national forests and parks representing the major vegetation and climatic conditions throughout the eastern forests. The relationship between fire activity and two climate variables was analyzed: mean annual moisture balance [precipitation P − potential evapotranspiration (PET)] and daily precipitation variability (coefficient of variability for daily precipitation). Fire activity is related to both climate variables but displays a stronger relationship with precipitation variability. The southeastern United States is particularly noteworthy for its high wildfire activity, which is associated with a warm, humid climate and a variable

* Corresponding author address: Charles W. Lafon, 3147 TAMU, College Station, TX 77843-3147.

E-mail address: clafon@geog.tamu.edu

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precipitation regime, which promote heavy fuel production and rapid drying of fuels.

KEYWORDS: Wildfire; Fire climatology; Precipitation variability; Climatic variability

1. Introduction

Climate exerts strong control over vegetation structure and function. Its influences extend from global biome distributions to rates of ecosystem processes at individual sites (Whittaker 1975; Lloyd and Taylor 1994; Mudrick et al. 1994). One way climate affects ecosystems is through periodic events such as severe storms or droughts that damage or kill plants. Such disturbances shape species composition, biodiversity, and landscape patterns (Frelich 2002). Broadscale spatial variations in disturbance regimes may influence geographic patterns of vegetation (Parker et al. 2001; Bond and Keeley 2005).

Here, we investigate how climate, specifically moisture, influences geographic patterns of wildfire in the eastern United States. Fire is an influential disturbance agent and major natural hazard that presents complex management challenges. Many factors, such as vegetation and land use, affect fire occurrence (Pyne 1982; Alaback et al. 2003), but climate is of fundamental importance in defining the conditions that permit fire. Thus climate helps shape geographic patterns of fire (Krawchuk et al. 2009). A long-recognized (Sauer 1952) and recently articulated (Meyn et al. 2007; Parisien and Moritz 2009) generalization about climate and fire is that locations with intermediate moisture provide the best fire "habitats." These include, for example, tropical savannas and dry temperate forests. More extreme environments burn less often: for example, arid regions with sparse fuels and wet environments with moist fuels.

Beyond this generalization, a fuller understanding of how climate shapes fire regimes requires a consideration of climatic variability (Schoennagel et al. 2004; Meyn et al. 2007). Even a climate with intermediate moisture conditions is not constantly prone to fire but has alternating wet and dry periods. A number of studies have demonstrated the importance of anomalously dry periods for fire occurrence (e.g., Swetnam 1993; Westerling et al. 2006). A better understanding is needed about how the degree of climatic variability influences the overall susceptibility of an environment to fire.

Climatic variability exerts more influence than the climatic mean on some ecological processes (Jentsch and Beierkuhnlein 2008). Consequently, changes in climatic variability may affect ecosystems more severely than shifts in the mean. In mesic grasslands, for example, a variable precipitation regime with long rain-free intervals has been shown to cause greater vegetation stress and less ecosystem productivity than one with more consistent rainfall, even with identical mean annual precipitation (Fay et al. 2003; Heisler-White et al. 2009). Likewise, we expect that a variable precipitation regime would generate more days per year that favor burning, hence a more fire-prone environment, than a climate with more consistent precipitation and short rain-free intervals. If this is true, spatial differences in precipitation regime should contribute to geographic patterns of fire.

Previous research on spatial patterns of wildfire in the central Appalachian Mountains prompted the work reported here. Lafon and Grissino-Mayer (Lafon and Grissino-Mayer 2007) examined wildfire data for federally managed lands that spanned three physiographic provinces with differing climates: First, the high eastern edge of the Appalachian Plateau physiographic province, which occupies the western edge of the study area, receives abundant orographic precipitation. Second, the Ridge and Valley province to the east, in the rain shadow of the plateau, has a drier climate. Farther east, the Blue Ridge has wetter conditions, similar to the plateau; it receives moisture from the Atlantic Ocean and also impedes some of that moisture from penetrating west to the Ridge and Valley.

The fire cycle (i.e., number of years needed to burn an area equivalent to the entire landscape) varied by two orders of magnitude among the three provinces, from 10 845 years on the Appalachian Plateau to 1274 years in the Ridge and Valley and 284 years on the Blue Ridge (Lafon and Grissino-Mayer 2007). All these are quite long, much longer than in the past when fires were not suppressed (e.g., Aldrich et al. 2010). Nonetheless, fire still occurs frequently enough in the Blue Ridge to play an important role in ecosystem functioning and vegetation patterns. Fire has a minimal influence on the Appalachian Plateau, however, despite annual precipitation totals that are about the same as those on the Blue Ridge. Lafon and Grissino-Mayer (Lafon and Grissino-Mayer 2007) suggested that a regime of less frequent but heavier precipitation events leads to longer dry spells and more fire in the Blue Ridge than the Appalachian Plateau, with a less variable regime of frequent, light precipitation events that keep fuels moist for much of the time.

In the current paper, we follow up on that study to determine whether, indeed, the Blue Ridge has greater precipitation variability than the other physiographic provinces. We also extend the study to the entire eastern United States, which encompasses a wider range of climates than the Appalachian Mountains. We explore the relationship of fire to both the average annual moisture condition and the variability of daily precipitation amount.

2. Methods

2.1. Precipitation regimes in the Appalachian Mountains

We obtained the 1971–2000 mean annual precipitation data (NCDC 2011a) for 42 climate stations in the central Appalachian Mountains (Figure 1; Table 1). The stations occupy the study area of Lafon and Grissino-Mayer (Lafon and Grissino-Mayer 2007). We also acquired daily precipitation amounts (NCDC 2005; NCDC 2009) for the period 1971–2000 and calculated the coefficient of variability (CV) for daily precipitation (Zar 1999) at each of the 42 stations. The CV expresses variability relative to the mean (Zar 1999) and therefore enables comparisons of precipitation between stations with different mean daily precipitation amounts. It is regularly used to characterize daily precipitation variability (e.g., Douville et al. 2001; Goswami et al. 2006).

We averaged the annual precipitation and CV data for the stations within each physiographic province. Kruskal–Wallis analysis (Zar 1999) was used to test whether the climatic variables differed among the provinces. We then performed pairwise comparisons between the provinces (Dunn 1964; Zar 1999).

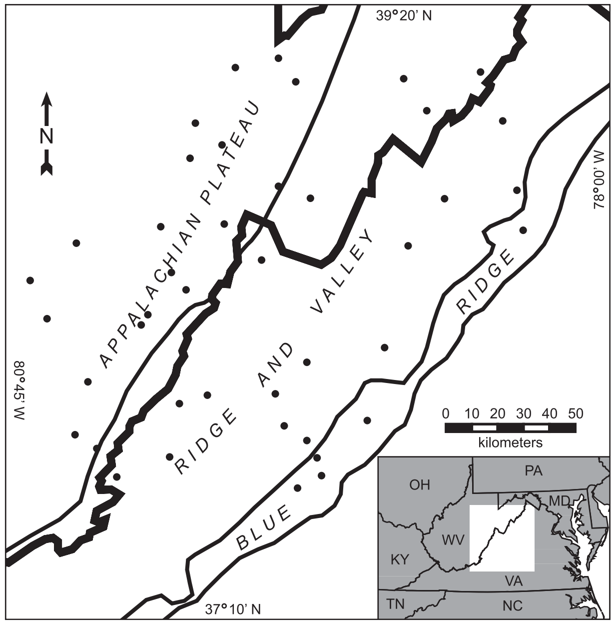

Figure 1. The central Appalachian Mountains. The heavy lines portray state boundaries, and the thin lines indicate physiographic boundaries (based on Fenneman 1938; Rodgers 1970; Bailey 1999). The points represent the climate stations used to analyze precipitation regimes for the central Appalachian NF and NP lands used by Lafon and Grissino-Mayer (Lafon and Grissino-Mayer 2007) in their analysis of central Appalachian fire regimes.

2.2. Fire–climate relationships across the eastern United States

We identified 34 national forests (NFs) and national parks (NPs) that span the range of moisture conditions found across the humid continental and humid subtropical zones of the eastern United States (Table 2). These federal lands represent the major forest types and physiographic regions of the temperate forest region in the eastern United States: from subtropical pine (*Pinus*)–dominated forests to the southern boreal forests and from dry oak (*Quercus*) forests to mesophytic and northern hardwoods forests. For each federal land, we obtained wildfire occurrence data archived in the National Interagency Fire Management Integrated Database (NIFMID; USDA Forest Service 1998), which contained fire occurrence data (e.g., date, cause) for 1970–2009 and reliable area-burned data for 1986–2009. These records permitted us to calculate the mean annual density of wildfires for 1970–2009 and the mean annual area burned for 1986–2009. We expressed annual fire density and area burned on the basis of a 400 000-ha area (i.e., fires per 400 000 ha yr^{-1}; area burned per 400 000 ha yr^{-1}). The 400 000-ha area approximates the 1 000 000-acre basis conventionally used in fire density calculations in the United States (e.g., Schroeder and Buck 1970). These calculations required data on the land area of each national forest/park; we gathered these data

Table 1. Climate stations in the central Appalachian Mountains.

Physiographic province	Climate station	Mean annual precipitation (mm)	CV of daily ppt (%)
Appalachian Plateau	Bartow, WV	1121	233
	Buckeye, WV	1158	237
	Camden on Gauley, WV	1398	209
	Canaan Valley, WV	1305	203
	Dailey, WV	1232	220
	Elkins, WV	1171	215
	Glady, WV	1346	207
	Lewisburg, WV	1031	247
	Marlinton, WV	1111	244
	Parsons, WV	1318	210
	Renick, WV	1083	246
	Richwood, WV	1344	208
	Seneca State Forest, WV	1216	234
	Snowshoe, WV	1515	207
	Spruce Knob, WV	1071	244
	Thomas, WV	1470	192
	Valley Head, WV	1264	209
	Webster Springs, WV	1202	227
	White Sulphur Springs, WV	1028	247
Ridge and Valley	Covington, VA	927	274
	Craigsville, VA	1107	274
	Dale Enterprise, VA	917	273
	Earlehurst, VA	997	254
	Gathright Dam, VA	983	266
	Goshen, VA	1122	271
	Hot Springs, VA	1090	263
	Kerrs Creek, VA	1150	279
	Lexington, VA	1015	280
	Monterey, VA	1112	245
	Staunton, VA	987	285
	Timberville, VA	894	279
	Woodstock, VA	953	273
	Franklin, WV	897	286
	Mathias, WV	948	271
	Moorefield, WV	835	283
	Wardensville, WV	897	277
Blue Ridge	Big Meadows, VA	1394	304
	Buena Vista, VA	987	291
	Glasgow, VA	1261	299
	Luray, VA	1057	296
	Montebello, VA	1348	290
	Pedlar Dam, VA	1135	278

from the U.S. Forest Service website (http://www.fs.fed.us/) and the NP index (NPS 2009).

Both measures of wildfire activity—fire density and area burned—are commonly used in research on fire regimes (e.g., Mitchener and Parker 2005; Lafon and Grissino-Mayer 2007). Area burned is particularly important because it reflects the extent of burning within a landscape. It is influenced by suppression efforts, however, which could obscure the climatic and ecological conditions that favor burning. Suppression

Table 2. Eastern U.S. federal lands incorporated in the study.

Federal land	Region	Representative climate station	Fire density (fires per 400 000 ha yr^{-1})	Area burned (ha per 400 000 ha yr^{-1})	P − PET (mm)	CV of daily ppt (%)
Nantahala NF	Appalachia	Franklin, NC	43.4	311	670	247
Pisgah NF	Appalachia	Celo, NC	48.0	774	832	277
Gr. Smoky Mtns. NP	Appalachia	Gatlinburg, TN	22.2	586	732	226
G. Washington NF	Appalachia	Hot Springs, VA	25.3	156	498	263
Jefferson NF	Appalachia	Staffordsville, VA	25.9	518	345	259
Shenandoah NP	Appalachia	Luray, VA	39.9	2322	328	296
Monongahela NF	Appalachia	Glady, WV	7.4	18	778	206
Huron NF	Great Lakes	Mio Hydro Plant, MI	37.7	421	103	271
Manistee NF	Great Lakes	Baldwin, MI	34.1	72	298	264
Ottawa NF	Great Lakes	Kenton, MI	5.2	14	172	283
Superior NF	Great Lakes	Babbitt, MN	18.0	743	235	291
Acadia NP	Northeast	Acadia NP, ME	72.4	29	866	263
White Mtns. NF	Northeast	Pinkham Notch, NH	6.6	6	985	246
Allegheny NF	Northeast	Kane, PA	12.2	20	708	217
Green Mtn. NF	Northeast	Dorset, VT	4.6	10	746	241
Ouachita NF	Southeast	Mena, AR	49.0	339	667	306
Appalachicola NF	Southeast	Tallahassee, FL	62.2	2191	554	291
Big Cypress NP	Southeast	Oasis Rgr Stn, FL	71.5	9138	163	286
Everglades NP	Southeast	Homestead, FL	18.5	3423	200	291
Ocala NF	Southeast	Ocala, FL	164.8	1149	142	298
Osceola NF	Southeast	Glen St Mary, FL	94.4	10 505	330	287
Shawnee NF	Southeast	Harrisburg, IL	43.8	147	393	281
Hoosier NF	Southeast	Oolitic Purdue Exp. Fm., IN	29.4	61	438	271
Bienville NF	Southeast	Forest, MS	81.6	381	653	280
Delta NF	Southeast	Yazoo City, MS	8.1	27	548	287
DeSoto NF	Southeast	Wiggins, MS	176.2	1759	649	337
Homochito NF	Southeast	Meadville, MS	53.6	531	621	282
Tombigbee NF	Southeast	Eupora, MS	75.6	362	589	293
Croatan NF	Southeast	New Bern, NC	61.2	2342	505	280
Uwharrie NF	Southeast	Jackson Springs, NC	81.4	309	372	275
Angelina NF	Southeast	Sam Rayburn Dam, TX	86.8	836	618	302
Davy Crockett NF	Southeast	Groveton, TX	62.3	209	196	323
Sabine NF	Southeast	Toledo Bend Dam, TX	66.6	294	488	303
Sam Houston NF	Southeast	Cold Springs, TX	79.8	220	307	325

does not affect fire density. Fire density therefore reflects the climatic and ecological conditions that lead to ignition (Gralewicz et al. 2011), although it does not reveal how those factors influence the spread of fire over a landscape. Using both measures offers more reliable insights about fire–climate relationships than using either one alone.

Table 3. Mean values of climatic variables for the weather stations in each physiographic province of the central Appalachian Mountains. Within a row, values followed by different letters differ significantly according to Kruskal–Wallis and post hoc pairwise tests.

	Appalachian Plateau $n = 19$	Ridge and Valley $n = 17$	Blue Ridge $n = 6$
Annual precipitation (mm)	1231(a)	990(b)	1197(a)
CV of daily precipitation (%)	223(a)	273(b)	293(b)

We assigned a climate station to represent the general conditions associated with each federal land. For each station, we first characterized the average annual moisture availability by calculating its annual moisture balance [precipitation $P -$ potential evapotranspiration (PET)]. We used Thornthwaite's (Thornthwaite 1948) method to estimate PET from the 1971–2000 monthly temperature averages (NCDC 2011a). We then conducted correlation analyses (Zar 1999) to test whether fire activity (mean annual fire density and mean annual area burned) was related to annual moisture balance.

Second, we calculated the CV of daily precipitation for 1971–2000 at each of the stations, using data from the National Climatic Data Center (NCDC 2005; NCDC 2009). We correlated fire activity with this variable to look for an influence of precipitation variability on fire activity. Finally, as the two climate variables (annual moisture balance and CV of daily precipitation) were correlated with each other ($r = -0.44$, $P < 0.05$), we calculated partial correlation coefficients (Zar 1999) to examine the relationship of fire activity with each of the two climate variables independently.

3. Results

3.1. Precipitation regimes in the Appalachian Mountains

Mean annual precipitation for the central Appalachian climate stations varied spatially according to the generally recognized pattern in the region. Significantly less precipitation fell over the Ridge and Valley than over the other two provinces (Table 3). Mean precipitation for stations in the Ridge and Valley ranged between 835 and 1150 mm yr^{-1} (Table 1). The stations in the Appalachian Plateau generally had wetter climates, annually receiving 1028–1515 mm of precipitation. Precipitation totals in the Blue Ridge were similar to those on the Appalachian Plateau (Table 3), with station totals averaging 987–1394 mm yr^{-1}.

Daily precipitation variability showed a different pattern, wherein the Appalachian Plateau had less variability than the more flammable provinces to the east (Table 3). Although precipitation variability did not differ significantly between the moderately fire-prone Ridge and Valley and the more fire-prone Blue Ridge, every station in the Blue Ridge but one (Pedlar Dam; Table 1) had a higher CV than the stations in the Ridge and Valley. The failure to obtain a statistically significant difference in precipitation variability between the Ridge and Valley and the Blue Ridge probably reflects the small sample size ($n = 6$) for the Blue Ridge.

Spatial variations in fire cycle correspond with the pattern of daily precipitation variability: fire cycle declined from 10 845 years on the Appalachian Plateau to

1274 years in the Ridge and Valley and 284 years in the Blue Ridge (Lafon and Grissino-Mayer 2007), paralleling the increase in CV of precipitation from west to east. The fire cycle did not vary in the same manner as total annual precipitation, however. The two wet environments (the Appalachian Plateau and the Blue Ridge) had contrasting fire regimes—one with little fire and the other with much fire—while the driest environment (the Ridge and Valley) had an intermediate level of burning compared to the wetter provinces. In the following section, we examine how fire activity relates to annual moisture level and daily precipitation variability across the entire eastern United States.

3.2. Fire–climate relationships across the eastern United States

Fire density tended to decline from the driest to wettest environments (Figure 2a), but the pattern was weak. Both high and low fire density could be found across the entire climatic moisture gradient, and a statistically significant correlation did not emerge (Table 4, relationship A). Area burned displayed a more pronounced decline (Figure 2b), with drier areas witnessing a greater areal extent of burning than moister environments, resulting in a negative correlation between area burned and moisture balance (Table 4, relationship B).

Fire activity showed stronger relationships with daily precipitation variability. Both fire density and area burned increased along the precipitation variability gradient (Figures 2c,d), and both showed positive correlations with CV of daily precipitation (Table 4, relationships C and D). In general, then, environments with high precipitation variability witnessed more fires and a greater areal extent of burning than did locations with relatively little precipitation variability.

Analyzing partial correlations revealed no significant relationship between fire activity and $P - \mathrm{PET}$ (Table 4, relationships E and F). According to this analysis, any tendency toward greater fire activity in the driest parts of the eastern United States was mostly a consequence of the greater precipitation variability in dry sites compared to wet sites, not a result of the average moisture levels themselves. Locations with higher precipitation variability had more burning than those with less variability, as indicated by positive partial correlations between fire activity and the CV of daily precipitation (Table 4, relationships G and H).

The interregional variations in fire activity across the eastern United States generally corresponded to their climatic differences (Figure 2). The fire-prone Southeast showed high precipitation variability. Most of the points on the right half of the precipitation variability axis (Figures 2c,d) represent locations in the Southeast. The southeastern locations were also relatively dry, in terms of annual moisture balance, compared to the Northeast and parts of Appalachia (Figures 2a,b). Delta National Forest, Mississippi, deviated in flammability from the rest of the Southeast. Its fire activity, in terms of both density and area burned, was among the lowest of all sites in the entire eastern United States, despite its climatic resemblance to the rest of the Southeast (Table 2).

The Great Lakes region had the driest climatic conditions of all the regions in terms of annual moisture balance (Figure 2; Table 2). It showed only a moderate level of burning, however, which matched its moderate precipitation variability. Ottawa National Forest, Michigan, witnessed an unusually low level of burning compared to the rest of the Great Lakes sites.

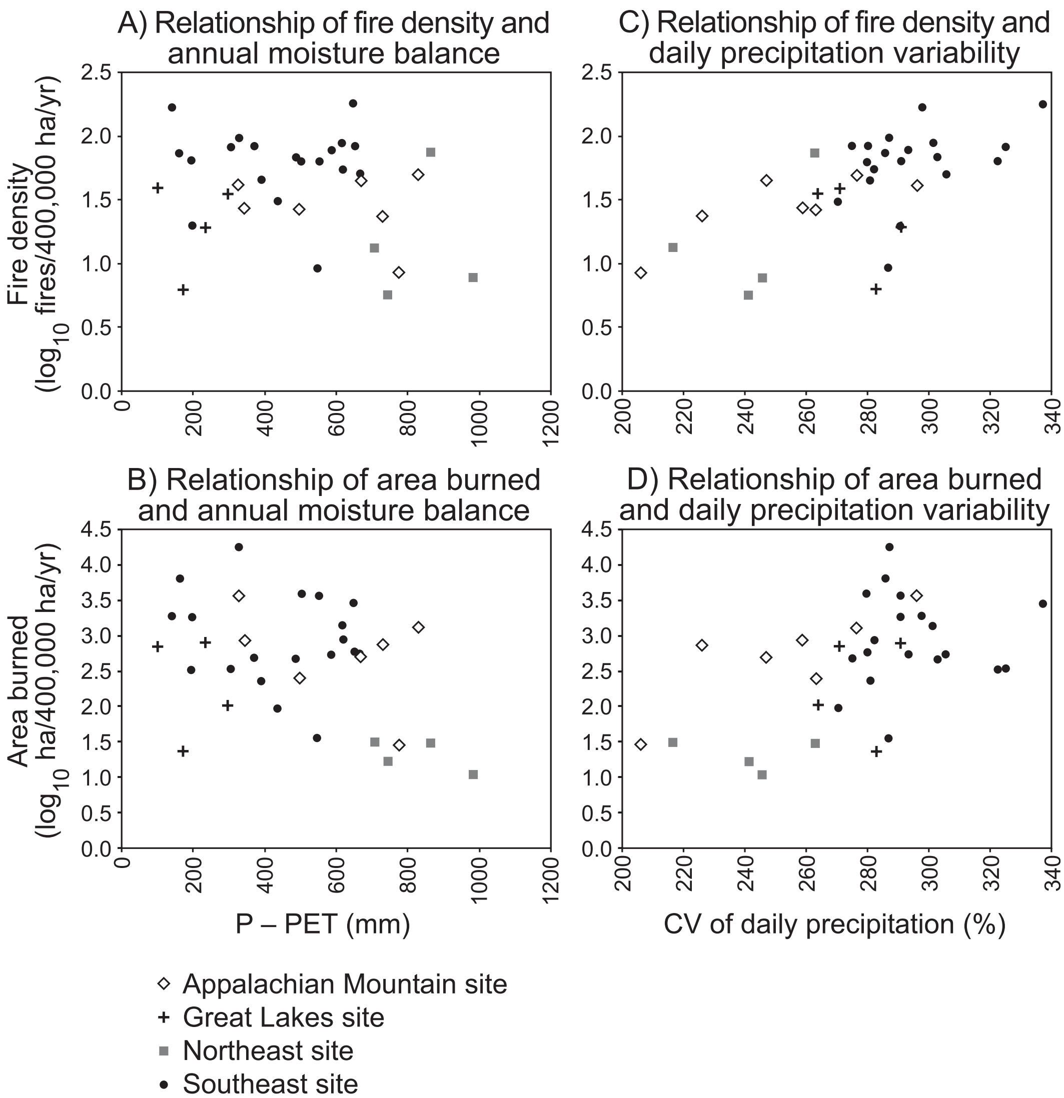

Figure 2. Relationship of fire activity to (a),(b) mean annual moisture balance and (c),(d) daily precipitation variability for NFs and NPs in the eastern United States. The graphs in (a),(c) portray fire activity in terms of mean annual fire density, while those in (b),(d) depict fire activity in terms of mean annual area burned. Each point on the scatterplots represents an NF or NP.

The wettest climates and least variable precipitation regimes occurred in the northeastern United States, which also had little fire activity (Figure 2; Table 2). Acadia National Park, Maine, was the only northeastern site with a moderate level of fire activity, at least in terms of fire density. It had one of the wettest climates in the entire eastern United States but exhibited relatively high precipitation variability, considerably higher than the other northeastern sites.

The Appalachian national forests and parks showed a wide range of climatic conditions and fire activity (Figure 2; Table 2), despite their geographic proximity.

Table 4. Correlations of fire activity to climate variables for national forests and parks across the eastern United States.

	Annual moisture availability ($P - \mathrm{PET}$)	Daily precipitation variability (CV of daily ppt)
	Correlations	
Fire density ($\log_{10}$ fires per 400 000 ha yr^{-1})	A: −0.20	C: 0.62*
Area burned ($\log_{10}$ ha per 400 000 ha yr^{-1})	B: −0.39*	D: 0.51*
	Partial correlations	
Fire density ($\log_{10}$ fires per 400 000 ha yr^{-1})	E: 0.11	G: 0.61*
Area burned ($\log_{10}$ ha per 400 000 ha yr^{-1})	F: −0.21	H: 0.41*

* Statistically significant correlations ($P < 0.05$).

Fire activity was quite high along the eastern edge of Appalachia: in the Blue Ridge Mountains of Shenandoah National Park, Virginia, and Pisgah National Forest, North Carolina. Precipitation variability was quite high at these two locations. On the other hand, Monongahela National Forest, West Virginia, had little fire activity. It is situated primarily on the Appalachian Plateau, where the moisture regime resembled that of the Northeast.

4. Discussion

The spatial pattern of fire activity across the central Appalachian physiographic provinces parallels that of daily precipitation variability, as suggested by Lafon and Grissino-Mayer (Lafon and Grissino-Mayer 2007). Fire activity does not correspond as well to the spatial pattern of total annual precipitation. On the basis of total annual precipitation, in fact, we would expect the Ridge and Valley to show the most fire activity and the Blue Ridge to exhibit less, perhaps about the same level as the Appalachian Plateau. Precipitation variability appears to offer a better explanation than total precipitation for the spatial differences in fire regime among the physiographic provinces of the Appalachian Mountains.

Clearly, the Appalachian Plateau is not too wet to burn on the basis of total annual precipitation, given that it receives about the same amount as the Blue Ridge. Instead, the plateau likely remains too wet to burn for much of the year because frequent light precipitation events persistently rewet the fuels. Konrad (Konrad 1994) showed that light precipitation events (defined as events with $<$1.27 cm of rain) occur more frequently on the western side of the Appalachian region than on the eastern side, where heavy events ($>$5.08 cm of rain) are more common. Despite similar annual averages, then, the regime of precipitation delivery varies from east to west as moisture-bearing winds and precipitation-generating mechanisms interact with the terrain. The eastern slopes of the Blue Ridge, in particular, favor convection of moist air imported from the Atlantic Ocean (Konrad 1994; Phillips 2001), leading occasionally to heavy rainfall in an otherwise relatively dry—and flammable—environment.

The patterns of fire and precipitation regime across three physiographic provinces do not suffice to establish a general trend. The broader fire–climate pattern for the entire temperate forest region of the eastern United States, however, evokes a general pattern consistent with that suggested by the central Appalachian fire and climate data considered in this study and in Lafon and Grissino-Mayer (Lafon and Grissino-Mayer 2007). Both annual moisture balance and daily precipitation variability appear to influence fire activity, but daily variability has the dominant effect, as indicated by the correlation analyses.

Some of the federal lands in our study, in fact, display high fire activity despite relatively wet climates, apparently because of their variable precipitation regime. The DeSoto National Forest, Mississippi, occupies one of the wettest locations in the Southeast, but its precipitation variability and fire density exceed those of all other study sites. Likewise, Acadia National Park, Maine, has a wet climate, but its precipitation variability and fire density are high compared to the other sites in the Northeast. Haines et al. (Haines et al. 1983) found that in the northeastern United States the probability of fire rises with the passage of more consecutive rain-free days. A variable precipitation regime should promote fire in a humid climate because it comprises episodic heavy rainfall events separated by multiple rainless days that permit fuels to dry and burn.

The southeastern United States, especially Florida and the Gulf Coastal Plain, is notable for its flammability. Despite its humid climate, the Southeast has a long history of frequent burning by humans and lightning (Pyne 1982; Lafon 2010) and currently has more wildfires annually than any other region of the United States (Andreu and Hermansen-Báez 2008). The abundant rainfall and high temperatures in the Southeast combine to generate a fire-prone environment. First, plant productivity is high under these moisture and temperature conditions, resulting in heavy fuel loads (Pyne 1982). Second, the fuels dry quickly because the warm environment induces high potential evapotranspiration. Third, despite abundant precipitation, the Southeast generally has less rain days annually than the other regions in our study (NCDC 2011b), giving the fuels longer to dry and burn. The high annual precipitation totals are possible because of the intense rainfall events that occur in the Southeast (Frederick et al. 1977). During summer, clockwise flow around the Bermuda high advects warm, moist air masses from the Gulf of Mexico into the Southeast. These unstable air masses produce convection that leads to afternoon thunderstorms (Soule 1998). Infrequent but heavy rain from tropical cyclones can contribute significant precipitation during the late summer and fall (Knight and Davis 2009).

Nonclimatic factors obviously affect fire activity too. Differences in terrain, vegetation, and human accessibility probably account for much of the scatter shown in our graphs. The Delta National Forest, Mississippi, for example, lags the rest of the Southeast in fire activity because it occupies frequently flooded bottomland hardwood forests. Further, in large and/or mountainous national forests or parks, our ''broad brush'' approach using a single climate station cannot represent the range of fire climates that exist across the entire landscape. Despite such limitations, our study reveals important patterns, particularly with respect to the consequences of precipitation variability for fire activity. Fire, like plant productivity (e.g., Fay et al. 2003; Heisler-White et al. 2009) and perhaps other ecological processes, responds to differences in precipitation variability as strongly as to differences in total moisture supply.

5. Conclusions and implications

In the eastern United States, precipitation variability influences flammability more strongly than does the total annual moisture supply. While the driest parts of the eastern United States tend to have more fire than the wettest parts, this pattern appears mainly to reflect the greater precipitation variability in dry sites, rather than an actual influence of average moisture levels. Our results suggest that the regime of precipitation delivery must be considered if we are to understand fire–climate relationships, at least within the range of environmental conditions found in the eastern United States. The association between fire and precipitation variability may apply to forested areas beyond the eastern United States. Preliminary analyses that we have conducted for the western United States (C. W. Lafon and S. M. Quiring 2011, unpublished manuscript) resemble those reported here and suggest the generality of the relationships.

Changes in precipitation variability could produce strong ecological effects (Jentsch and Beierkuhnlein 2008), but they have received less attention than changes in climatic averages. Our results suggest that a shift toward less frequent but more intense rainfall events could promote greater fire activity, regardless of whether the average moisture level changes. The observation record indicates that precipitation has increased in the eastern and southeastern United States over the last century (Karl and Knight 1998). Most of the increase in the southeastern United States can be attributed to greater intensities of very heavy and extreme precipitation events (top 10% of events). The observations also show that the duration of prolonged periods of warm season dry episodes increased in the eastern United States during the last 40 years (Groisman and Knight 2008). Apparently, then, eastern U.S. climates are trending toward greater variability in precipitation delivery, with prolonged dry periods punctuated by extreme precipitation events. The trend varies within the region (Keim 1997), but for the eastern United States as a whole it may portend increasing wildfire occurrences.

The fire–climate relationships that we have considered here likely influence biogeographic distributions. Several fire-dependent species—for example, the mountain golden heather (*Hudsonia montana* Nutt.; cf. USFWS 2011), eastern turkeybeard [*Xerophyllum asphodeloides* (L.) Nutt.; cf. Flora of North America Editorial Committee 1993], and Table Mountain pine (*Pinus pungens* Lamb.; cf. Della-Bianca 1990)—occupy eastern parts of the Appalachian Mountains but not the less flammable western portions. Similarly, the pine (*Pinus* L.) woodlands and savannas that historically dominated the coastal plains of the Southeast developed under a regime of frequent burning that restricted the survival of competing hardwood trees. Komarek (Komarek 1968) suggested that the irregular occurrence of convective storms interspersed with long, hot rainless periods enabled the frequent fires that sustained the pine stands. He noted that the deciduous forests to the north and interior occupy a region with more regular precipitation, which reduces opportunities for extensive burning.

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