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Constraints on global fire activity vary across a resource gradient

Meg A. Krawchuk[1] and Max A. Moritz

Department of Environmental Science, Policy and Management, 137 Mulford Hall, MC#3114, University of California, Berkeley, California 94720 USA

Abstract. We provide an empirical, global test of the varying constraints hypothesis, which predicts systematic heterogeneity in the relative importance of biomass resources to burn and atmospheric conditions suitable to burning (weather/climate) across a spatial gradient of long-term resource availability. Analyses were based on relationships between monthly global wildfire activity, soil moisture, and mid-tropospheric circulation data from 2001 to 2007, synthesized across a gradient of long-term averages in resources (net primary productivity), annual temperature, and terrestrial biome.

We demonstrate support for the varying constraints hypothesis, showing that, while key biophysical factors must coincide for wildfires to occur, the relative influence of resources to burn and moisture/weather conditions on fire activity shows predictable spatial patterns. In areas where resources are always available for burning during the fire season, such as subtropical/tropical biomes with mid-high annual long-term net primary productivity, fuel moisture conditions exert their strongest constraint on fire activity. In areas where resources are more limiting or variable, such as deserts, xeric shrublands, or grasslands/savannas, fuel moisture has a diminished constraint on wildfire, and metrics indicating availability of burnable fuels produced during the antecedent wet growing seasons reflect a more pronounced constraint on wildfire. This macro-scaled evidence for spatially varying constraints provides a synthesis with studies performed at local and regional scales, enhances our understanding of fire as a global process, and indicates how sensitivity to future changes in temperature and precipitation may differ across the world.

Key words: circulation anomalies; climate; constraints on wildfire; energy and moisture gradients; global pyrogeography; resources and conditions; soil moisture; Spearman rank correlation; zero-inflated negative binomial regression.

Introduction

Pyrogeography considers biophysical factors controlling the distribution and abundance of wildfire activity (Krawchuk et al. 2009), including biomass resources to burn, atmospheric conditions suitable for combustion and propagation of fire, and ignition agents (Fig. 1a). Although fire always needs these resources, conditions, and an ignition, landscape-scale studies have highlighted vast spatial and temporal heterogeneity in how each of the factors contributes to variability in wildfire (e.g., Turner and Romme 1994, Bessie and Johnson 1995, Cumming 2001, Moritz 2003, Mermoz et al. 2005, Krawchuk et al. 2006). Earlier global pyrogeographies have developed our understanding of macro-scaled controls over fire (Dwyer et al. 2000, Scholze et al. 2006, Le Page et al. 2007, Chuvieco et al. 2008, Marlon et al. 2008, Krawchuk et al. 2009), but none have formally examined the relative contribution of fuels (resources) and weather (conditions). Quantifying how the relative roles of these factors fluctuate to generate variability in global fire activity begins a synthesis of global studies with landscape studies, developing our understanding of the codependence of ecosystems and fire through vegetation–disturbance–climate interactions (Stephenson 1990, Bond et al. 2005) and how climate change may alter these patterns (Scholze et al. 2006, Bowman et al. 2009, Krawchuk et al. 2009).

A conceptual synthesis of local and regional wildfire studies by Meyn et al. (2007) outlined environmental gradients across which relative control over large, infrequent fires might vary. Though Meyn et al. (2007) illustrated the idea with respect to large, infrequent events, the rationale holds for variation in fire activity, too. Drier weather conditions during the fire season tend to increase fire activity in biomass-rich areas such as wet forests, where the dominant limiting factor is arguably fuel moisture rather than fuel amount (see Plate 1). At the other end of the spectrum, dry weather conditions are common, and the dominant limiting factor for fire is the ephemeral amount and/or connectivity of resources to burn, such as in grasslands and some shrublands; here, temperature and precipitation in the years or growing period preceding the fire season tend to drive fire activity through accumulation of fine fuels or by modulating live fuel moisture. This conceptual model, which we refer to here as the varying constraints hypothesis, provides a framework that explicitly con-

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[1] E-mail: megk@berkeley.edu

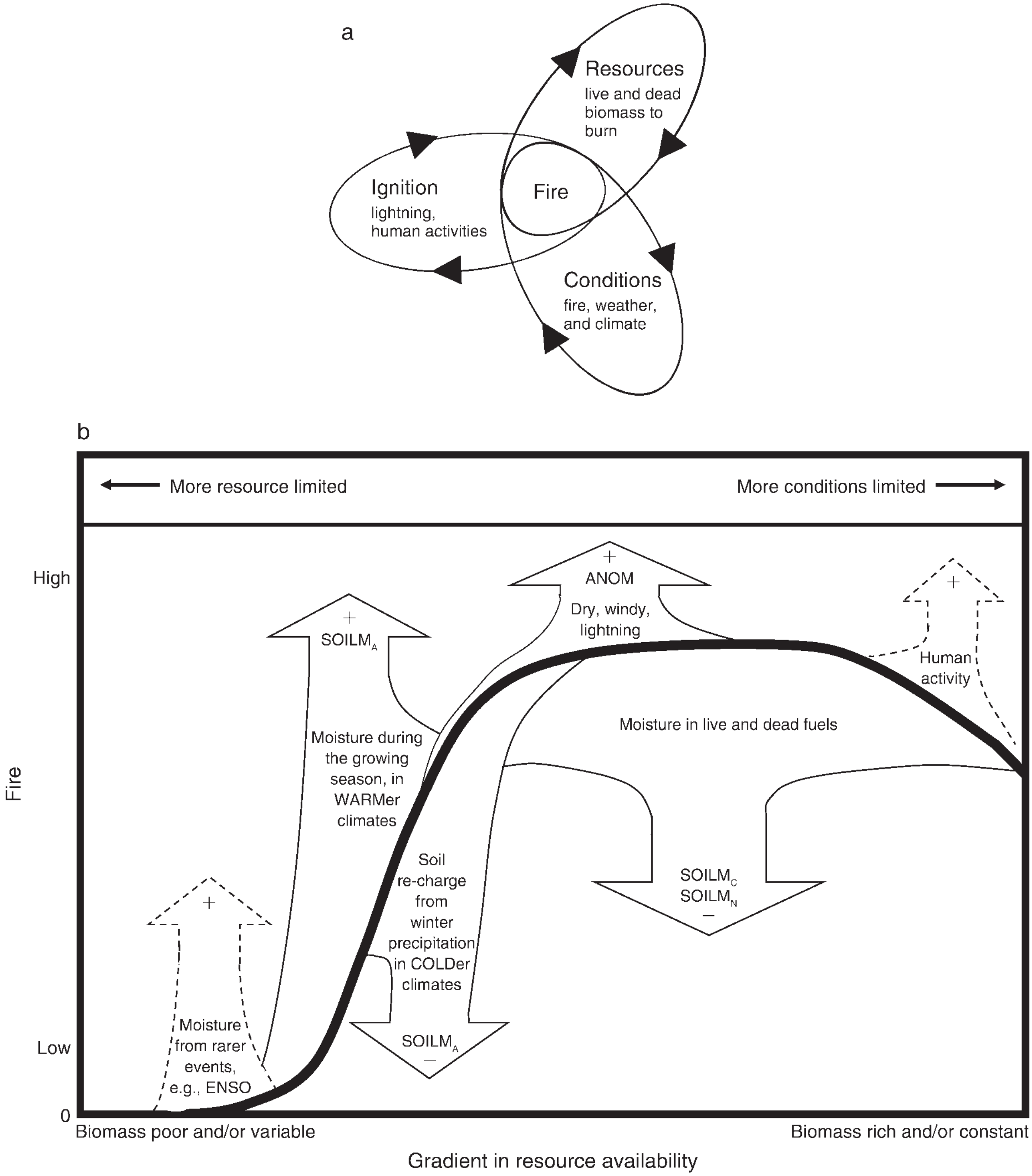

FIG. 1. (a) Fire activity requires the coincidence of resources, conditions, and ignition; these are dynamic in space and time. (b) We hypothesized that the relative influence of resources and conditions for fire would vary such that SOILM$_C$, SOILM$_N$, SOILM$_A$, and ANOM would have characteristically positive or negative relationships (arrows) with fire activity (*y*-axis) according to a global gradient in resource availability (*x*-axis). (SOILM$_C$, SOILM$_N$, SOILM$_A$ represent current soil moisture conditions, near-term conditions, and antecedent conditions, respectively; ANOM represents the 500 hPa height [midtropospheric] circulation anomaly.) The thick line depicts an abstracted baseline relationship between long-term fire probability and global resources to burn, depicted by net primary productivity (NPP), as estimated by Krawchuk et al. (2009). The locations of arrows are approximate, but they indicate the general region along the global resource gradient where we expected to see these varying constraints. Dashed arrows indicate examples of additional strong controls over wildfire activity that were not tested explicitly in the study but are mentioned in the *Discussion*.

siders spatial gradients in the relative importance of controls over wildfire, rather than a binary view of weather/fuel moisture vs. fuel amount. Specifically, we propose that the relative influence changes systematically according to scarcity or variability: where resources to burn are available all the time, then fuel moisture conditions are likely to be relatively more important; in contrast, if resources are ephemeral, then their availability should regulate wildfire.

Supporting evidence for the varying constraints hypothesis comes from geographically diverse studies ranging from western North America (Swetnam and Betancourt 1990, Westerling et al. 2003, Gedalof et al. 2005, Sherriff and Veblen 2008, Littell et al. 2009) to the tropics/subtropics (van der Werf et al. 2008), but this conceptual model has not been quantitatively tested for global consistency. Furthermore, many of the constituent studies provide local evidence for varying constraints, yet do not address a resource gradient explicitly. The goal of our study was thus to determine whether the importance of resources and conditions for wildfire changed predictably over a global gradient in biomass resource availability, using globally extensive empirical data. Our analyses examined the relationship between remotely sensed monthly global fire activity (2001–2007) vs. monthly moisture metrics during the fire season and those leading up to it. In addition to soil moisture, we proposed a further metric of fire weather conditions, anomaly in mean monthly 500 hPa geopotential height, that has been shown to characterize prime conditions for fire (Johnson and Wowchuk 1993) in mid and high latitudes.

Materials and Methods

We sampled all study variables at a spatial resolution of 50 km (i.e., 2500 km^2) using a Behrmann equal area projection. The sample included only terrestrial areas of the globe and excluded Greenland and Antarctica, resulting in a total of 52 298 sample points.

Fire

We acquired monthly summaries of MODIS (Moderate Resolution Imaging Spectroradiometer) Collection 5 corrected active fire data (Giglio et al. 2006*a*) detected by the Terra satellite from January 2001 to December 2007, resulting in 84 months of data. The MODIS sensor provides data at a spatial resolution of 1 km from twice-daily passes of the Terra satellite over the globe, and detects actively burning fires using infrared bands. MODIS can detect flaming and smoldering fires of ~1000 m^2, and under good conditions fires of 100 m^2 can be detected. Raw data corrections include adjustment for multiple satellite overpasses, cloud cover, and persistent static fire sources indicative of nonvegetation fire. The resulting data are provided as 0.5° monthly climate model grids (CMG) for the globe (Giglio et al. 2006*a*). We selected the Terra Collection over the Aqua satellite since the former had a longer period of record. As with all remotely sensed fire data, there are omission (e.g., undetectable understory fires or short-duration fires occurring between twice daily satellite passes) and commission errors; however, extensive diagnostics on the MODIS active fire data show them as a robust index of global fire activity (Giglio et al. 2006*a*, *b*).

Plate 1. Fire burning in a mixed conifer forest in California (USA), an environment with intermediate amounts of biomass availability within the global rersource gradient. Photo credit: M. A. Krawchuk.

After registering fire data to our 50-km resolution sampling grid, we determined the dominant fire season for each location based on observed temporal patterns of fires. We identified the peak of the fire season as the month of the year with the highest number of events over the seven-year record. Patterns observed in van der Werf et al. (2003) and Giglio et al. (2006*a*) showed peak fire activity to be very similar to our calculations. We then described the potential fire season as the three months preceding and following this peak, based liberally on length of fire season presented in Giglio et al. (2006*a*). This is a simplification of fire seasonality, but one that allowed us to confine analyses to the most relevant time periods. We also used the fire season's peak to inform calculations of fire constraints (see *Fire constraints*: SOILM$_A$).

Fire constraints

We used four metrics to test hypotheses examining whether seasonal constraints on wildfire activity vary across a global long-term resource gradient (Fig. 1b). Three metrics were derived from soil moisture data and one from 500-hPa tropospheric heights. We confined our assessment to these four metrics, since the goal was to test particular hypotheses associated with their variability, rather than to build a global predictive model of fire activity or seasonality. Current soil moisture ($\mathrm{SOILM_C}$) was calculated for each month for each location to characterize the moisture (dryness) of live and dead fuels and their propensity to burn; for example, $\mathrm{SOILM_C}$ would then be analyzed with respect to the amount of fire activity in that month and location. Near-term soil moisture ($\mathrm{SOILM_N}$) was calculated from mean monthly soil moisture in the first and second months prior to the month of fire activity, representing slightly longer-term drought conditions. Antecedent soil moisture conditions ($\mathrm{SOILM_A}$) were calculated as mean monthly soil moisture of the fourth to eighth months prior to the peak of the fire season. For warmer and drier climates where burning conditions are common and fuels may be limiting, $\mathrm{SOILM_A}$ indicated moisture availability in the growing period prior to the fire season as a proxy for resources to burn. For example, high $\mathrm{SOILM_A}$ would lead to more productivity, and these fuels would then cure during the dry season, resulting in a greater fire activity (Spessa et al. 2005). Phenology differs among types of fine fuels (e.g., herbaceous plants) and fuel accumulation may occur over numerous years, but the $\mathrm{SOILM_A}$ metric provides a relatively simple index of potential variability in amount of fine fuel available to burn. In colder climates, higher soil moisture in months preceding the fire season's peak characterizes accumulation of precipitation (hypothetically, snow), which would contribute to soil recharge and generate higher moisture conditions and thus less fire during the fire season. Fig. 1b illustrates our hypothesized relationships between fire activity and SOILM variables, as well as how they might vary across a gradient in resource availability.

All three SOILM indices were generated from the Climate Prediction Center's Soil Moisture data, provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, available at a 0.5-degree spatial resolution (*available online*).[2] These soil moisture data are modeled, based on monthly averaged soil moisture water height equivalents. High values indicate more soil moisture. Units are in millimeters, and values represent soil moisture in a single column of 1.6 m, taking on a maximum value of 760 mm (ranges in Appendix A). These data have been validated in the United States (van den Dool et al. 2003), and are described in Fan and van den Dool (2004). Soil properties are assumed constant in the model. There is no equation for snow and ice, so precipitation is added as a liquid at all times. The effect of measuring snow in liquid form is an overestimation of water supply during winter in colder climates, followed by underestimation when snow melts. This would have most influence on calculations of $\mathrm{SOILM_A}$ in temperate, boreal, and high-elevation parts of the world where snow occurs during the months preceding the fire season. However, moisture accumulation as snow would have an equivalent effect from year to year, with the relative amount of soil moisture recharge from snow melt varying according to precipitation. Our primary analyses were performed for time series data at each grid location rather than among locations, so correlations between $\mathrm{SOILM_A}$ and fire activity would not be invalidated by differences in water phase.

In addition to the three soil moisture metrics, we generated the 500 hPa height (midtropospheric) circulation anomaly (ANOM) for each month and location to quantify potential fire weather conditions. Studies in the boreal forest (Skinner et al. 2002, Macias Fauria and Johnson 2008), northwestern United States (Gedalof et al. 2005), and Portugal (Pereira et al. 2005) have shown the regional utility of these anomalies as synoptic fire weather indices (Johnson and Wowchuk 1993), where positive values represent upper air blocking high-pressure systems that obstruct atmospheric circulation and lead to a lack of precipitation and rapid drying of fuels. Blocking ridges are features of the mid and high latitudes where westerly upper flow prevails. The breakdown of these ridges can generate strong surface winds and enhanced lightning, which in association with dried fuels, result in prime conditions for fire. The ANOM index was calculated using monthly values of 500 hPa height from NCEP Reanalysis 1 data (Kalnay et al. 1996), provided by the NOAA/OAR/ESRL PDS in Boulder, Colorado, USA on their web site at a spatial resolution of 2.5 degrees (see footnote 2). We used the monthly data to create a long-term monthly mean for each location, and anomalies were then calculated as the difference between the month's 500 hPa height and the long-term mean for that month (ranges in Appendix A), following Skinner et al. (2002).

Global gradients

We calculated three resource-related variables that are long-term measures, or "normals," quantifying gradients in radiant energy and water across the globe. These variables were used to describe long-term variation in resources for wildfire across which we hypothesized that constraints would differ (Fig. 1b). Global gradients were represented by mean annual temperature, net primary productivity, and terrestrial biome (ranges in Appendix A). Mean annual temperature (TEMP) was assigned based on the WorldClim database (Hijmans et al. 2005), generated from observed weather data from 1950 to 2000 and provided at a spatial resolution of 10 arc-minutes. Net primary productivity (NPP), the amount of carbon produced by an ecosystem per year, was assigned for each location based on simulated NPP values provided by Imhoff and Bounoua (2006) at a

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[2] ⟨http://www.cdc.noaa.gov/⟩

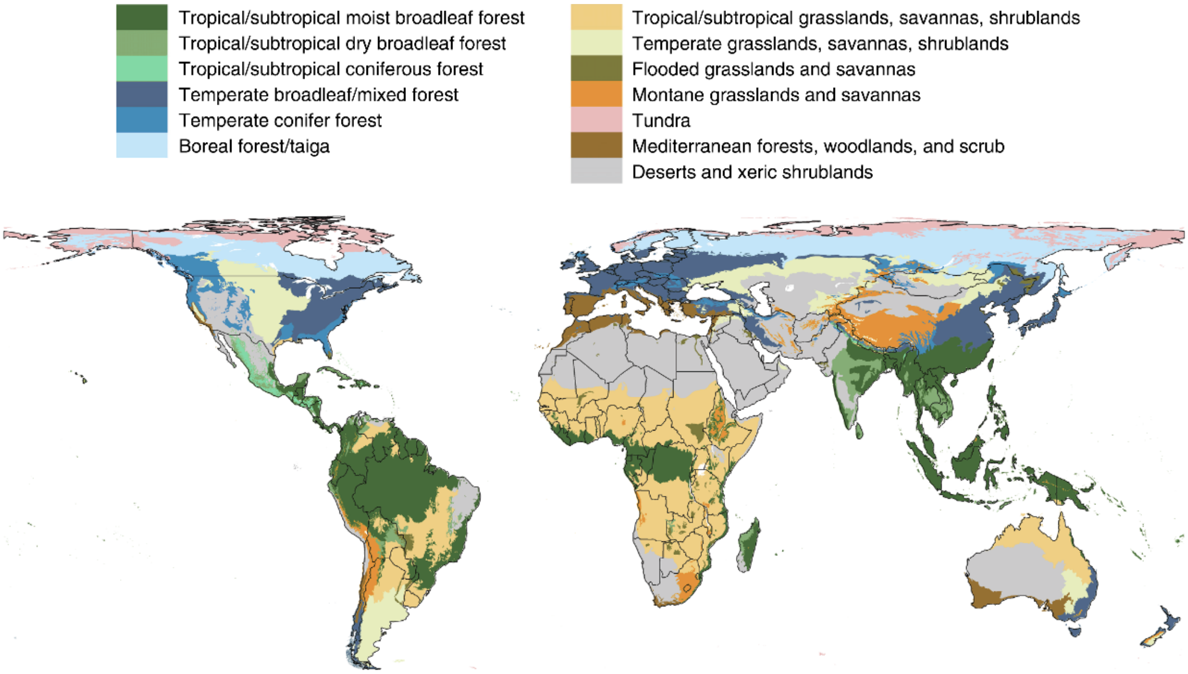

Fig. 2. The 13 terrestrial BIOMEs used in the study, based on Olson et al.'s (2001) classification.

resolution of 0.25 degrees from the CASA model (Potter et al. 1993). The CASA model uses satellite and climate data to estimate the fixation and release of carbon. Terrestrial biome (BIOME) was adopted from Olson et al.'s (2001) classification (Fig. 2). We divided biomes into three broad groupings according to temperature conditions during the fire season: (1) warm, including tropical/subtropical, temperate, and mediterranean biomes; (2) hot/dry, including deserts and xeric shrublands that provide rare and extremely ephemeral vegetation for burning; and (3) cold, including montane, boreal, and tundra biomes that have low amounts of resources to burn and occur in relatively cold environments. We excluded the mangrove biome from analyses outright since these areas are not fire prone and would not respond to SOILM variability.

Analyses

We used two analytical frameworks to test the hypothesis of spatially varying constraints. Local correlation analysis was the principal tool, which used the series of data at each location to examine how fire activity was correlated with explanatory variables over the study period. The benefit of this technique was the ability to focus on fire–climate relationships at each location independently; the disadvantage was its potential sensitivity to the number of zeroes in the data. Generalized multivariate global regression analysis was the supporting tool we used, which aggregated data from all locations and times together. The benefit of this method was its explicit handling of zero-inflated response data; however, the disadvantage for our purposes was that information from different locations would be pooled together, thus obscuring particular relationships occurring at a given location through time. The global regression analysis was used as supporting evidence for forms and patterns found in the main correlation analysis.

For correlation analyses, we quantified fire–SOILM and fire–ANOM relationships in each month of the fire season at each sampling location, and then determined whether these relationships varied predictably according to long-term resource availability gradients characterized by NPP, TEMP, and BIOME. At each location, we used a Spearman rank correlation test to quantify the approximately linear fire–SOILM and fire–ANOM relationships. We performed analyses on all locations where fire was detected in three or more months and then further restricted analyses to locations with fire detected in >10 months. The latter cut-off was used to test the robustness of the correlation analyses. By focusing on areas where three or more fire events occurred over the study period, we were unable to examine varying constraints in environments where fire is extremely rare or infrequent. Further, we limited our analyses to the fire season to focus on variation, rather than general seasonality or overall prediction of fire activity.

We used the nonparametric Spearman rank correlation because data were not bivariate-normally distributed; in some locations there were a high number of zeroes in monthly fire activity. We found strong support for a monotonic form in the fire–SOILM relationships and moderate support for fire–ANOM using loess smoothers of scatter plot data across randomly sampled locations; for the latter, fire increased with ANOM, followed by a slight decrease at high, positive values. Given these exploratory analyses, we judged a monotonic correlation test for the time series of data at each location to be appropriate for our data.

To examine spatial patterns in the resulting fire–SOILM and fire–ANOM relationships, we mapped the correlation coefficients. We then examined the polarity and magnitude of correlation coefficients against gradients in NPP, TEMP, and BIOME using covariate plots and box-and-whisker plots to determine if there were systematic global patterns that supported or refuted the varying constraints hypothesis.

For the supporting regression analysis, we pooled data from the full spatial and temporal extent of the study area together and quantified the relationship between monthly fire activity and each of the three SOILM variables using regression analysis. So that results would be comparable with correlation analyses, we built separate models to test each of the fire–SOILM relationships, using locations where three or more months of fire were detected. We used zero-inflated negative binomial (ZINB) multivariate regression, which considered fire data to be a mixture of two distributions, a negative binomial and a binomial. Explanatory variables in the negative binomial (count) component of the model included $\mathrm{SOILM_C}$ (or $\mathrm{SOILM_N}$ or $\mathrm{SOILM_A}$), BIOME, and their interaction. The SOILM–BIOME interaction allowed rough comparison with correlation analyses. Variables included in the zero-inflated (binomial) component included NPP, lightning activity, and the human footprint. These non-SOILM variables were used to account for some of the additional underlying factors underlying fire activity in the pooled data. Human activity and lightning are strongly connected with fire activity through ignition, and we used two available products, the human footprint (Sanderson et al. 2002) and NASA's lightning climatology (Christian et al. 2003) as long-term estimates of their distribution across the globe. Though the fire relationship with these two variables is extremely complex, we included them here as simple linear relationships.

Since we were using the ZINB analysis as corroboration for the local correlation analyses, we did not focus on strongly spatial or temporal structure inherent in the pooled fire data (e.g., autocorrelation); instead, we simply used a random 20% subset of data for the ZINB analysis, and repeated the subset and model procedure 10 times to check for consistent results in the polarity of parameter estimates.

RESULTS

Our fire activity cutoff of three or more months resulted in sampling 28 728 locations, and a cut-off of 10 or more months resulted in 18 869 locations, representing 55% and 36% of the terrestrial sampling area, respectively (Fig. 3). Locations excluded from this cutoff occurred in biomes where fire is known to be relatively uncommon, but >25% of locations from all biomes were maintained in analyses (Appendix B), with the exception of the tundra, where cold temperatures generally diminish primary productivity and fire. Spearman rank correlations between fire activity and $\mathrm{SOILM_{(C,N,A)}}$ varied in magnitude and polarity across the globe (Fig. 3). Soil moisture at the time of fire activity ($\mathrm{SOILM_C}$) was the most pervasive constraint (Fig. 3a), and statistically significant increases in activity occurred with decreasing $\mathrm{SOILM_C}$ in many locations (Fig. 3b). The fire–$\mathrm{SOILM_C}$ relationships varied systematically across energy–moisture metrics characterized by NPP, TEMP, and BIOME (Fig. 4a). Fire–$\mathrm{SOILM_C}$ constraints were increasingly negative at higher levels of NPP within each of the biome groupings in warmer climates, and increasingly negative overall in cold climates (Fig. 4a). Trends observed in the biome-wise calculations were supported by ZINB models, and with even stronger negative relationships for cold biome types than observed in correlation analyses (Appendix C).

We proposed a negative fire–$\mathrm{SOILM_N}$ relationship in parallel with fire–$\mathrm{SOILM_C}$, suggesting $\mathrm{SOILM_N}$ would characterize prolonged drought conditions leading up to the fire season. Low $\mathrm{SOILM_N}$ should generate prime conditions for burning, especially in more mesic and cold climates that would presumably be more constrained by weather/climate conditions. Some of these areas did exhibit strong, negative fire–$\mathrm{SOILM_N}$ relationships (Fig. 3c, d), yet we also detected spatially contiguous positive fire–$\mathrm{SOILM_N}$ correlations across the African Sahel, south-central Africa, Australia, western India, and parts of South America. These unexpected positive relationships largely occurred in tropical/subtropical grassland biomes (Fig. 4b). Similar trends were observed for biome-wise interactions in ZINB models (Appendix C), although the montane biome exhibited a positive relationship inconsistent with local correlation analyses. Such slight differences between the ZINB and correlation models are not unexpected given the pooling of all data and inclusion of additional variables within the ZINB.

We hypothesized that in regions of the globe with lower and more variable resource availability, such as grasslands, woodlands, shrublands, and xeric shrublands, the stimulation of vegetative productivity by higher soil moisture conditions in antecedent growing period ($\mathrm{SOILM_A}$), i.e., before the fire season, could generate increased fine fuels and thus precondition the area to more fire. Positive correlations with $\mathrm{SOILM_A}$ were detected over warmer resource-poor parts of the world, and statistically significant correlations dominated in dry/hot desert areas, as well as central Argentinean grasslands, and were patchily distributed through eastern and southern African grasslands (Tanzania and Botswana; Fig. 3e, f). Box-and-whisker plots showed a tendency for deserts to have a positive median

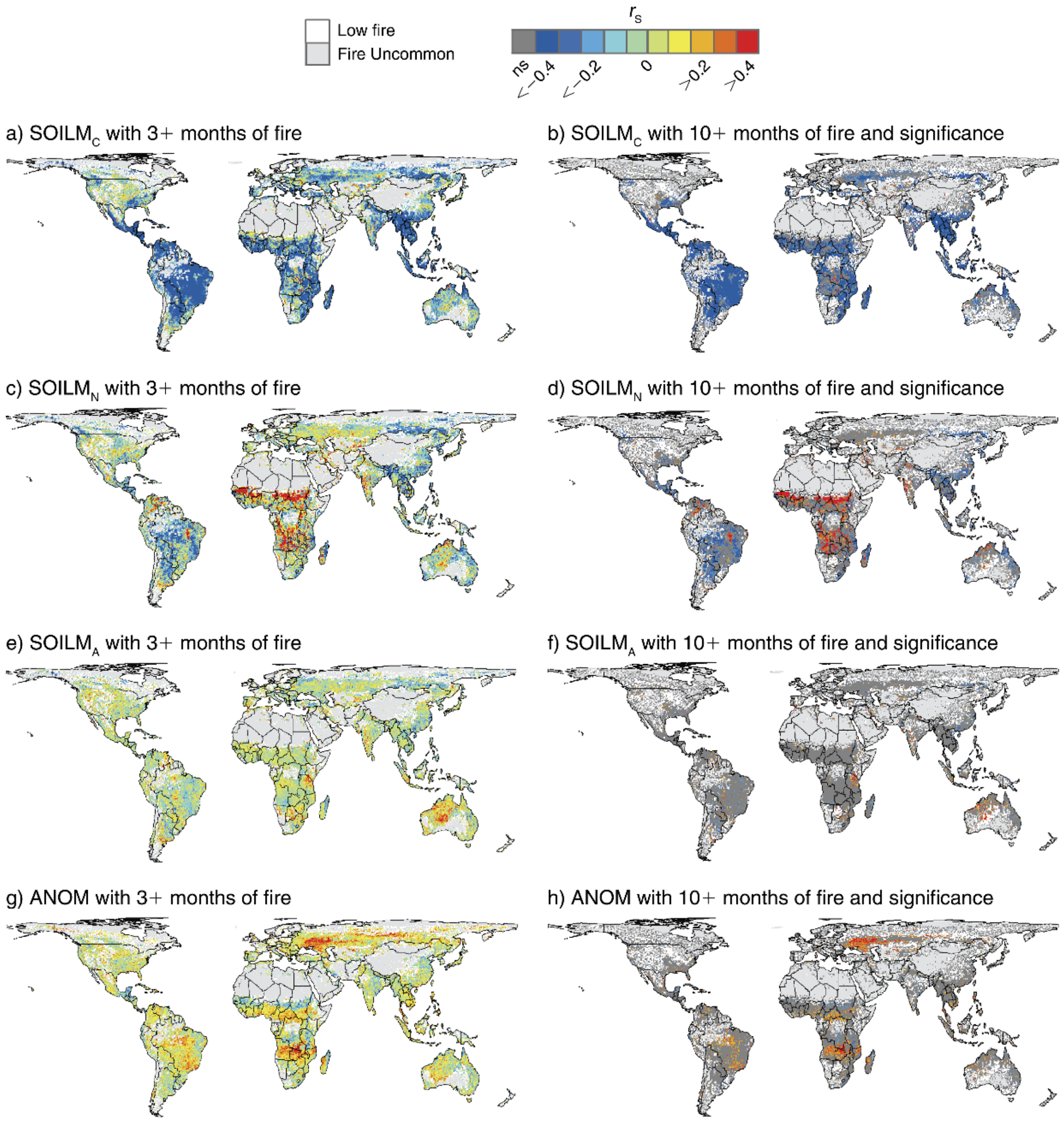

FIG. 3. Mapped Spearman rank correlations between fire activity and SOILM$_C$, SOILM$_N$, SOILM$_A$, and ANOM, with negative relationships illustrated in cool colors and positives ones in warm colors. (See Fig. 1 for an explanation of the acronyms.) Correlations calculated from locations with 3+ months of fire activity are presented in panels (a), (c), (e), and (g); locations with 10+ months of fire activity and statistically significant correlations are in panels (b), (d), (f), and (h); "low fire" refers to <3 or <10 months of fire activity, respectively. "Fire uncommon" indicates areas where fire was never detected during the study. Statistically significant correlations are shown in panels (b), (d), (f), and (g); "ns" indicates no significance.

value in SOILM$_A$ and a mild tendency for grass/shrub biomes and hot/dry desert and xeric shrublands (Fig. 4c). In comparison, we proposed higher SOILM$_A$ could equate to more precipitation (snow) and greater soil recharge in colder biomes, leading to decreased fire activity. Accordingly, the boreal and tundra biomes exhibited negative correlations with SOILM$_A$ (Fig. 4c). Biome-wise interactions in ZINB models showed parallel patterns to correlation analyses in general, but with notable increased strength of relationships, especially in the montane biome, and a negative relationship in temperate grass biome (Appendix C).

We proposed that the occurrence of short pulses of extreme fire weather might be characterized by ANOM in areas where fire–anomaly relationships had been previously documented, but also that they may be

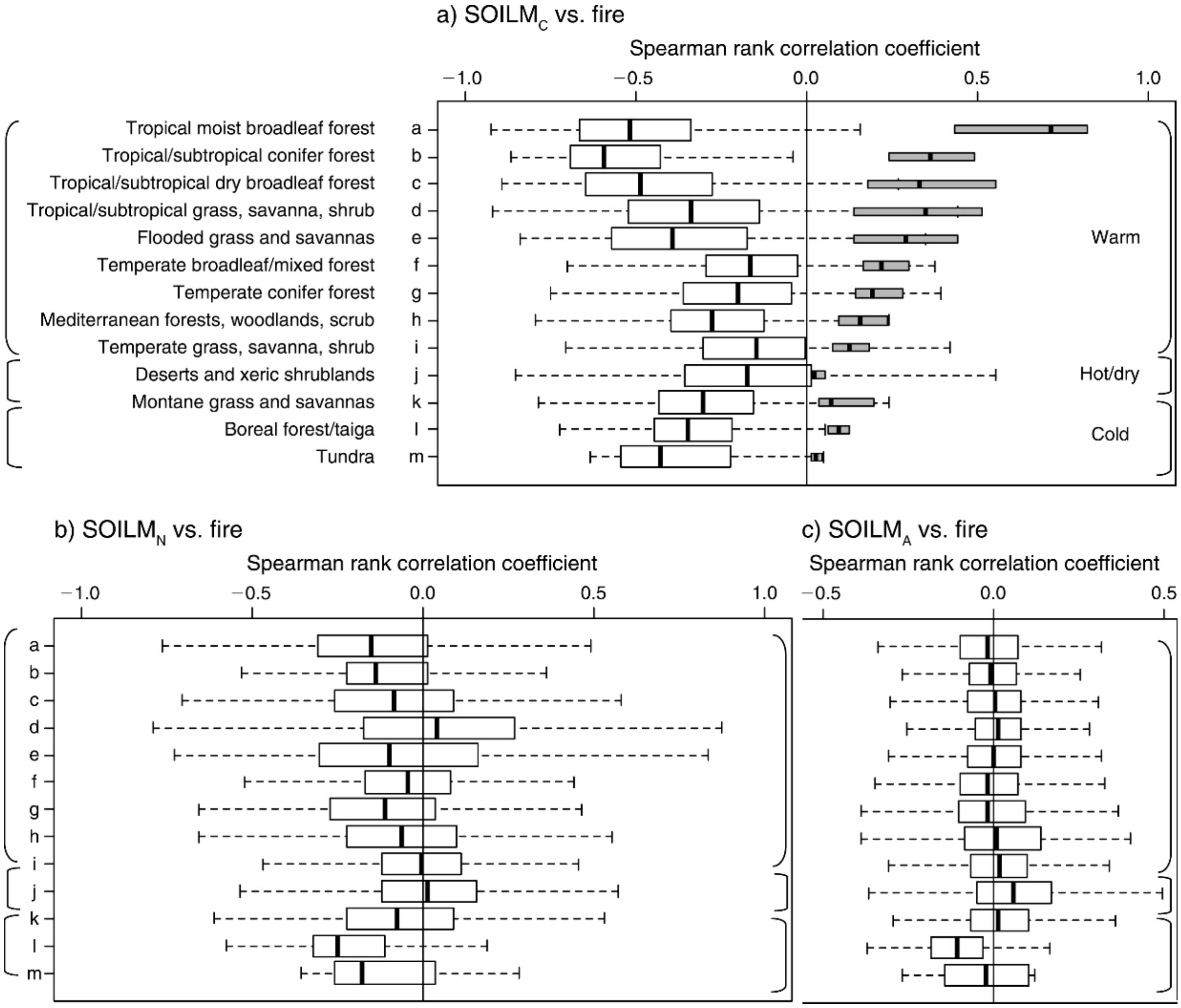

FIG. 4. Box-and-whisker plot distributions of the Spearman rank correlation coefficients between fire activity and (a) $\mathrm{SOILM_C}$, (b) $\mathrm{SOILM_N}$, and (c) $\mathrm{SOILM_A}$ according to BIOMEs using data from Fig. 3b, d, and f. In the box-and-whisker plots, the box indicates the 25th and 75th percentile (inter-quartile range) of the data, the mid band indicates the median, and whiskers indicate points within 1.5 times the inter-quartile range. In panel (a) the normalized distribution of net primary productivity (NPP) for each BIOME is presented in gray to illustrate a gradient in resource availability; normalized values are NPP (g/C/year/0.5° divided by 1.2×10^{12}). Biomes are bracketed into groups according to general climate types.

important in new, as yet unstudied regions of the globe. Though our correlation analysis showed evidence for a strong positive relationship with fire activity in some locations (Fig. 3g, h), none of the patterns aligned consistently with BIOME or gradients in NPP or TEMP.

DISCUSSION

Our global test of the varying constraints hypothesis demonstrates that while key biophysical factors must coincide for wildfires to occur, the influence of moisture/weather conditions and resources available to burn varies spatially and shows predictable patterns based on global gradients in primary productivity, temperature, and biome. Patterns in fire activity illustrated here include signals from both seasonality and interannual variability, e.g., within and between years, but the key message is the clear spatial variability in the strength and polarity of fire–environment relationships. These varying constraints on wildfire are akin to spatially varying trade-offs in limiting conditions of temperature (or radiant energy) and moisture purported to underlie biotic assemblages (Stephenson 1990, Hawkins et al. 2003, Brown et al. 2004, Kreft and Jetz 2007). Such trade-offs, described in Hawkins et al. (2003) as the water–energy dynamics hypothesis, suggest that species richness at higher (i.e., colder) latitudes is controlled by the availability of heat, whereas in the warmer, lower latitudes, water- and humidity-related variables are the main driving factors. For wildfire, we see that as resources to burn are increasingly available, energy limitation through drying of fuels via fuel/soil moisture conditions are a stronger constraint on wildfire activity, especially in more mesic and/or colder areas. In warmer, more arid climates where resources are more variable or scarce, evidence that water availability prompting production of vegetation during the growing season, which would then cure for burning, was an increasingly important constraint on fire. Though our use of relatively coarse spatial resolution may obscure within-pixel heterogeneity in resources and conditions, uncovering these systematic patterns in climate-based constraints on fire suggests a macroscopic framework is effective at synthesizing our understanding of global fire, and its potential sensitivities to changing climate.

In more mesic areas where biomass is relatively abundant, i.e., measured by mid-high levels of net primary productivity (Kindermann et al. 2008), the drying of live and dead/downed fuels indexed by increasingly low measures of soil moisture resulted in more fire activity detected during the burning season. Our analyses showed increasingly negative fire–soil moisture correlations ($\mathrm{SOILM_C}$) as net primary productivity moved from low to mid-high levels in the warm and hot/dry biomes, and this pattern was clear in both the local correlation and global regression analyses. Highly productive areas include moist tropical and subtropical forests, where complex forest structure tends to inhibit water loss from the understory and maintain a moist microclimate that historically made them relatively fire free (Cochrane 2003). However, dry spells in conjunction with anthropogenic ignitions and manipulation of forest structure to aid in burning for land clearing (Nepstad et al. 2001, Cochrane 2003) has led to increasing fire activity in these, and other high-productivity areas ("human activity" in Fig. 1b). In the colder biomes, fire–soil moisture correlations were strongly negative, despite relatively low primary productivity, suggesting a strong moisture constraint resulting from low temperatures leading to low rates of evaporation.

In addition to examining effects of soil moisture during the month of fire activity we also looked at the effect of conditions in the two months preceding ($\mathrm{SOILM_N}$), as an indicator of more chronic drought. Though the expected negative correlations with $\mathrm{SOILM_N}$ in many parts of the world suggested that prolonged dry spells did indeed lead to increased fire activity, we also detected positive correlations suggesting more fire when soil moisture was higher in deserts/xeric shrublands and savanna regions. The global regression models suggested positive relationships might also occur in the montane savanna/grassland biome; similarly, Archibald et al. (2009) suggest that in Southern Africa, growth of grasses with late rains, and therefore high $\mathrm{SOILM_N}$, followed by rapid drying of these fine fuels, could lead to increased fire activity. This scenario is an accelerated form of the relationship we proposed for soil moisture during the growing season ($\mathrm{SOILM_A}$) in warm/hot, resource-poor climates. Further, human-caused fires early in the dry season are common in West Africa, due to land-burning practices enacted to protect areas from later dry-season fires (Nielsen and Rasmussen 2001, Laris and Wardell 2006), so that fire activity may in fact follow wetter months that generate conditions allowing for more controllable early burning.

In warm, dry grass/shrub type biomes or hot/dry desert biomes where annual mean productivity is mid-low and resource availability more variable, we proposed that temporal variation in resources to burn would be a strong constraint on fire activity. Whereas Spessa et al. (2005) show relationships between monthly rainfall, vegetation, and fire frequency in grassland and woodland communities in the northern Australian wet–dry tropics, we did not test explicitly for variation in vegetation green-up resulting from a wetter growing season. We instead used higher soil moisture during the growing period ($\mathrm{SOILM_A}$) prior to the fire season as a proxy for productivity of fuels that would subsequently cure during the dry season, and then contribute to fire activity. In support of our hypothesis, we detected spatially contiguous patterns of positive correlations between fire activity and soil moisture in the growing period for hot/dry and warm areas of central-northern Australia, Tanzania, and Botswana, representing desert and xeric shrubland, tropical/subtropical grassland, and temperate grassland biomes; there was also a smattering of positive correlations through dry areas of the United States, Argentina, and India. In contrast, for colder areas such as tundra and boreal forest biomes, we detected some negative fire–$\mathrm{SOILM_A}$ relationships, supporting our hypothesis that higher precipitation in the cold winter months (as a data-constrained proxy of snow) could result in more soil recharge and less fire activity. In reality, spring run-off in mountainous terrain would likely also affect nearby areas as well, but we did not include this mechanism in our analyses. Recent increases in fire activity over the western United States have been attributed to earlier snowmelt and decreased winter (snow) precipitation (Westerling et al. 2006), so our results suggest additional locations where changes projected for winter precipitation by climate models could have a relatively strong influence on fire activity in the future.

Our evidence for lagged relationships between soil moisture and fire activity aligns with some existing regional studies, yet not with others, and the overall extent of the signal was relatively small. Where our results overlap with the spatial extent of regional work by van der Werf et al. (2008) in the tropics, the patterns are encouraging, especially in central-northern Australia. Using different metrics than ours, van der Werf et al. (2008) showed that dryness during the fire season was a strong driver of fire activity in biomass-rich areas, while cumulative precipitation during the growing season in advance of fire activity was a stronger driver in biomass-poor regions. However, we were surprised to find only limited time-lagged fire–$\mathrm{SOILM_A}$ correlations in the western United States, given that previous work has demonstrated relationships with fire and indices of antecedent productivity in the region (Swetnam and Betancourt 1998, Westerling et al. 2003, Littell et al. 2009), largely characterized here as desert and xeric shrubland biome. Our short sample period and relatively fine spatiotemporal study resolution may have contributed to the poor showing, given that previous works have been based on regional area-burned statistics and included multiple years in lag times in soil moisture. The aggregation of diverse fire regime and ecosystem types within each study pixel may also obscure relationships somewhat, but the justification of such a coarse scale comes from the need to simplify, or stand back, to uncover more general macroscopic trends. In doing so, our data show patterns that support our predications, which were largely generated from observations of local- and regional-scaled dynamics.

We found limited support to suggest that circulation anomalies (ANOM) provide stand-alone synoptic characterization of fire weather over mid-high latitudes or over a global extent. Gedalof et al. (2005) demonstrated that high fire activity in wetter forests of the northwestern United States required both severe drought and prolonged blocking highs, suggesting that fire seasons with chronic lower soil moisture could set the stage for fire activity and that coincidence of a positive circulation anomaly could provide conditions necessary for enhanced fire activity; we did not explore these interactions in our study. Previous studies have also demonstrated correlations that are spatially offset. Since the anomaly data we used were generated at a coarser scale than fire activity (2.5 vs. 0.5 degrees), they inadvertently included upstream, or contextual, positive anomalies from the spatial neighborhood. We had hoped that circulation anomalies, and/or their resulting breakdown, might provide a macro-scaled index of fire weather conditions that integrated dry weather conditions as well as winds, since winds are the bellows of high fire activity in many locations, including the famous Santa Ana winds of California (Moritz et al. 2010) and the Bergwinds of South Africa (Geldenhuys 1994), and they are a common factor used to calculate many fire weather indices (Fosberg 1978, van Wagner 1987). As wind data become increasingly available for many parts of the world through reanalysis data (Kalnay et al. 1996) and developments in weather modeling (Hughes and Hall 2009), it will be helpful to include them in future global pyrogeographies.

Overall, increased soil moisture during the growing season (warm-climate $\mathrm{SOILM_A}$) led to more fire activity in grassland, savanna, shrubs, or woodlands, where resource availability might vary among years due to seasonality of herbaceous materials. There was little overlap with the locations where we detected significant relationships suggesting more fire in months with decreased soil moisture (i.e., $\mathrm{SOILM_C}$ and $\mathrm{SOILM_N}$). Local fire–soil moisture correlations provided very similar results to those estimated by the supporting global regression analyses, giving credibility to the hypothesis that constraints on fire activity vary spatially across locations and biomes, and predictably along resource availability gradients (Fig. 1b).

Fire–climate relationships were detected broadly across the fire-prone areas of the globe, indicating that climate is still a strong engine defining fire's domain, despite the important contribution of human activity to wildfire through ignition and suppression of fires, as well as alteration of fuel structure. However, there were places where fire activity was not strongly related to the soil moisture metrics or circulation anomalies. These may be areas where anthropogenic activities such as land management, industrial farming, and fire suppression may interact with climate regulation over fire particularly strongly, or asynchronously (Le Page et al. 2010). For example, if small fires are detected quickly, they can often be suppressed by initial attack before they grow to be large (Arienti et al. 2006). Also, while the study's relatively coarse spatial resolution was chosen, in part, to aggregate sufficient data for robust analyses, some areas may not have experienced sufficient fire to expose significant relationships in either the correlation or regression analyses.

Together, the family of meso-meteorological indices show evidence in support of spatially varying constraints on fire that are systematic across the globe as a function of a gradient in resource availability. While climate is a superordinate driver over both conditions and resources for wildfire, we show that the direct effect of climate on fuel moisture and fire weather conditions is a relatively stronger constraint over wildfire in some parts of the planet, while other parts are constrained more strongly by the indirect effect of climate on fuel accumulation and structure. It will be an ongoing challenge to understand how climate changes may shift fire's range and activity as a function of these varying constraints, alongside and interacting with future changes in biodiversity, productivity, and human behavior.

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APPENDIX A

Summary of variables used for each 50-km^2 grid location in the study (*Ecological Archives* E092-010-A1).

APPENDIX B

The proportion of terrestrial biomes (Biome) where fire was detected over the study period (Fire) and where fire was detected in three or more months (3+ months), and the proportion of the global study area covered by each biome (Global). Note that mangroves were removed for this analysis (*Ecological Archives* E092-010-A2).

APPENDIX C

Boxplots of regression coefficients for SOILM:BIOME interactions (*Ecological Archives* E092-010-A3).