Global Analysis of Fire Regimes: Burnt Area and Fire Intensity

Ruisen Luo[1, 2], Lingbing Wu[3],Zhoulu Yu[1],Zhangquan Shen[1],Hongwei Xu[1],Ke Wang[1]*, Jinsong Deng[1]*

[1]College of Environmental & Resource Sciences, Zhejiang University, Hangzhou 310058, China
[2]Department of Botany and Microbiology, University of Oklahoma, Norman, Oklahoma 73019, USA
[3] College of Life Sciences, Zhejiang University, Hangzhou 310058, China
kwang@zju.edu.cn; jsong_deng@zju.edu.cn.

Abstract: Delineating global fire zones and analyzing their variations in different vegetation types areimportant to understand the climate-vegetation-fire coupling, and could serve as a reference to policy makers. However, few studies have investigated the two prominent fire characteristics (burnt area and fire intensity) together, and their variations in different vegetation types. As a first step to exploring these two fire characteristics as a whole, we presented a flexible classification of global fire zones based on metrics of burnt area and fire radiative power derived from satellite data. The distribution of the fire zones in different vegetation types and their relationships with the variables on climate, ignition, and anthropogenic activity were analyzed further. We found that fire zone of both largeburnt area and high fire intensity coincidedmainly with low anthropogenic activities (population density < 20 people km^{-2}).In contrast, fire zone of both smallburnt area and low fire intensity showeda clear tendency to high population density (> 90 people km^{-2}). Additionally, the distribution of fire zones greatly varied with vegetation types, but this was presumably attributed to different causes. Insights from this study could have important implications for biodiversity conservation and be used to direct fire management efforts, given the important roles of burnt area and fire intensity in fire regime studies. Although only two dimensions of fire regimes were considered in this study, the framework of our analysis could be generalized to integrate more indicators of fire regimes at large scales.
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1. Introduction

Fire is a force shaping global vegetation distribution (Bond and Keeley, 2005)and influencingclimate via greenhouse gas emissions (Ichoku *et al.*, 2012b). Fire regimes refer to average fire characteristics (frequency, intensity, seasonality, size, etc.) occurring over a long period of time (Morgan *et al.*, 2001). Understanding of globalfire regimes isa key to exploitthe couplings betweenfire and carbon cycle, due to the direct link between fire and greenhouse gas emissions (Westerling *et al.*, 2011). Also, it could serve as a reference to policy makers and conservation managers (Archibald *et al.*, 2010). However, few studies have quantified fire regimes in terms of both burnt area and fire intensity at global scales (Murphy *et al.*, 2011).

Burnt area is important in many ways.First, it is essential for quantifying pyrogenic trace gas and aerosol emissions (Ichoku *et al.* , 2012a). Second, burnt area is a signal of fire activity (Langmann*et al*., 2009) and can be used to derive other fire characteristics, e.g., fire seasonality and inter annual variation (Giglio *et al.* , 2010, Magi *et al.* , 2012), and fire frequency (Bond and Keeley, 2005). Third, burnt area accounts for the impact of fire on landscape pattern, i.e., whether fire occur in small size frequently or in large size sporadically (Chuvieco *et al.* , 2008). Fire intensity affects the impacts of fire on vegetation and soil. High intensity fire kills trees and initiates secondary succession,shifting the age and structure of stand, and changing subsequentfuel loadings. In contrast, low intensity fire tends to recover to the pre-fire status. However, most previous studies on fire regime only address one component of a fire regime, leading to misunderstanding of substantial different fire regimes. For example, the difference of fire regimes between two vegetation types in Australia is suggested to lies only in the intensity of fire when it eventually occur (Murphy *et al.* , 2011).

Fire radiative power (FRP) is shown to be an effective indicator of fire intensity via experimental work in southern Africa (Roberts *et al.* , 2005). It is demonstrated to be directly proportional to the rate of biomass consumption(Wooster *et al.* , 2005). Many studies have used FRP to investigate biomass burning and smoke emissions, demonstrating that FRP can be an efficient, relatively direct and realistic means to measure emissions of wildfire greenhouse gas emissions (Ichoku *et al.* , 2012a), determine organic and black carbon inventories (Vermote *et al.* , 2009), and characterize biomass-burning patterns (Ichoku *et al.* , 2008).

Table 1 Summary of data sources and treatments for the variables used.

Variable	Source and treatment	Reference
Temperature (℃) and precipitation (mm)	Center for Climatic Research, University of Delaware, gridded using a monthly time series based on monthly-mean air temperature data from climate stations including the Global Historical Climatology Network, and interpolated to fit a 0.5°×0.5° grid, using a combination of spatial interpolation methods	Legates and Willmott, 1990a, b
Lightning density (flash km^{-2} $year^{-1}$)	Total lightning bulk production LIS/OTD 0.5 HRFC data, produced by the NASA LIS/OTD Science Team led by Dr. Christian (NASA/ Marshall Space Flight Center)	Christian *et al.* , 2003
Population density (people km^{-2})	GPWv3 in the year of 2000, 0.5°×0.5° spatial resolution data, adjusted to match United Nation totals, CIESIN, Columbia University, and CIAT. The hypothesis here is that population increases should also enhance fire at the frontiers of agricultural and forest.	CIESIN, 2005

It is commonly assumed that fire activity depends on the coincidence of three elements, including fuel structure (fuel amount and connectivity), flammable conditions, and ignition (Stott, 2000, Meyn *et al.* , 2007, Pausas and Paula, 2012). Furthermore, it is admitted that the relative importance of explanatory variables on fire activity varies along a global gradient of vegetation types (Krawchuk and Moritz, 2011). Ichoku (2008) tested the possibility of ecosystem types in explaining global FRP variation (Ichoku *et al.* , 2008) and found that ecosystem type alone is not sufficient to identify the levelsof fire (Ichoku *et al.* , 2008). Incorporating other environmental and anthropogenic factors might be helpful to identify fire levels.

The objectives of this study are to investigate both burnt area and fire intensity,and to explore the distribution of fire zones in different vegetation types, the key differences environmental, and anthropogenic conditions within each fire zone. Both burnt area and fire intensity, were incorporated into the analysis, based on indices derived from GFED3 burnt area product and MODIS active fire data. The information from the two core concepts in fire regime studies might provide certain references to policy makers and environmental and biodiversity protection. The flexible analyzing framework might be generalized to more detailed classification of fire regime with the developmentof satellite-based and field knowledge.

2.Materials and Methods

Materials: Along with the rapid development of satellite remote sensing, products of global burnt area are available. Among them, burnt area in the Global fire Emission Database 3 (GFED3) product is monthly burnt area estimated from four satellite data sets. Comparisons with other global burnt area products and independent ground-based fire statistics in several countries demonstrate the reliability of this product (Kasischke *et al.* , 2011).We calculated bunt area via GFED3 (Giglio *et al.* , 2010) and fire intensity via MODIS from Jan, 2001 to Dec, 2007.GFED3 burnt area were averaged over the 7 years, and divided by the area of its corresponding cell (in the unit of percentile).

Terra MODIS Collection 5 Monthly Climate Modeling Grid (CMG) fire products (MOD14CMH) from Jan, 2001 to Dec, 2007were used to characterize global fire intensity.We calculated a metric-Weighted Average Fire Intensity (WAFI, Formula 1) - to quantify fire intensity, following the previous study (Giglio *et al.* , 2006).

$$WAFI_i = \frac{\sum_{t=1}^{n}(C_{i,t} \times P_{i,t})}{\sum_{t=1}^{n} C_{i,t}}, \quad (1)$$

where$C_{i,t}$ is the monthly fire pixel counts in a specific grid cell over a calendar month indexed by t, and there are n calendar months in k years, total. $P_{i,t}$ is the mean fire radiative power (FRP) in the corresponding cell, i, and calendar month. The multi-years averaging of fire data can enhance the reliability of knowledge we provided, although it is not suitable to incorporate data cumulated over years (Archibald *et al.* , 2009, Aldersley *et al.* , 2011). Granted, the product of disturbance dimensions would lead to loss ofinformation within each indicator(Miller *et al.* , 2011); therefore, we considered them individually.

Table 2 Cells and areas of the different fire zones.

Fire zone	Burnt area	Fire intensity	#Cells	Area（km^2）	Area（%）
HH	High	High	9576	22243900	31.33
HL	High	Low	5621	15461980	21.78
LH	Low	High	5560	10760180	15.15
LL	Low	Low	9494	22539010	31.74

Spatially resolved data were obtained for key variables of climate, ignition, and human activity. Table 1 summarizes the variables and data treatment. We chose temperature and annual precipitation because they are the basic determinant of ecological processes, and were widespread chosen to quantify and predict the climatic influences (Olson *et al.* , 2001, Archibald *et al.* , 2009). Lightning density quantify the amount of natural ignition (Aldersley *et al.* , 2011). Population density could signify thequantity of human ignition, as well as anthropogenic suppression on fire (Kloster *et al.* , 2010).

Extreme weather events and wind speed were not included in this study because global data are not available for the short time periods at which they operate (Aldersley *et al.* , 2011). All data were referenced to the same 0.5°×0.5° resolution (approximately 55 km×55 km at the equator) and coordinates and structured in the WGS-84 geographic coordinate system.

Certain original vegetation types were combined to avoid excessive cluttering, if they are typically collocated geographically or have the same characteristics in relation to fire, following the criteria of the previous study (Ichoku *et al.* , 2008). The seven grouped vegetation types and their constituents are shown in Table 3, and their distributions in the fire-prone regions are shown in Figure 1.

Statistical analysis: Data were analyzed in the SPSS 16.0 statistical program (http://www.spss.com/). Nonparametric statistics were used to identify the relations between fire zones and the environmental and anthropogenic factors, because the normality was uniformly not met. Cross-tabulation matric was constructed between fire zones and the simplified vegetation types. The Sakoda's adjusted Contingency coefficient, termed C*, was used to measure the degree of correlation, following the previous study (Chuvieco *et al.* , 2008). Please see the references for more details of C* (Chuvieco *et al.* , 2008). In addition, the mean and standard errors of fire, environmental, and anthropogenic variables within each fire zones were calculated. The significance of difference among fire zones were tested by the One-Way Analysis of Variance (ANOVA) (Davar Molazem, 2013).

Classification scheme of fire zones: The fact that individual pixel burnt area and FRP values can span three orders of magnitude in range, even within the same locality demonstrates the wide range of possible fire strengths. Therefore, in the case of fire disasters, the FRP values themselves would be too detailed as a means of communicating the fire status (Ichoku *et al.* , 2008).

Table 3 Descriptions of simplified vegetation types.

Simplified vegetation type	#Cells	Area（km^2）	Original vegetation type
1 Tropical Forest	2517	7543918	Evergreen broadleaf forest
2 Boreal Forest	2552	3810075	Evergreen needleaf forest, deciduous needleaf forest
3 Other Forests	2348	4683643	Deciduous broadleaf forest, mixed forest
4 Savanna	11206	28621894	Woody savanna, savanna, grassland
5 Agricultural	6551	14936610	Cropland, crop mosaic
6 Shrub	4006	8944929	Closed shrubland, open shrubland
7 Sparsely Vegetated	1071	2464002	Barren/desert, urban and built-up, snow and ice, permanent wetland
Total	30251	71005070	

Table 4 Cross-tabulation of simplified vegetation types (row) and fire zones (column).*

	HH	HL	LH	LL	Total
1	15.30	20.66	8.66	55.38	100.00
2	37.66	2.16	40.87	19.32	100.00
3	16.91	8.01	34.50	40.59	100.00
4	41.50	26.40	12.20	20.00	100.00
5	18.99	23.40	13.36	44.25	100.00
6	44.18	5.72	24.46	25.64	100.00
7	16.15	13.35	25.02	45.47	100.00
Total	31.66	18.58	18.38	31.38	100.00

*Percentages refer to the total of the vegetation types

The classification scheme was modified from the previous work (Chuvieco *et al.* , 2008),based on simple half partitions of fire indices. Two dimensions were considered: burnt area and fire intensity. Burnt area was defined from multi-years averaging of GFED3 burnt area, and fire intensity was derived from FRP (see text above). To simplify the number of resulting categories, each dimension had only two classes (high and low), separated via the median (50%) of each fire index. The description of the resultant four fire zones can be summarized as follows: High burnt area, high fire intensity (HH), defined by the regions where fire spread over medium to high area, and the average FRP was also medium to high through the years. High burnt area, low fire intensity (HL), defined by regions where fire covered medium to high area, and the average FRP was low to medium averaged over the years. Low burnt area, high fire intensity (LH), defined by regions where fire covered low to medium area, and the average FRP was medium to high. Low burnt area, low fire intensity (LL), defined by regions where fire covered low to medium area, and the average FRP was low to medium as well.

Results

Figure 2provides information on the global spatial distribution of burnt area and FRP. The half-degree grid cells with significant fire activity (fire-prone zones) summed up to 71005070 km^2, or 34% of all land area. The most extensive area burned occurred in Northern Hemisphere (NH) and Southern Hemisphere (SH) Africa, and the remaining parts were composed primarily of area burned in Australia, followed by South America and Central Asia. In terms of fire intensity, high FPP zones mainly distributed in high-altitude boreal regions in North America and Siberia. Interestingly, the highest FRP and the most extensive burnt area basically did not occurred simultaneously, with the only exceptions in North Australia and grassland in Kazakhstan.

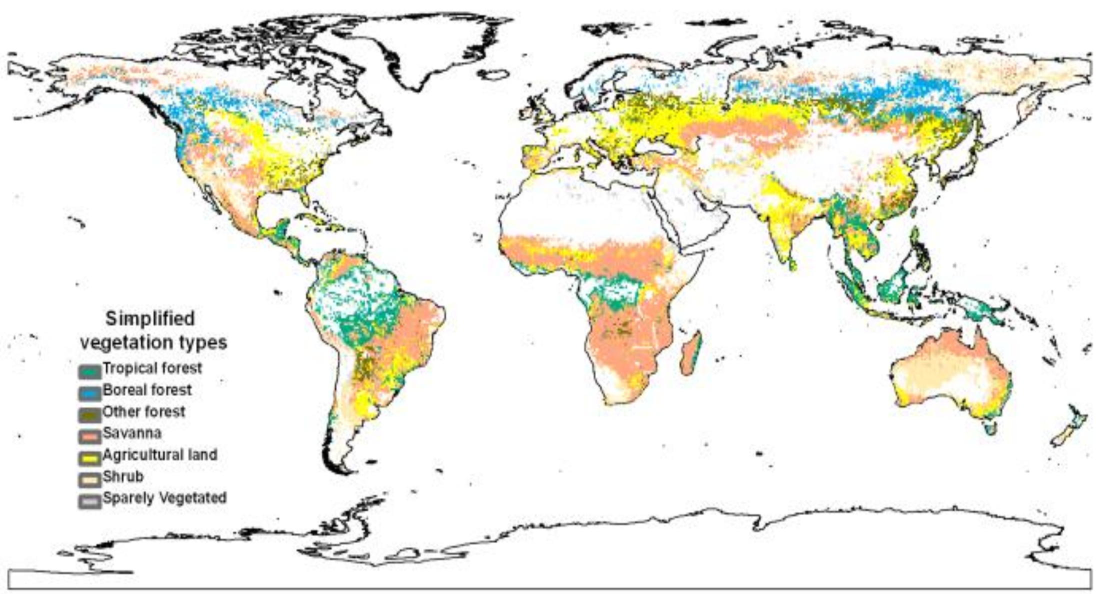

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Figure 1 Simplified vegetation types for the areas with significant fire activity.

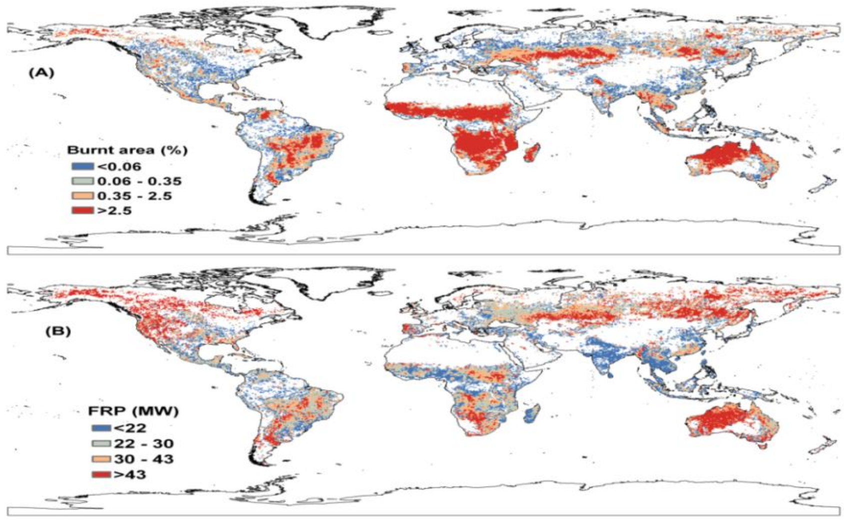

Figure 2 Fire metrics used for the fire characteristics classification: (A) Burnt area, (B) Fire radiative power (see text for definitions).

Burntarea and FRP were displayed in the form of classification, to facilitate visualizing the spatial variations. The breakpoints were according to the percentiles (25%, 50%, 75%, and 100%) of burnt area and FRP.

Fire zones: The Table 1 andFigure 3 illustrate the composition of the four fire zones. The high burnt area and high fire intensity zone (HH) and low burnt area and low fire intensity zone (LL) made up of 31.33% and 31.74% of the fire-prone zones, respectively. The fire zones of 2 and 3 (HL and LH) took up 21.78% and 15.15% of the fire-prone zones,respectively. There were significant differences between burnt area in the high and the low burnt area classes (P<0.01). The average burnt area of fire zones HH and HL was above 6% of the area of the grid cell, but the mean burnt area of fire zones LH and LL was less than 0.2% of the area of the grid cell. This held true for fire intensity. The mean FRPs of the high fire intensity classes (HH and LH) were about 50 MW, significantly higher than that of the low fire intensity classes (around 22 MW in HL and LL, P<0.01).

The fire zones with both high burnt area and intensity (31.33%) were observed in the central South America, in the fire belts of subtropical Africa, and the northern part of Australia. They were also noticeable in the tundra regions and the grasslands belts along Russia-China/Kazakhstan boundaries. The low burnt area and high fire intensity zones (15.15%) were mainly in the boreal forest in Siberia and North America, as well as parts of mixed forest in the conterminous America. The fire zone of high burnt area and low intensity (21.78%) were mainly distributed in Africa except the Sahara Desert with little burning material and the rainforest in theDemocratic Republic of the Congo. Finally, 31.74% of the fire-prone zones were classified as having both low burnt area and low fire intensity, which is shown in America, Africa, Asia, and Australia (Table 2 and Figure 2).

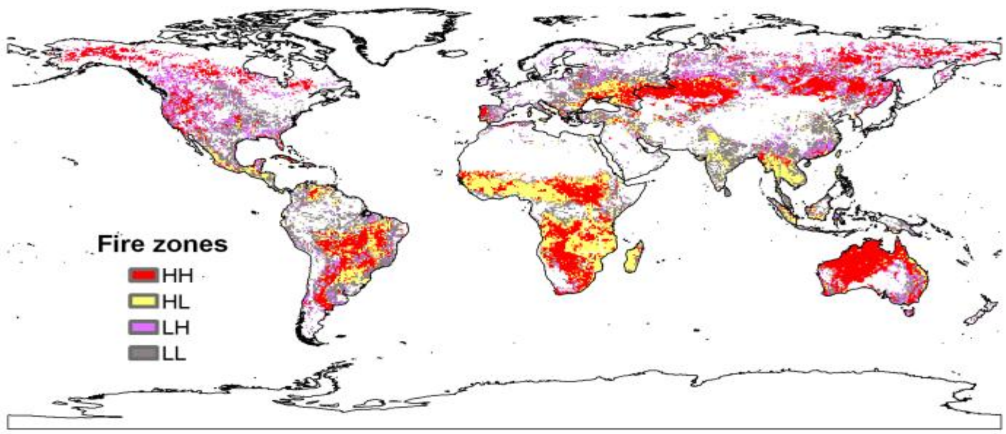

Figure 3 Fire characteristics classification. Fire zones as described in the text and in Table 2. The order accounts for burnt area and fire intensity, respectively. ‘H’ refers to high values and ‘L’ to low values.

Environmental and anthropogenic factors*:* The cross-tabulation of the seven simplified vegetation types and the fire zones was significant: C* =0.46 (*P*<0.01), although the fire zones included commonly a mixture of vegetation types. The cross-tabulation ofthe fire zones and the simplified vegetation typesisincluded in Table 4. Tropical forest was found to be mostly dominant in the fire zone of LL (both low burnt area and low fire intensity, 55.38%).

Boreal forest was characterized by high fire intensity, no matter low or high burnt area. Other forests mainlycoincidedwiththe fire zones of low burnt area, regardless of fire intenisty (34.50% and 43.59% in the LH and LL fire zones, respectively). Savanna expressed high burnt area (the proportion of HH and HL made up of 67.90% of the total fire-prone areas). The agricultural lands tended to have a low fire activity (44.25% in the fire zone of LL). This was also the case for sparsely vegetated places (45.47%). In comparison, shrub showed a tendency of both high burnt area and fire intensity (44.18%).

There were also significant differences of other environmental and anthropogenic factors within each fire group (*P*<0.01, Figure 4). For instance, the fire zone of HL coincided mainly with high mean annual temperature (>20 ℃), high annual precipitation (>1000 mm), high ignitions (lightning density > 6 flash km^{-2} $year^{-1}$), and intermediate population density（around 60 people km^{-2}). In addition, the fire zone of LL showed a much higher presence of anthropogenic activities (population density above 95 people km^{-2}), while the HH fire zone was predominantly associated with low population density (< 20 people km^{-2}). In terms of the fire zone of LH, temperature, precipitation, lightning density, and population density all showed dominance of low values, and the tendency to low temperature (below 7 ℃), and low ignition (flash rate density < 1 flash km-2 year-1) was even clearer.

Discussion

There are predominant tendencies of environmental and anthropogenic factors in different fire zones. In addition, the distribution of fire zones greatly varies with vegetation types, but ispresumably caused by different reasons. For instance, tropical forest, agricultural lands, andsparselyvegetated lands had similar dominances in the fire zone of both low burnt area and fire intensity. However, it might be due to over precipitation, high human activity, and insufficient rainfall, respectively.

The fire zone of HH coincides mainly with low anthropogenic activities (population density <20 people km^{-2}). In contrast, LL fire zone has a clear tendency to high population density (above 90 people km^{-2}). This highlights the importance of human behaviors in shaping global fire regimes. In terms of burnt area, human constructions result in fragmented landscape, thus hampering the spread of fire. In terms of fire intensity, humans actively suppress large fire to protect the property and life safety (Pechony and Shindell, 2009, Bowman *et al.* , 2011). The fire zone of HL is associated with high temperature, high precipitation, and high flash rate density (Figure 4). By contrast, the low temperature, rainfall, and lightning density in the fire zone of LH might be responsible for the low occurrences of fire there, but providing sufficient time for the accumulation of burning materials. It is suggested that the fuel loads in boreal forest is high (Giglio *et al.* , 2006), and the occurrences of intensive fire are more likely. In addition, the FRP gradient along latitude in Ukraine, Russia, and Kazakhstan corresponds to the human-induced land cover transition closely (Giglio *et al.* , 2006).

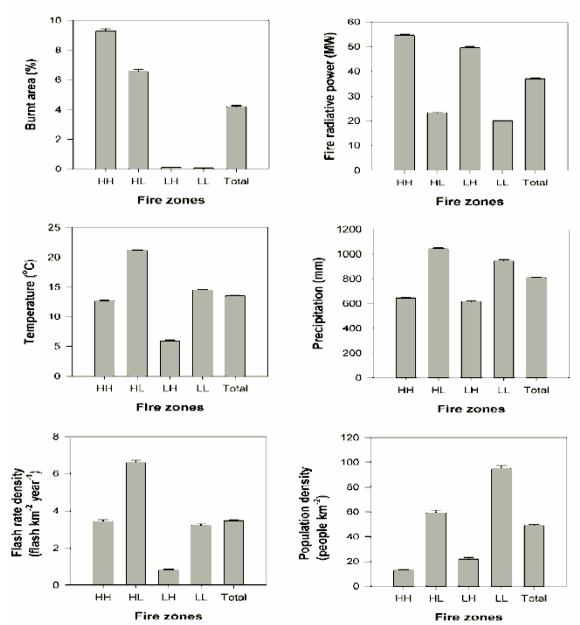

Figure 4 Means of fire characteristics and environmental and anthropogenic factors in each fire zone. The error bars stand for the standard errors of means (5%).

The low fire activity in tropical forest is reversely coincided with the high precipitation there (about 2000 mm per year). Previous studies suggest that the highest burnt area is associated with intermediate rainfall, and burnt area tend to be suppressed in regions of annual rainfall higher than 1100 mm (Archibald *et al.* , 2009, Aldersley *et al.* , 2011). Thresholds analysis illustrates that fire of large extent isvery unlikely to occur under moist conditions, because the response of burnt area to increasing dryness would decline rapidly after a high threshold(Loepfe *et al.* , 2012). Additionally, the high FRP (above 50 MW) in the boreal forest is consistent with previous findings (Giglio *et al.* , 2006). The lightning density in boreal forest is extremely low (Figure 3), which would give burning materials sufficient time to accumulate. Higher radiative power is also presumably expected from the more energetic crown fire in these regions (Kasischke *et al.* , 1999, Giglio *et al.* , 2006).

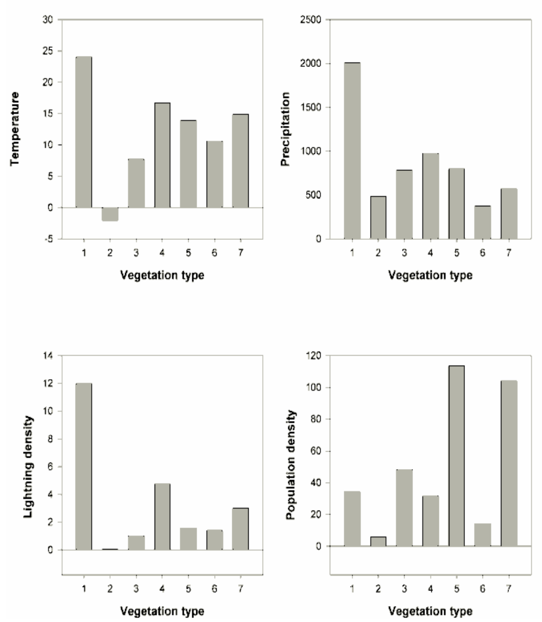

Figure 5 Means of environmental and anthropogenic factors in each vegetation type. See Table 1 for the illustrations of the environmental and anthropogenic factors and Table 3 for the descriptions of simplified vegetation types.

Savanna and grassland environments could produce fine fuels that dry out rapidly when there is no rain.Much of the region has seasonal rainfall; therefore fuels can develop and cure within a short span, resulting in parts of the most extensive burning zones on Earth (Archibald *et al.* , 2010). Also, fire in the places occupied by burning materials with low height (e.g., grasslands, savannas) tends to be surface fire, and thus having relatively low fire intensity(Bond and Keeley, 2005). In addition, both of agricultural and sparsely vegetated lands are characterized of strong human influences, with population density above 100 people km^{-2}. Human-induced prescribed fire are commonly to be under control and could substantially reduce the possibility of catastrophic fire (Pechony and Shindell, 2009, Bowman *et al.* , 2011). Finally, the low precipitation in shrub is consistent with the high fire danger index in shrub (van der Werf *et al.* , 2010), which would result in extreme flammable weather conditions, and is presumably attributed to the high fire activity there (Figure 5).

The analysis of the fire regimes (in terms of burnt area and fire radiative power) might be useful as an overview planning tool toward more cost-effective allocating of personnel and equipment for fire management. The utility of such maps is only limited to broad-scale planning, resource allocation, but not for the actual fire management in the field (Ichoku *et al.* , 2008)

Conclusion

This study presented a preliminary analysis of global fire zones, and revealed the key differences ofenvironmental and anthropogenic variables among fire zones. The distribution of different fire zones in each vegetation type was investigated. Both burnt area and fire intensity were incorporated into the analysis, based on indices derived from GFED3 burnt area product and MODIS active fire data. Although this is only a first trial on analyzing the global fire regimes in terms of burnt area and fire intensity, insights from this study might provide useful references forfire management and biodiversityconservation, due tothe important roles of burnt area and fire intensity. In addition, given the rapid development of satellite data and field expert knowledge (Murphy *et al.* , 2011), the flexible framework we provided could be generalized to more detailed classification of fire regime as well.

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Corresponding Author:

1.Ke Wang ,College of Environmental & Resource Sciences,Zhejiang University,Hangzhou 310058,China

2.Jinsong Deng,College of Environmental & Resource Sciences,Zhejiang University,Hangzhou 310058,China

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