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RESEARCH PAPER

# Fire regimes of China: inference from statistical comparison with the United States

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## ABSTRACT

**Aim** Substantial overlap in the climate characteristics of the United States and China results in similar land-cover types and weather conditions, especially in the eastern half of the two countries. These parallels suggest similarities in fire regimes as well, yet relatively little is known about the historical role of fire in Chinese ecosystems. Consequently, we aimed to infer fire regime characteristics for China based on our understanding of climate–fire relationships in the United States.

**Location** The conterminous United States and the People's Republic of China.

**Methods** We used generalized additive models to quantify the relationship between reference fire regime classes adopted by the LANDFIRE initiative in the United States, and a global climate data set. With the models, we determined which climate variables best described the distribution of fire regimes in the United States then used these models to predict the spatial distribution of fire regimes in China. The fitted models were validated quantitatively using receiver operating characteristic area under the curve (AUC). We validated the predicted fire regimes in China by comparison with palaeoecological fire data and satellite-derived estimates of current fire activity.

**Results** Quantitative validation using the AUC indicated good discrimination of the distribution of fire regimes by models for the United States. Overall, fire regimes with more frequent return intervals were more likely in the east than in the west. The resolution of available historical and prehistorical fire data for China, including sediment cores, allowed only coarse, qualitative validation, but provided supporting evidence that fire has long been a part of ecosystem function in eastern China. MODIS satellite data illustrated that fire frequency within the last decade supported the classification of much of western China as relatively fire-free; however, much of south-eastern China experiences more fire activity than predicted with our models, probably as a function of the extensive use of fire by people.

**Conclusions** While acknowledging there are many cultural, environmental and historical differences between the United States and China, our fire regime models based on climate data demonstrate potential historical fire regimes for China, and propose that large areas of China share historical fire–vegetation–climate complexes with the United States.

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**Keywords**

**China, climatic comparison, conservation initiatives, ecosystem process, fire ecology, fire regimes, LANDFIRE, statistical distribution models, USA.**

## INTRODUCTION

The United States and China share geographical characteristics of latitude and extent that encourage ecological comparisons between the two land masses. Interest in Asian–American similarities is not new (Boufford & Spongberg, 1983; Qian, 2002); botanists have noted close affinity between the temperate floras of eastern Asia and eastern North America since the times

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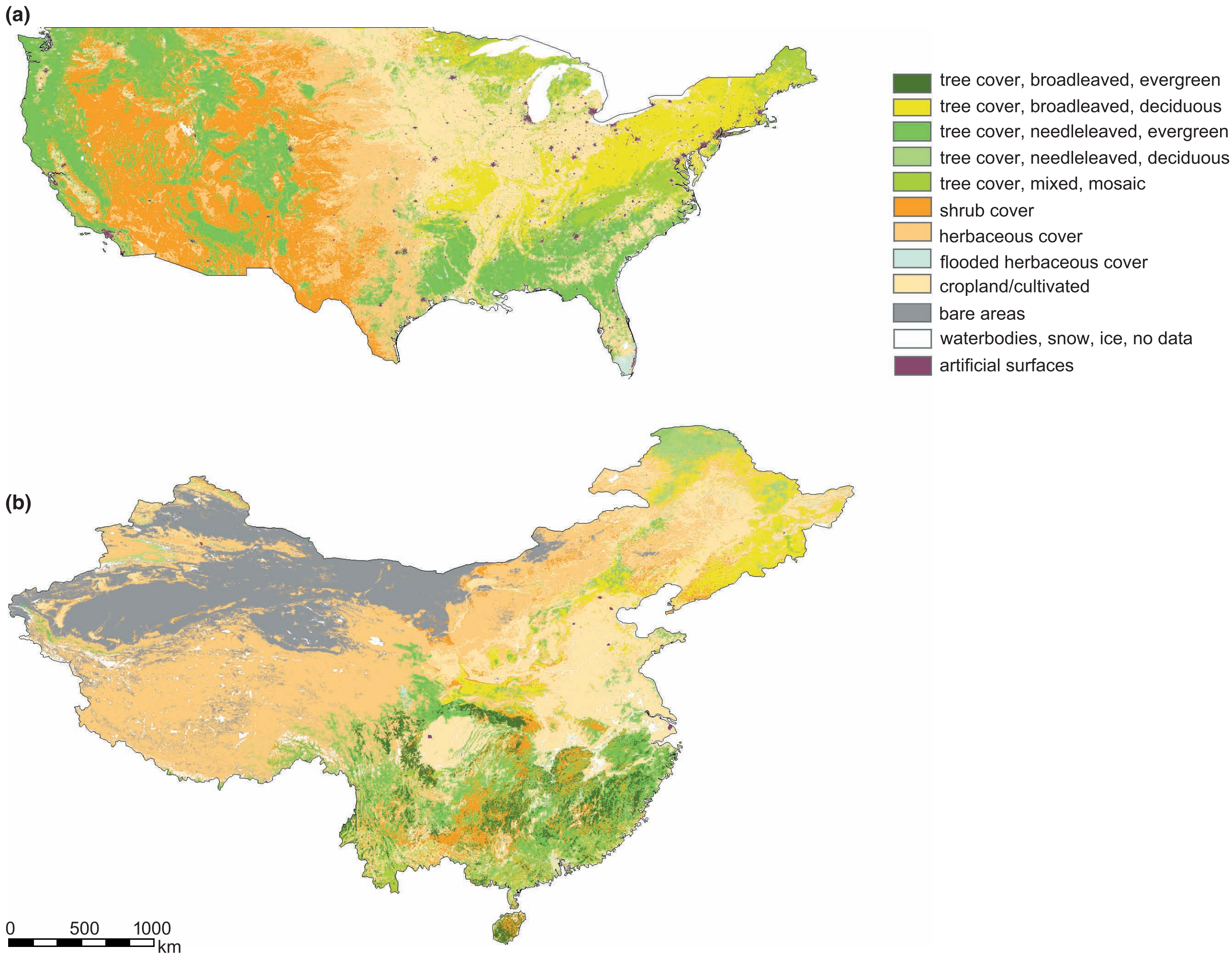


Figure 1 The Global Land Cover 2000 vegetation classes illustrate similarities in current land-cover types between (a) the United States and (b) China. The maps were produced using the Behrmann equal area projection.

of Carolus Linneaus (Halenius, 1750), Thomas Nuttall (Nuttall, 1818) and Asa Gray (Gray, 1846). More recently, strong floristic analogies have been documented between the eastern temperate, grassland and forest regions of the United States and eastern China (Guo *et al*., 1998; Guo, 1999; Qian & Ricklefs, 1999; Qian, 2002). These floristic similarities result from the interplay of shared historical and climatic conditions over the United States and China in the past, such as geomorphological and glaciation events, as well as a more recent, shared current climate (Guo, 1999). Present similarities in general vegetation types between the two countries can be readily seen in remotely sensed land-cover data (Fig. 1 showing Global Land Cover 2000) as well as in simulated, potential natural vegetation for the United States (Schmidt *et al*., 2002) and for China (Ni *et al*., 2000).

The intercontinental parallels in climate and vegetation of the United States and China suggest that shared characteristics should extend beyond floristics. As Guo (1999) suggests, attention to further ecological comparisons between the two countries is long overdue. This is particularly relevant given the development of scientific emphasis on the understanding of ecological processes and systems beyond simple descriptions of the locations of species. Based on the importance of vegetation and climate on fire regime (Moritz *et al*., 2005), and the apparent overlap in these two environmental components between China and the United States, we propose that our understanding of fire in the United States be used to infer fire regime characteristics in China. However, in these bio- and pyrogeographical comparisons, it is important to note that differences also exist between the two regions, especially in the west. The United States is bounded by ocean on both the eastern and western margins, while China abuts the large Eurasian landmass on its western boundary. The warm, dry climate of the north-west (Xinjiang Uyghur Autonomous Region) and the cool, dry, south-west (Tibetan Plateau in the Xizang (Tibet) Autonomous Region) of China possibly lack the clear analogue in the United States that is apparent in the east. Furthermore, ignition agents play a necessary role in generating fire regimes and there are insufficient data to gauge the degree of similarity between the two regions.

Wildfires are ecological disturbance processes that have a heterogeneous distribution as a function of spatial and temporal changes in the environmental resources and conditions necessary for fire. Wildfires occur as a function of fuel availability (resources: vegetation cover, biomass to burn), fuel moisture (conditions: weather/climate conducive to fire) and ignition sources (lightning or human caused); the relative influence of these elements and the variables useful to quantify their effect vary across spatial and temporal scales (McKenzie *et al*., 1996; Moritz *et al*., 2005). Wildfire regimes are the outcome of a long-term interaction of these elements, and in most parts of the world they implicitly include the influence of human activity, but to varying degrees. Relatively little is known about the historical ecological role of vegetation fires across China (Huang *et al*., 2006). Palaeoecological studies (Sun *et al*., 2000; Huang *et al*., 2006; Zhou *et al*., 2007; Gu *et al*., 2008; Jiang *et al*., 2008) have demonstrated spatial and temporal variability in fire at coarse scales at select locations in China. Field observations of fires exist, and Song *et al*. (2001) used the fire records available for China between 1950 and 1989 to present evidence for power-law distributions in fire size data, but these data have not been used to look more formally at patterns of fire and the environment. Remote sensors such as MODIS (Giglio *et al*., 2006) and ATSR (Mota *et al*., 2006) illustrate that current levels of fire activity are relatively high across many parts of China. However, the relatively short period of record for these data limits their use in quantifying fire regimes, and provides no information about historical activity. Chinese fire research has largely been limited to operations research, combustion science (Yang *et al*., 2005) and fire effects (Zhang *et al*., 2005), so that relatively little research has focused on quantifying fire events from an earth science or ecological perspective. A recent focus on fire regimes and management in north-eastern forests (Wang *et al*., 2001; He *et al*., 2002, 2005) is a noteworthy exception. Given recent interest within China in the development of their protected areas network and ecosystem classification systems, understanding the potential historical role of wildfire in ecosystem dynamics, and thus its role in the conservation of ecosystems, is an important area of research to be tackled alongside studies of current fire activity.

Research on the environmental causes and effects of wildfire has been prolific in the United States over the last decades. As part of this ongoing focus on fire-related research, the LANDFIRE (Landscape Fire and Resource Management Planning Tools Project; http://www.landfire.gov/) initiative developed comprehensive data sets describing vegetation and fire regimes across the United States. To some degree, this framework provides a synthesis of the myriad studies of fire across the country. One of the products from this initiative was a reference fire regime classification (Schmidt *et al*., 2002; Rollins & Frame, 2006) that estimated the spatial distribution of fire regimes thought to be prevalent across the United States in the pre-European era. The reference fire regime classification provides an informative, though simplified and at times contentious, country-wide framework describing fire activity purported to occur prior to large-scale land conversion or fire management.

China has a very different human history and culture from the United States, but we suggest that the spatial relationship between climate and the LANDFIRE reference fire regimes in the United States could be used as a first step to infer historical fire regimes for China. This genre of information is necessary to understand where and what type of fire regimes might have played a role as agents of ecological disturbance in the development of China's ecosystems, and to inform land-management decisions aimed at the conservation of ecosystems and their ecological processes. Similarities found in previous intercontinental comparisons of fire regime based on parallels in climate, such as that between forested regions of Colorado, United States and the Northern Patagonian Andes, Argentina (Veblen & Kitzberger, 2002), demonstrate the relevance of this macroecological approach. Our objectives for this study were to quantify the climatic controls on fire regimes in the United States, then predict the emergent distribution of each fire regime in China based on climate data, and assess the validity of these predictions. While we acknowledge that the dearth of fire regime data for China prohibits a direct validation, we gauged the relevance of our preliminary predictions based on data from existing studies of historical and prehistorical fire activity and remotely sensed (MODIS) data illustrating fire activity within the last decade.

## METHODS

We developed statistical distribution models to quantify the relationship between LANDFIRE Rapid Assessment 2005 (http://www.landfire.gov/) reference fire regime classes (Table 1, Fig. 2) and climate data (Table 2, Fig. 3) for the United States. We then used parameter estimates from these models with climate data for China to predict the spatial distribution of reference fire regimes across China. Our models used a binomial (1 or 0) response variable to describe the distribution of each fire regime class (1) against the remaining classes (0) at a spatial resolution of 100 km (data assembled in a Behrmann equal area projection).

### Fire regimes

We used reference fire regime classes to describe variability in fire activity across the conterminous United States. Data from the LANDFIRE Rapid Assessment provided five classes that describe the frequency and severity of fire under the historical range of variability, proposed to represent fire regimes occurring in the pre-European era (*c*. AD 1600–1900). These fire regime classes were compiled by LANDFIRE at a spatial resolution ranging from 30 m to 1 km, based on expert opinion informed by the Rapid Assessment Potential Natural Vegetation Groups (PNVGs), which integrate several pre-existing vegetation and biophysical data layers including potential natural vegetation (Schmidt *et al*., 2002), ecological regions, elevation, soil texture, existing forest and non-forest cover types (http://www.landfire.gov/ra1.php). The fire regime classes provided by the Rapid Assessment are a relatively simplified and coarse description of potential fire activity that include numerous assumptions and subjective decisions, but are incredibly valuable because they provide a consistent synthesis of fire information over the United States. The LANDFIRE National Project (http://www.landfire.gov/)

Table 1 Reference fire regimes used in the study, classified by their characteristic fire return interval and ecological effect. The number of cells classified to each regime is indicated in the first column.

| Regime* | Return interval (years) | Description of typical vegetation and ecological effect |
|---|---|---|
| R0-35$_{forest}$ (Regime I) $n$ = 228 | 0–35 | Evergreen conifer and mixed-wood forests with grass/shrub understorey<br>Surface fire in a forest, understorey biomass, including seedlings/saplings, is consumed; non-lethal for mature trees, but infrequent patches of higher-severity burning |
| R0-35$_{grass}$ (Regime II) $n$ = 292 | 0–35 | Grasslands, steppe, prairie and shrublands<br>Surface fire in a grasses and shrubs that leads to the replacement of biomass, non-lethal for any mature trees |
| R35-200$_{forest}$ (Regime III) $n$ = 58 | 35–200 | Mixed-wood/evergreen conifer forests with shrub understorey, shrublands<br>Surface fire in a forest, understorey biomass, including seedlings/saplings, is consumed, non-lethal for mature trees |
| R35-200$_{shrub}$ (Regime IV) $n$ = 80 | 35–200 | Sagebrush and shrublands, chaparral<br>Replacement fire in shrubland, shrub biomass is consumed, understorey is consumed |
| (Regime Va) $n$ = 9 | 200+ | Coastal north-west forests<br>Replacement fire when it occurs |
| Rbarren (Regime Vb) $n$ = 12 | | Barren, or extremely discontinuous vegetation, succulents<br>No fire, or extremely infrequent, biomass limited |
| R200+$_{desert}$ (Regime Vc) $n$ = 36 | 200+ | Deserts, sparse vegetation<br>Surface fire in the desert, that leads to the replacement of all grass biomass, but non-lethal for larger shrubs or cacti |
| R200+$_{forest}$ (Regime Vd) $n$ = 51 | 200+ | Northern deciduous broadleaved hardwoods, north-eastern oak–pine<br>Replacement fire in forest, understorey and part of tree biomass is consumed |

*Regimes I–V are the classifications used by LANDFIRE; we extended Regime V to include four subcategories a–d. Regime Va was not included in this study.

now provides an upgraded reference fire regime product, but it was unavailable when our study was initiated.

We aggregated the fire regime classes to a resolution of 100 km because of our goal to focus on coarse-scaled patterns of pyrogeography, to acknowledge the scarcity of weather stations used to generate the climate fields used in China and to recognize that the LANDFIRE National Project would probably, and does, include changes to fine-scale classifications of the reference fire regime map – a 100-km product was more likely to maintain consistency of fire regimes among different classification methods used by LANDFIRE over time. Aggregations were made using the zonal majority function, which selected the dominant class found within each 100-km pixel (Fig. 2) and resulted in 766 terrestrial pixels. Visual comparison of the fine-scaled and aggregated fire regime classes (Fig. 2) suggested the overall spatial structure of regime classes was maintained with scaling of the fire regime classes from 1 km to 100 km. Consistency in the regional, spatial structure of fire regimes can also be seen in the National Product (data not presented, now available at http://www.landfire.gov/).

We retained the general structure of the original fire regime classification for our analyses, but divided Regime V (infrequent, high-severity fire) into four subcategories (Table 1). This was done to differentiate areas where the same general regime occurs as a function of different biophysical factors. For example, areas in the south-western United States are relatively hot and dry, and fire is limited by low biomass and fuel availability. In comparison, areas in the north-east and north-west are cooler and moist with abundant biomass, and fire is more strongly limited by fuel moisture conditions. In exploratory analyses, we determined that the climate of the north-west coastal region (Fig. 2, Regime Va) was very distant from any analogue in China. As such, we removed this regime type from analyses *a priori*. We also decided it was important to maintain the difference between barren areas with very little, or succulent, vegetation and desert areas with sparse, yet burnable, vegetation. As a result, we further classified part of Regime V in the south-west to barren and desert, according to a previous version of the Rapid Assessment (Historical Natural Fire Regimes Version 2000), where some of these areas had been explicitly identified as barren. The remaining pixels in the south-western vegetated desert area of Regime V were classified apart from the hardwood-dominated forests of the north-eastern United States (Fig. 2).

The attributes originally adopted by LANDFIRE for the fire regime classification are relatively simple metrics of frequency and severity. In this classification, fire frequency is the time interval between fire events at a given location, also referred to as a return interval. Fire severity is used as a measure of the effect of a fire event on vegetation within the burned area; it focuses on the effect on height-dominant vegetation and is thus vegetation dependent. Using this classification, a 'replacement' severity fire in grassland vegetation is analogous in intensity (kW m$^{-1}$) to a 'low'- or 'mixed'-severity fire in a forest, since in grasslands the height-dominant vegetation is grass, and the grasses are completely consumed. Whereas in a forest, the burning of a grassy understorey is classified as low severity, since the height-dominant trees are only scorched on the lower bark, and the height of the

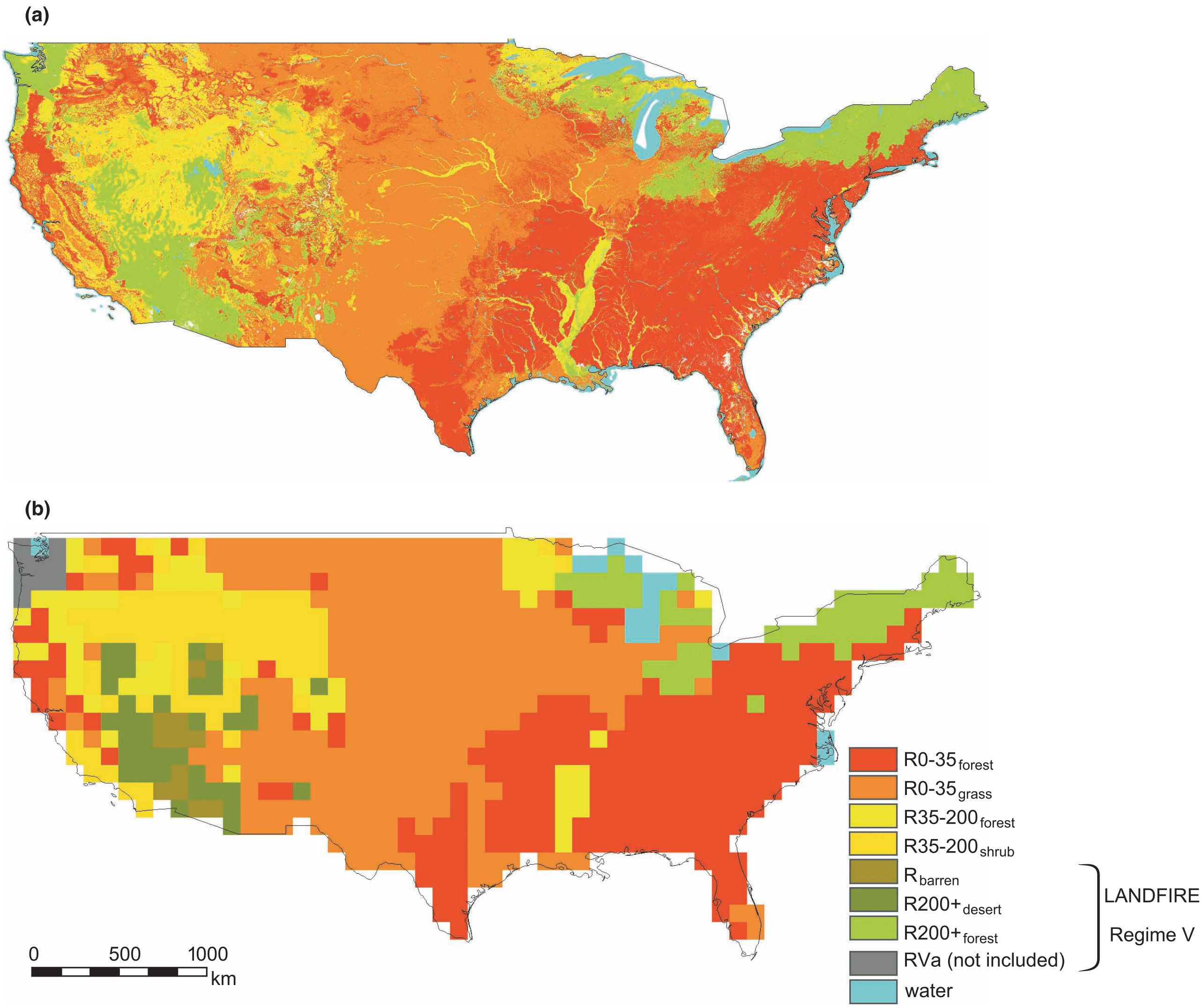


Figure 2 Reference fire regime classes for the United States, presented at the resolution of (a) 1 km and (b) 100 km, the resolution used in this study. Fire regime classes are identified using the letter R, followed by the return interval for the class (0–35, 35–200 or 200+ years), and the vegetation type in which it typically occurred (forest, shrub, grass). The R200+ regimes and $R_{barren}$ are subsets of LANDFIRE's Regime V. Note that RVa was not used in the analyses. The map was produced using the Behrmann equal area projection.

tree is not consumed by fire. To recognize these differences, we translated the original regime severity classes into ecological effects (Table 1) to describe the effect of fire in a more general framework that might aid in interpreting the distribution of regimes when inferred for China.

## Climate data

We used existing interpolated global climate surface data from two sources to describe variation in 14 climate variables for the United States and China (Table 2, Fig. 3). Climate surfaces described in Hijmans *et al.* (2005) were provided at 30 arcsec resolution (*c.* 1 km) from monthly precipitation and mean, minimum and maximum temperature measured at weather stations around the globe from 1950 to 2000. Data described in Legates & Willmott (1990a,b) provided global gridded monthly climatologies of the Willmott & Feddema (1992) moisture index. The index was interpolated at a 0.5° resolution from observed temperature and precipitation monthly averages from 1950 to 1999. This moisture index quantifies an integrated effect of temperature and precipitation using a rescaled version of Thornthwaite's moisture index to provide a dimensionless value limited between –1 and 1, and symmetric about zero. Wet climates have positive moisture index values and dry climates have negative values. We calculated two metrics from the moisture index: the annual water balance and the water balance frequency. The first was the net moisture index over the entire year, the second was a count of the number of months when the index was negative, providing a water deficit index.

We aggregated all climate data to a resolution of 100 km to match the fire regime data. This resolution was also amenable to the climate data for China, because surfaces were derived from

Table 2 Thirteen variables used to describe the climate of the United States and China. The distribution of the variables is illustrated in Fig. 3; all temperatures are expressed as °C × 10.

| |
|---|
| Temperature: |
| Annual mean temperature |
| Mean diurnal range [mean of monthly (maximum temperature – minimum temperature)] |
| Isothermality (mean diurnal range/temperature annual range) (×100) |
| Temperature seasonality (standard deviation × 100) |
| Maximum temperature of the warmest month |
| Minimum temperature of the coldest month |
| Temperature annual range (maximum temperature of the warmest month – minimum temperate of the coldest month) |
| Precipitation: |
| Annual precipitation (mm) |
| Precipitation of wettest month (mm day$^{-1}$) |
| Precipitation of driest month (mm day$^{-1}$) |
| Precipitation Seasonality (coefficient of variation) |
| Water balance (climate moisture index) |
| Annual mean water balance (annual mean of monthly climate moisture indices) |
| Water balance frequency (number of months where climate moisture index was negative) |

relatively sparsely distributed weather stations in that region of the world (Hijmans *et al.*, 2005). The comparative distribution of climate variables between China and the United States is illustrated in Fig. 3. We used current era climate normals for our analyses rather than estimates aligned to pre-European conditions in the United States for practical reasons; relatively highly resolved, current climate data were readily available for both the United States and China, whereas prehistorical estimates were limited. However, temperature data compiled by Ge *et al.* (2008) for eastern China from 14 data sources illustrate that despite temperature increases from the 17th to 20th centuries, the magnitude of temperature change is small relative to the broad range of data values we used (annual mean temperatures from –8 °C to 25 °C), with anomalies over that timeframe ranging between –1 °C and +1 °C. We propose that the relatively small changes in climate normals over the last 400 years would have a limited effect on our models or inferences.

## Statistical models

We developed seven statistical distribution models to quantify the relationship between climate and fire in the United States, one for each of our regime classes. Climate is not the only variable that generates a fire regime but it does play a strong role at coarse, regional and continental scales (Swetnam & Betancourt, 1998; Westerling *et al.*, 2003). A mechanistic model examining the explicit processes involved in fire would provide an alternative study method, but would be difficult to parameterize. Our statistical model framework provides a suitable first step in understanding potential historical fire activity. The response data for each model were the presence or absence of a given regime class in a 100-km pixel. The statistical relationships were estimated using generalized additive models (GAMs) in the R environment (R Development Core Team, 2007) with a binomial family of response. The GAMs allowed us to estimate nonlinear relationships between fire regime and climate variables. Given this flexibility, model complexity needed to be constrained as not to over-fit the model to the data. We used the Akaike information criterion (AIC) as a model selection tool, due to its foundations in the principle of parsimony.

We built statistical models for each regime class using random subsets of the full data set in order to reduce the spatial structure inherent in all variables and to allow for model validation. Spatial data require careful consideration in statistics due to the effect of spatial dependence in the response and predictor variables on the effective information contained in each sample (Legendre *et al.*, 2002; Currie, 2007), and because residual autocorrelation can affect variable selection (Legendre *et al.*, 2002) and model selection (Hoeting *et al.*, 2006). Because the determination of an effective sample size for multiple, autocorrelated variables is not a straightforward calculation (Dutilleul *et al.*, 2008), we used an *ad hoc* approximation to define an effective sample size. Based on the structure of the data, we approximated that a 40% random subset of the data in association with a conservative interpretation of AIC values would reduce the influence of spatial dependence in response and explanatory variables. The exception was the regime $R_{barren}$, where we used all available data for model building due to a small sample size of 12 pixels.

We assessed the sensitivity of the fire–climate relationships to the subset selection of data using a simple ranking scheme. We generated 10 random subsets, each containing 40% of the data for each regime class. For each subset, we ranked the relative explanatory power of each climate variable independently, according to the reduction in AIC when it was included as the only variable in the statistical model. For the ranking, we allowed the GAM function to estimate relationships with seven degrees of freedom. For all fire regime classes, the 10 random subsets of data provided very similar rankings of the top climate variables. Because of these consistent results, we judged it was appropriate to select a single subset of the data for further development toward a final model.

Using the single subset of data, we selected models using a forward step-wise procedure, where each variable entered the model in the order provided by the independent ranking described above. We used the AIC to identify the most parsimonious model both in the climate variables retained and in the shape of their relationships. We used a reduction in AIC of greater than five as a threshold for a variable to be selected in the model, and to select the shape of the relationship, following Burnham & Anderson (2002).

Once the final models were selected for each fire regime class, we verified the model assumption of independent errors, using spatial variograms and Geary's *C* statistics to evaluate residual autocorrelation. Little or no autocorrelation would indicate that one of the key assumptions of regression, independent errors, was met, and that the AIC was valid as a model selection criterion (Hoeting *et al.*, 2006). We used the receiver operating characteristic area under the curve (AUC) to validate models (Fielding & Bell,

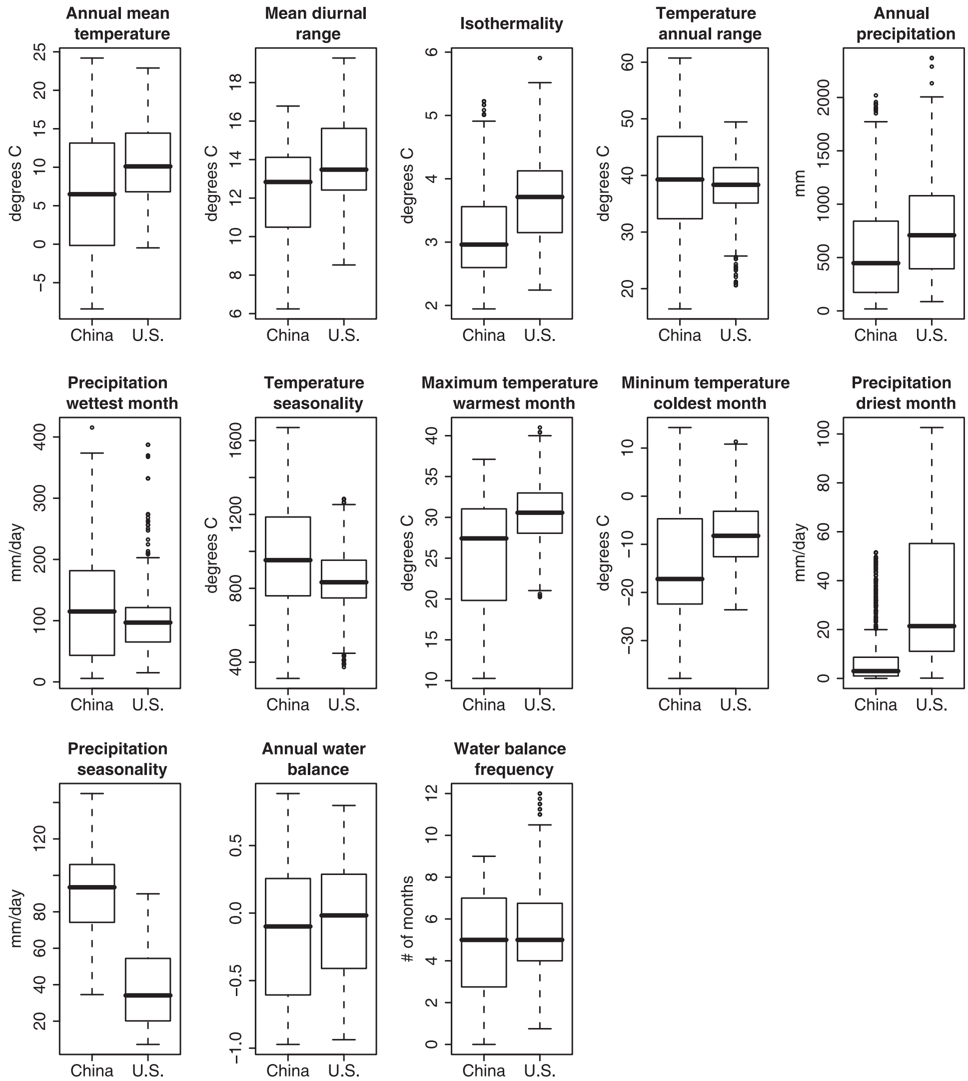


Figure 3 The boxplot distribution in values of climate variables outlined in Table 1, presented for China and the United States. Table 1 describes the units for each climate variable.

1997; Boyce *et al.*, 2002). The AUC quantifies predictive performance and the ability of the model to discriminate each fire regime class. We calculated AUC values for models given the training data (40% of the data), and also for the models given the testing data that were withheld from model development (60% of the data).

The parameter estimates from the final model for each fire regime class were used with climate data to predict, and map the distribution of, the probability of fire regimes in the United States and China. Despite the similarity in the range of climate data between the two countries, we used variable truncation to avoid spurious predictions from the GAMs in regions of China where the distribution of climate data extended beyond the range observed in the United States. The truncation of a variable constrains any extreme values of the new data (China) to the maximum or minimum values observed in the training data (United States).

We collected data to validate our predictions of historical fire regimes in China from existing historical and prehistorical studies of fire, and MODIS satellite data archiving recent fire activity. We used the MODIS Climate Modelling Grid (CMG) Terra Collection 5 Active Fire product (2002–07) to quantify the frequency and distribution of fire activity in China within the last decade. Though the fire regimes in our modelling study are based on historical rather than current fire activity, a comparison with the MODIS data provides a rough validation of regions in China that are more or less fire-prone and fire-free. The MODIS CMGs provide daily estimates of fire activity detected by MODIS, summarized monthly at a 0.5° spatial resolution (Giglio *et al.*, 2006). We aggregated these data to an annual, 100-km resolution, and any detected fire activity within a pixel within the year led to assignment of a value of '1'. We then calculated the number of years fire was detected in each pixel as a relative index of fire frequency.

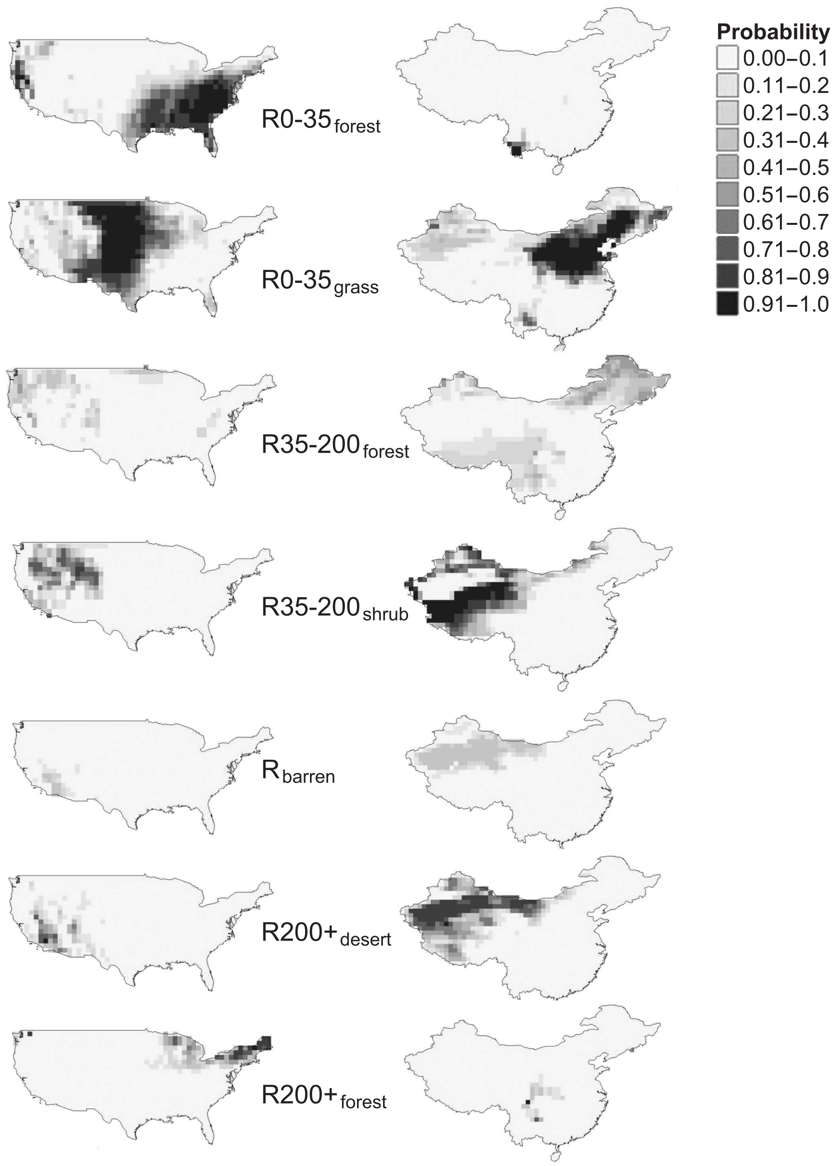


Figure 4 The statistically based predictions of reference fire regimes across the United States and China. The identifiers for regimes classes include the letter R, followed by the return interval for the class (0–35, 35–200 or 200+ years), and the vegetation type in which it typically occurred (forest, shrub, grass). Barren areas, where fire was expected not to occur, received no interval ($R_{barren}$). The maps were produced using the Behrmann equal area projection.

## RESULTS

The distributions of fire regime classes in the United States were differentiated by models that never included more than five climate variables, and the shapes of these relationships were relatively simple (see Appendix S1 in Supporting Information). The model for $R_{barren}$ (no fire) was estimated from the lowest sample size and it included only one variable, a negative, linear relationship with mean water balance. The model for R0-$35_{grass}$ (0–35 years return interval, grassland fire) had the greatest number of climate variables, five. The AUC values suggested that models were excellent to outstanding at discriminating the distribution of fire regimes, according to criteria described by Hosmer & Lemeshow (2000). The AUC values ranged between 0.85 (R35-$200_{forest}$) and 0.96 (R35-$200_{shrub}$) for training data, and 0.79 (R35-$200_{forest}$) to 0.95 (R200$+_{forest}$) for testing data.

Visual comparison of the predicted distribution of fire regimes in the United States (Fig. 4) with the original data confirmed the spatial patterns of the historical fire regimes were well discriminated by the statistical models. However, the predicted probabilities for R35-$200_{forest}$ and $R_{barren}$ in the United States were low, suggesting that important variables describing their distribution may be lacking. These regimes had relatively low occurrences overall, and this small sample size could limit the detection of significant relationships between climate and their distribution. There was minimal autocorrelation in model residuals, occurring to a maximum of two pixels (200 km), when present at all.

Each of the seven fire regime classes occurred in China based on the climate-generated predictions (Fig. 4). Here, we used the liberal cut-off in predicted probability $> 0.1$ to indicate the potential occurrence of a given fire regime. Figure 4 demonstrates that many regimes also had extensive areas in the United States and China with a predicted probability of less than 0.1; the R0-$35_{forest}$ and R200$+_{forest}$ classes had very restricted ranges in China, while the remaining regimes had broader distributions.

Table 3 Examples and description of historical and prehistorical fire activity in China.

| Location | Time | Description | Author |
|---|---|---|---|
| Yunnan, south-western China | Last 2000 years | Palaeoevidence of 12 fire episodes over 2000 years providing support for drought-induced fire events in tropical forests | Gu *et al.* (2008) |
| Yunnan, south-western China | NA | Tibetan farmers entered the region more than 2000 years ago and yak herders used fire to control shrub and tree invasion into alpine meadows | Baker & Moseley (2007) |
| North-eastern China | Pre-suppression (before 1950) | Proposed 120–150 year fire return interval in northern forests prior to suppression activities | Chang *et al.* (2008) |
| North-eastern China | Last 100 years | Proposed fires occur in spring and autumn as surface or ground fire of weak to medium severity. Fire return interval estimated to range from 110–120 years in the north to 15–20 years in the south | Wang *et al.* (2001) |
| North-eastern China (peat bog) | 10,000 years | Two charcoal layers in a peat bog over 10,000 years. Suggest that farming by the Han began up to 7000 years ago, before which there was nomadic living, and burning was probably used to support grazing of stock | Jiang *et al.* (2008) |
| Northern China, Loess plateau | Last 3100 years | Palaeoevidence for high levels of biomass burning during the late Holocene, proposed to be human dominated because of intensive land use | Huang *et al.* (2006) |
| Northern China, Loess Plateau | Last 5000 years | Fire activity detected using palaeoevidence | Zhou *et al.* (2007) |
| South-eastern China | Last 300 years | Evidence of fire events, probably caused by human activity | Yang *et al.* (2002) |
| South-eastern China | Last 4000 years | Palaeoevidence that fire increased in the mid to late Holocene, probably associated with land management, rice agriculture | Dodson *et al.* (2006) |
| South China Sea | Last 37,000 years | Palaeoevidence for fire from eastern mainland China | Sun *et al.* (2000) |
| South China Sea | Last 10,000 years | Palaeoevidence for fire over the Holocene, but relatively smaller amounts of charcoals than over the preceding palaeoecological record (i.e. Sun *et al.*, 2000) | Luo *et al.* (2001) |

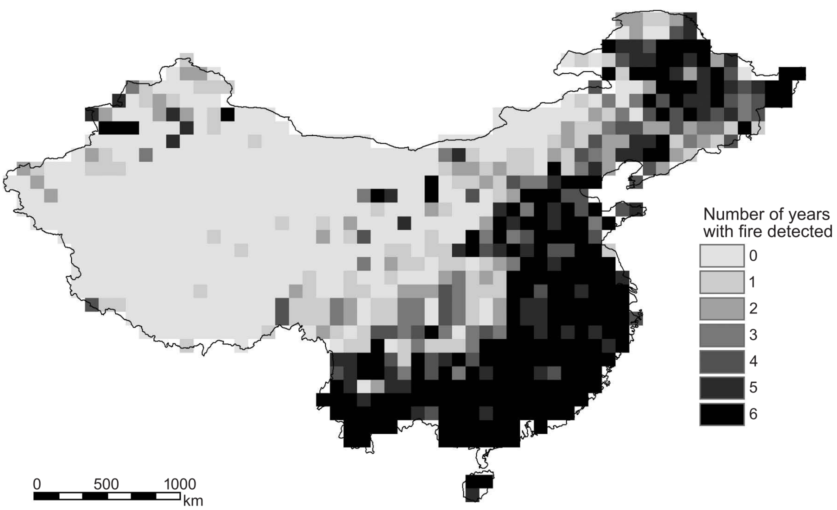


Figure 5 Recent fire activity in China detected using MODIS Terra sensor. The number of years when at least one fire event per 100-km pixel was detected is illustrated for data between 2002 and 2007. The map was produced using the Behrmann equal area projection.

For each regime, the magnitude of the predicted values took on a similar range to those predicted in the United States. For example, though R35-$200_{forest}$ was widely distributed in both the United States and China, it was predicted at an intermediate probability. In comparison, R0-$35_{grass}$ had a broad range and high probability of occurrence. As expected, the $R_{barren}$ class appeared as a geographical subset of R200$+_{desert}$ in both the United States and China.

Comparison with historical and prehistorical data provided some support for our predicted fire regimes inasmuch as they documented fire activity in eastern China (Table 3). The temporal resolution and spatial extent of these data prohibited a more refined comparison. The distribution of current fire activity in China based on MODIS CMG data (Fig. 5) showed that overall, relative fire frequency was highest in eastern China demonstrating similarities to our predictions in the north-east, but also substantial discrepancies in the south-east where our models do not predict a fire regime at all. Frequent fire observed in south-east China is probably a function of intense human activity. Given the differences in temporal extent and context of the MODIS data and our modelled predictions, the most important evidence from the comparison comes from western China, where bare areas designated as $R_{barren}$ and R200$+_{desert}$ by the models (Fig. 4) also clearly exhibit little or no fire in the present day (Fig. 5). This consistency gives at least nominal support for the transferability of the climate–fire models from the United States to China. Fire regime R35-$200_{shrub}$ in the central Tibetan Plateau contrasts with the observed absence of fire in the MODIS data, but the MODIS data support the potential for fire in the north-west (Xinjiang). The high fire frequency observed in north-east China notionally supports our model predictions of fire regime R35-$200_{forest}$ there.

## DISCUSSION

Our predictions of fire regimes provide a starting point for studying the potential role of fire across China's ecosystems and for developing our understanding of the relevance of fire in vegetation dynamics and ecological communities. However, the inferred fire regimes are by no means a conclusive representation of historical fire activity. Though there are climatic similarities between the United States and China, the proposed fire regimes need to be interpreted cautiously given differences in seasonality, vegetation, cultural history, land management and ignition sources that exist between the two countries.

There is a great deal of controversy over how long, and to what extent, humans have influenced fire regimes through the ignition of fires, fire suppression and alteration of land cover, including debate over the distribution of early humans (Gilbert *et al.*, 2008) and their use of fire (Weiner *et al.*, 1998) in the distant past. Many argue that humans have had considerable influence on vegetation fires in the United States for thousands of years, proposing that Native Americans used fire for land clearing and to generate resources from the land (Keeley, 2002; Stephens *et al.*, 2007; Bean & Sanderson, 2008). However, the intensity of fire management by Native Americans was in all likelihood spatially heterogeneous (Keeley, 2002), influencing disturbance regimes in some regions but not others. In parallel, there have been changes in climate through the Holocene, leading to concomitant changes in fire regime over regional and continental scales (Power *et al.*, 2008). The reference fire regimes in the United States aim to reflect wildfire disturbance rates in the last centuries prior to Euro-American settlement, *c.* AD 1600–1900. The degree to which these reference data are relevant to the human–environmental history of China is debatable; however, we propose that our models provide a reasonable hypothesis of this historical fire activity.

The relationship between fire, vegetation and climate is a complex one due to the superordinate effect of climate over both fire and vegetation patterns (Meyn *et al.*, 2007). Climate largely determines the availability of biomass burn through patterns of productivity and vegetation structure; however, the existence of suitable burning conditions via fire weather and ignitions overlays this distribution such that we cannot understand fire regimes by simply mapping vegetation. Quantifying this area of intersection provided by the spatial and temporal overlap of vegetation to burn and burnable conditions is a cornerstone of fire science. The historical fire regime data in the United States show strong regionalization that we quantify using climate variables, with short fire return intervals dominating in the south-east and central parts of the continent and longer return intervals in the west and north-east. It is intriguing to consider how such climate–productivity–disturbance patterns are distributed across the globe, and how strongly they are coupled.

Our fire–climate models predicted the occurrence of R0-$35_{forest}$ over a very limited range of the Yunnan Plateau of southern China. The R0-$35_{forest}$ class is characterized as a surface fire regime with a short return interval, occurring within forested stands. In China, the World Wildlife Fund terrestrial ecoregions classification identifies the R0-$35_{forest}$ area as subtropical moist forest and suggests that species in the low-elevation seasonal forests, such as the palms *Phoenix roebelenii* O'Brien and *Phoenix acaulis* Roxb., are adapted to a regime of frequent fire. Stott (1988) suggests that overlapping leaf bases protect the short stems of the palms from fire, and that the underground stems of *P. acaulis* may be a fire-adapted trait. Though the pine-dominated forests supporting R0-$35_{forest}$ in the United States differ from a *Phoenix* palm forest, these plant communities may be functionally analogous. For example, the long-leaf pines (*Pinus palustris* Mill), common in the south-eastern United States, have been long recognized as having a syndrome of adaptations that allows them to thrive under short fire return intervals (e.g. Pinchot, 1899). Similarities in climate and biomass between the two regions suggest they could support similar tendencies in their fire regimes, though differences in vegetation structure and ignition density could lead to differences in fire regimes. Gu *et al.* (2008) present a palaeoecological study for a rainforest site in southern China (Yunnan Province) illustrating fire occurrence, but indicate 12 fire episodes within 2000 years based on a profile of fluvial sediment in a seasonal pond, suggesting infrequent fires around the site. Given the large amount of fine-scaled heterogeneity aggregated within each of the 100-km pixels used as sample units for our study, this could be interpreted as evidence for variation around the proposed tendency in the region for more frequent fire. Site-based differences existing within each pixel could certainly support very different fire regimes, in addition to the dominant regime predicted for the area.

The R0-$35_{grass}$ regime describes a short-interval surface fire in grassland, prairie and savannas of the central-eastern United States. This regime was predicted to occur in northern grassland, steppe, Loess Plateau, mixed-wood forests (Inner Mongolia) and the temperate lowlands of eastern China. These eastern lowlands in China are largely cultivated, similar to the cultivated prairies of the United States. Huang *et al.* (2006) and Zhou *et al.* (2007) illustrate that fire was relatively common in this region during the last 5000 years, based on charcoal identification in soil profiles from the Loess Plateau, but the resolution of the data do not permit further detailed comparison. Small pockets of R0-$35_{grass}$ were predicted in the western arid steppes and southern subtropical forests.

The R35-$200_{forest}$ regime is characterized in the United States as a 35–200 year return interval surface fire burn with some crown fire, in mid- to high-elevation forested landscapes. The relatively frequent surface fires maintain a clear understorey beneath mature trees. This regime is predicted to occur in multiple locations across China, including the north-east where open boreal *Larix* forests are known to thrive with a surface fire regime

(Wang *et al.*, 2001). The R35-200$_{forest}$ regime was also predicted with lower probabilities in the central south, including the temperate region of the Tibetan Plateau in south-western China and Yunnan Province in the south, as well as in the north-west (Xinjian Uyghur Autonomous Region). These regions have very different flora; the Tibetan Plateau is the largest and highest plateau in the world, a cold region that supports a heterogeneous mosaic of herbaceous cover, shrubland and meadow, underlain by permafrost (Jin *et al.*, 2000), while in the south Yunnan Province includes regions of needle-leaved evergreen forest.

Our models predicted that R35-200$_{shrub}$, characterized as a 35–200 year return interval burning arid shrublands in the western United States, might occur across north-western parts of the Tibetan Plateau, further west than areas predicted with R200$_{forest}$. These areas are adjacent to the Taklamakan Desert in the west of China, and where Inner Mongolia meets Mongolia at its western border in the central north of China. These are areas with sparse, herbaceous cover, and could be considered regions with limited climate and vegetation analogy in the conterminous United States. For example, mountain regions in the western United States receive 80% of precipitation in the winter months as snow whereas on the Tibetan Plateau most precipitation falls during the summer growing season (Klein *et al.*, 2007). Further research is required to determine the appropriateness of allocating this regime to these areas, especially since R200+$_{desert}$, with a very rare, 200+ year fire return interval in sparse, desert vegetation, overlapped strongly with some locations predicted with R35-200$_{shrub}$. The overlap suggests that climate conditions could be appropriate for extremely rare fire events, depending on local edaphic, biotic or topographic conditions. Satellite data show limited fire activity across the Tibetan Plateau under current environmental and cultural conditions. However, this region is expected to incur dramatic changes in the near future. Climate changes, including a marked decrease in permafrost (Jin *et al.*, 2000) in conjunction with increased human use motivated by the newly completed railway line across the Tibetan Plateau region to Lhasa (Tibet), may result in a substantial alteration to its environment in the near future, and this is likely to include increased fire activity. In fact, preliminary projections of future fire regimes in China could be generated using parameter estimates from our statistical models with simulated global climate model output under a suite of emissions scenarios, though multiple sources of uncertainty in these estimates would need to be highlighted.

Areas expected to have no fire, or extremely infrequent events, were classified as R$_{barren}$, and were predicted in the deserts of China including the Taklamakan in the west, and the Gobi that lines China's boundary with Mongolia in the north. Given the scarcity of vegetation to burn in these hot and dry regions, these predictions appear sound. The R200+$_{desert}$ regime had a large overlap with R$_{barren}$, but, as mentioned earlier, also extended outward across the western Tibetan Plateau. No fire regime was predicted to occur in south-eastern China, though charcoal samples from palaeoecological sediment cores suggest evidence for fire over the Holocene (Sun *et al.*, 2000; Luo *et al.*, 2001; Dodson *et al.*, 2006) and in the last 300 years (Yang *et al.*, 2002) from human activity. The distribution of R200+$_{forest}$, characterized as a 200+ year return interval, crowning fire regime in northern broadleaved hardwood forests of the United States was predicted over a small extent of Sichuan Province in central China. This is a heterogeneous area of broadleaf forests, shrubland meadows and conifer forests. Areas of north-eastern China (the Xiao XinAn Mountains and the ChangBai Mountains) also contain northern hardwoods suggested to be analogous to the north-eastern United States, yet surprisingly the R200+$_{forest}$ regime was not predicted to occur in that region based on our models.

While satellite data are beginning to give us a global perspective of current fire activity, the relatively short-term archive lacks the information needed to gain an understanding of the long-term role or regime of fire in China's ecological systems. Despite these shortcomings, we used MODIS fire activity data to examine current regional patterns of fire in China as a form of model validation that might, in the least, corroborate with areas we identify as fire free. The MODIS data provided clear support for the R$_{barren}$ and R200+$_{desert}$ regimes in the west, given that little or no fire was detected remotely. These are areas largely devoid of vegetation to burn. In contrast, the MODIS data echoed the palaeoecological evidence and showed a high frequency of fire in south-east China where none of our models predicted fire. This region is biomass-rich, where human activity is likely to be responsible for the majority of fire activity. Obviously, predicting an absence of fire in areas with little biomass to burn is quite easy, while the interaction of anthropogenic activity with abundant fuels can lead to a broad range of outcomes from pyrogeographical boundaries dominated by human behaviour.

Recent studies of global patterns of fire provide additional data for comparison with our predicted fire regimes. Mouillot & Field (2005) provided a first approximation of burned area values across the globe for a time period between 1900 and 2000. Their calculations suggest very little fire in China over the last century, and only a weak analogue to the United States. However, Mouillot & Field (2005) infer historical burned area from relatively small samples of current data (the 1980s and 1990s), which may not capture longer-termed patterns, especially in areas as densely populated as China. Lavorel *et al.* (2007) provided a caricature of global fire regimes, but they did not include any reference to source data, nor descriptions of how these regimes were concluded. Qualitative information on global fire regimes has been amassed through the Global Fire Assessment (GFA) of The Nature Conservancy Global Fire Initiative (Shlisky *et al.*, 2007). These descriptions, acquired from local knowledge and expert opinion, form a starting point for validation of our inferences of fire regimes for China. The GFA supported the designation of south-central, and north-eastern regions of China as fire dependent, but there are still no data available for large parts of the country including the east and north-west (Shlisky *et al.*, 2007).

The overall practicality of discussing reference fire regimes in China might seem imprudent, given the strict fire suppression laws, the density of people across much of China and changes in vegetation that have occurred from centuries of organized human settlement. However, we suggest that explicit consideration of the historical, current and future role of fire in China's ecosystems is necessary for understanding global pyrogeography, to complement the environmental framework growing within China and to aid in developing sound fire management policy. In many regions of the United States, the management of ecosystems and fire risk are tightly entwined, and there has been gradual realization that suppression efforts have, in part, contributed to undesirable and unprecedented fire activity through fuel build-up, and altered ecosystems through loss of fire-dependent species/communities. The fire regime map for China that we propose here may help to develop social and environmental policy that recognizes the potential for a positive, long-term role of fire both in fuel reduction and ecosystem management. Further research on the ecological role of fire in China is necessary, and we suggest the development of methods presented here to include more sensitive integration of monthly water balance metrics and seasonality, as well as ignition sources, in future research. Lastly, the macroecological perspective of our study allows us to move ecological theory forward by examining the potential generality of disturbance–climate relationships across two similar, but vastly disjoint, parts of the globe.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Appendix S1** Fire–climate relationships estimated between reference regime classes and climate data using generalized additive models.

As a service to our authors and readers, this journal provides supporting information supplied by the authors. Such materials are peer-reviewed and may be re-organized for online delivery, but are not copy-edited or typeset. Technical support issues arising from supporting information (other than missing files) should be addressed to the authors.

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