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ORIGINAL PAPER

Spatiotemporal variation in forest fire danger from 1996 to 2010 in Jilin Province, China

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Abstract We evaluated the spatial and temporal patterns of forest fires in two fire seasons (March to June and September to November) from 1996 to 2010 in Jilin Province, China, using the Canadian Forest Fire Weather Index System. Fire data were obtained from the Provincial Fire Agency, and historical climate records of daily weather observations were collected from 36 weather stations in Jilin and its neighboring provinces. A linear regression model was used to analyze linear trends between climate and fire weather indices with time treated as an independent variable. Correlation analysis was used to detect correlations between fire frequency, areas burned, and fire weather indices. A thin-plate smooth spline model was used to interpolate the point data of 36 weather stations to generate a surface covering the whole province. Our analyses indicated fire frequency and areas burned were significantly correlated with fire weather indices. Overall, the Canadian Forest Fire Weather Index System appeared to be work well for determining the fire danger rating in Jilin Province. Also, our analyses indicated that in the forthcoming decades, the overall fire danger in March and April should decrease across the province, but the chance of a large fire in these months would increase. The fire danger in the fall fire season would increase in the future, and the chance of large fire would also increase. Historically, because most fires have occurred in the spring in Jilin Province, such a shift in the future fire danger between the two fire seasons would be beneficial for the province's fire management.

Keywords Canadian Forest Fire Weather Index System · Correlation analysis · Human-caused fires · Linear regression · Thin-plate smooth spline model

Introduction

Wildland fire is a critical component in the terrestrial and atmospheric dynamics of our earth. Recent annual area burned estimates range from 300 to 450 Mha for our planet (Tansey et al. 2008; Van Der Werf et al. 2006). Fire activity is strongly influenced by four factors: fuels, weather, ignition agents, and people (Flannigan et al. 2005). Fuel amount, type, continuity, structure, and moisture content are critical elements for fire occurrence and spread. Fuel

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structure can also be important in fire dynamics, for example, understory trees and shrubs in a forest can act as ladder fuels that help a surface fire to reach the tree crowns and thereby generate a faster moving and much more intense fire. Although the amount of fuel, or fuel load, and fuel distribution (vertical and horizontal) affect fire activity, fuel moisture largely determines fire behaviour and has been found to be an important factor in the amount of area burned (Flannigan et al. 2009). Weather and climate, including temperature, precipitation, wind, and atmospheric moisture, are critical aspects of fire activity. Weather is a key factor in its own right, but it also influences fuel and ignitions. Fuel moisture, which may be the most important aspect of fuel, is a function of the weather. Weather and climate also in part determines the type and amount of vegetation (fuel) at any given location. Meteorological conditions also largely determine the risk of lightning, one of the two main causes of wildland fire. Weather is the best predictor of regional fire activity for time periods of a month or longer. For example, Cary et al. (2006) found that weather and climate best explained model area burned estimated from landscape fire models compared with variation in terrain and fuel pattern. Although wind speed may be the primary meteorological factor affecting growth of an individual fire, numerous studies suggest that temperature is the most important variable affecting overall annual wildland fire activity, with warmer temperatures leading to increased fire activity (Gillett et al. 2004; Flannigan et al. 2005; Parisien et al. 2011).

According to the 8th National Forest Inventory conducted by the State Forestry Bureau of China, forest area in China totals 2.1×10^8 ha, approximately 21.7% of the nation's total area. Among the forested area, 1.2×10^8 ha is natural forest, and 6.9×10^7 ha is plantation. Average forest area and average potential timber supply per head in China is far below the world average. Also, forested areas across the country are clustered rather than continuous; major forest areas are in northeastern, southwestern, and southeastern China (http://www.forestry.gov.cn/). Forest fire has long been a serious issue in China's forest regions, especially in the northeastern forest region of Heilongjiang, Jilin, Liaoning, and the eastern part of the Inner Mongolia Autonomous Region. Annual average fire occurrence in this region from 1950 to 1987 is 751, and annual average area burned for the region is approximately 6.0×10^5 ha, about 55% of the national average. Since the areas burned in the northeastern forest region account for more than half of the areas burned in China, this forest region is considered the key region where forest fire prevention needs to be strictly enforced (Shu et al. 2006), especially for those caused by people, the other main source of wildfire ignition. In China, approximately 99% of forest fires are caused by humans (Hu 2005).

Jilin province is in northeastern China (E121°38′–131°19′ and N40°52′–46°18′; see Fig. 1) and in the northern temperate zone. The province has a total area of 187,400 km^2 that accounts for 12% of the areas of the country. Topographically, elevation is high in the southeastern mountainous part of the province and decreases toward the northwest. The landscape of the province is diversified: the eastern area of the province is forested and mountainous; wetlands are scattered throughout the central area, and the western part is dominated by plains. Statistically, the mountainous areas account for 36% of the total provincial area; wetlands cover approximately 28.2% of the total area, and hills occupy 5.8% (Zai 2011). Along the east–west gradient, the soil changes from a dark brown soil zone of coniferous-deciduous mixed woods to a black soil zone and chernozem zone of temperate semi-moist forest-steppes, and then to a dark chestnut Armenia zone of temperate semi-arid prairie. According to the fourth national census, Jilin has a population of 24.659 million, accounting for 2.18% of national population in 1990; the population density for the province is 126.5 persons per km^2 (Wang 2005).

As one of the key forest provinces in the country, the land area in Jilin used for forest purposes totals

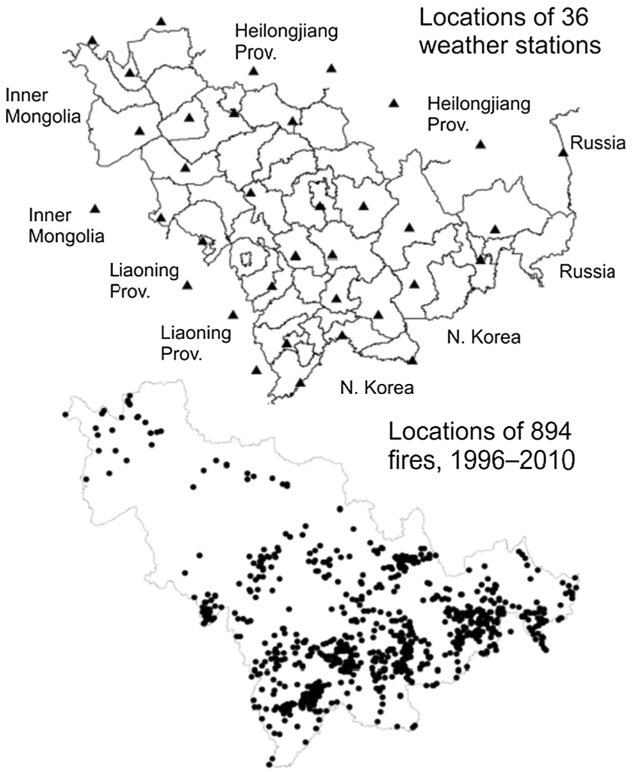


Fig. 1 Location of Jilin Province in northeastern China, with weather stations marked by *triangles* (*upper map*), and the locations of 894 fires in the province from 1996 to 2010 marked as dots (*lower map*)

approximately 8.56 million ha, 45.7% of provincial's total area. In terms of forest coverage, Jilin ranks fifth in China with a coverage of 40.38% in Jilin Province (State Forest Bureau 2010). Jilin is rich in timber species; major coniferous species are *Pinus koraiensis* Sieb., *Picea jezoensis* Carr. Komarovii (V.Vassil.) Cheng et L.K.Fu, *Abies holophylla* Maxim., *Larix olgensis* Henry, and important deciduous species include *Fraxinus mandshurica* Rupr., *Juglans mandshurica* Maxim., *Phellodendron amureuse* Rupr., *Populus davidiana* Dode., *Betula platyphylla* Suk. and *B. costata* Trautv. (Bai and Zhu 1991). Located at the eastern edge of the Euro-Asia continent, Jilin's climate is between temperate and sub-frigid zones. Eastern Jilin is close to the Yellow and Japan Seas, and the climate is humid and with heavy rainfalls in summer. In contrast, western Jilin is far from the ocean and close to the Mongolian Plateau; therefore, the climate is dry. Generally, Jilin has a temperate continental climate, with four distinct seasons: a short, dry and windy spring, a hot and rainy summer, a comfortable and cool autumn, and a long and cold winter. Annual average temperature in the province is 2–6 °C, and the province receives 2200–3000 h of bright sunshine per year. Annual precipitation ranges from 400 to 850 mm from west to east (http://www.jl.gov.cn/jlgk/dldm/xhtz/).

According to historical records, forest fires occurred most frequently in the 1960s with an annual average of 415 occurrences. In the 1970s, the province experienced the worst damage in terms of areas burned with an annual average area burned of 96,190 ha, which was approximately 1.48% of the provincial forested area, and average area burned per fire was 330.4 ha in the decade. The largest fire between 1969 and 2014, on April 24, 1971, burned a total area of 3510 and 2510 ha of forest. Since the provincial government began giving fire prevention high priority in the 1980s, forest fires have drastically decreased in frequency and in area burned (Yang et al. 1997). Almost all fires in the province are human-caused, and government regulations require all fires must be suppressed. There are two fire seasons in the province: the spring fire season from March 1 to June 15 and the fall fire season from September 1 to November 30. Approximately 87% of fires in Jilin are small fires that burn less than 4 ha.

The fire situation in the province can deteriorate if the enforcement of preventive measures is relaxed. To manage forest fires effectively, fire danger rating systems are needed to keep track of the day-to-day risk of forests to fire. The purpose of this study was to use the Canadian Forest Fire Weather Index System (FWI System) to examine spatiotemporal variations in forest fire danger in the province for the period 1996–2010, to help forest managers become aware of long-term trends in fire patterns in both time and space and thus be better prepared for potential forest fire dangers. Also, after extensive validation, we hope to adopt the FWI System as the province's daily operational tool for province-wide daily fire danger rating and fire prevention operation.

Materials and methods

Climate data, 1996–2010

Historical climate records of daily weather observations for 36 weather stations were downloaded from the China Meteorological Data Sharing Service System, managed by China Meteorology Bureau (http://cdc.cma.gov.cn/home.do), for the period 1996–2010. Among the stations, 24 are in Jilin Province; the other 12 stations are in the neighboring provinces of Liaoning (3 stations), Inner Mongolia Autonomous Region (3 stations), and Heilongjiang (6 stations) (Fig. 1). Because interpolation will be used in our analyses, the stations outside of the province boundary were used as buffer points such that the interpolated results will be better than those without buffering (Boer et al. 2001). The individual components of the FWI System should be based on daily measurements recorded at noon local standard time (LST) of dry bulb temperature, relative humidity, 10-m open wind speed, and 24-h accumulated precipitation. The values of the components are considered representative of the daily peak in fire danger later in the day, generally considered to be around 1600 h LST (Lawson and Armitage 2008). Due to the limitations on our climate data, we had to use the following daily records as input to the FWI System: daily maximum temperature (TEMP), daily minimum relative humidity (RHUM), daily maximum wind speed (WIND), and daily precipitations (PRCP).

Fire data, 1996–2010

Fire records from 1996 to 2010 were obtained from the Headquarters of Forest Fire Prevention, the Department of Forestry, Jilin for the location of the fires (longitude and latitude) (Fig. 1), dates of occurrence and extinguishment, ignition causes, gross burned area, forest area burned, and so forth. Of the 894 forest fires in the period, approximately 99.2% were surface fires. Lightning caused only one fire; all other fires were confirmed as human-caused.

Forest fire danger rating systems

The FWI System (Van Wagner and Pickett 1975, 1985; Van Wagner 1987) was adopted for rating fire danger in the province. The FWI System, one of the most widely recognised and applied fire danger rating systems in the world (Stocks et al. 1989; Amiro et al. 2004; De Groot et al. 2007), has been proposed as the basis for a global fire weather index (De Groot et al. 2006). Lawler (2004) compared the American National Fire Danger Rating System (NFDRS) and the FWI System for use in the Superior National Forest in Minnesota and found the FWI System to be less cumbersome and easier to understand and interpret.

The FWI System consists of six indices that are calculated using daily weather measurements (Lawson and Armitage 2008). The values of the different indices are considered representative of the daily peak in fire danger, which are fine fuel moisture code (FFMC), duff moisture code (DMC), drought code (DC), initial spread index (ISI), build-up index (BUI), and fire weather index (FWI). The first two indices (FFMC and DMC) represent the moisture contents of litter/fine fuel and loosely compacted decomposing organic matter on forest floors. The DC represents the moisture content of a deep layer of compacted organic matter. The codes for fire behaviour are ISI, BUI, and FWI; ISI indicates initial rate of fire spread; BUI represents total fuel available to a fire, and FWI is a combination of ISI and BUI, signifying the intensity of a spreading fire.

During the 1980s, the FWI System was first introduced to the Daxing'anling region of northern China (Jin et al. 1985) through a fire management collaboration project between China and Canada (Thomas 1990; White and Rush 1990). The initial use of the FWI System in the Daxing'anling region worked well for assessing fire danger (Lynham and Stocks 1987). Recently, Tian et al. (2011, 2014) used the FWI System to evaluate fire danger in the Daxing'anling region of northeastern China and in southwestern China. The system was found to reflect regional fire danger and could be effectively used for fire management.

Thin-plate smooth spline model (TSPLINE)

This model uses the penalized least squares method to fit a nonparametric regression model. It computes thin-plate smoothing splines to approximate smooth multivariate functions observed with noise. The model allows great flexibility in the possible form of the regression surface; the generalized cross validation (GCV) function is usually used to select the amount of smoothing. Specifically, the model will be used to interpolate the point data of 36 weather stations to generate a surface covering the whole province. The theoretical foundations for the thin-plate smoothing spline were described by Duchon (1976, 1977) and Meinguet (1979). The model can be described as the following for interpolating our data. Suppose that $\{w_i,\ i = 1, 2, 3, \ldots 36\}$ are the weather observations from the 36 stations and that $\{(x_i y_i),\ i = 1, 2, 3, \ldots 36\}$ are the geographic coordinates of the stations, then the 36 data points can be used to estimate values at any other location in the grid such that we convert point data into a grid data format. Numerous sources on the mathematical details are available (e.g., SAS User's Guide; SAS Institute 2004).

Several computer packages are available to conduct the TSPLINE analysis; we used the Fortran 77 source code developed by Gu (1989) and Gu and Wahba (1991) for splining. The code was downloaded from the Netlib repository website which contains software source codes for scientific computing maintained by AT&T, Bell Laboratories, the University of Tennessee and Oak Ridge National laboratory. Netlib comprises a large number of separate programs and libraries, and most of the codes were written in Fortran (http://www.netlib.org/gcv/index.html).

Create grid data

TSPLINE was used to convert the point data from the 36 weather stations into a grid data format covering the whole province. We tried different spatial resolutions for creating the grid and chose a spatial resolution of 1 km for its good representation of weather and fire conditions in the province. With such a resolution, the grid covering the province consists of 617 rows and 771 columns. In total, there were 5479 days in the period 1996–2010, and we have 5479 daily weather observations of TEMP, RHUM, WIND, and PRCP from all 36 weather stations. In our analyses, we first calculate the FWI indices for each weather station using the station's weather observations. Then, we used TSPLINE to convert the point weather data or point FWI index data from the 36 stations to grid format. With the data in grid format, we can overlay ignition locations with weather or fire danger index grids to visually examine possible correspondence between fire ignition and weather and/or fire danger.

Analyses

Preliminary statistics of fires were produced to reveal possible temporal dynamics between time and fire. First, we examined monthly summations of fire frequency and monthly areas burned across the province versus month as a monthly time series; in this analysis, the province-wide monthly sums were plotted against 180 months from January 1996 to December 2010. Then, annual summations of fire data could be examined in the same fashion for the 15 years from 1996 to 2010. Finally, the summations were obtained for March, April, May, June, September, October, and November over the 15 years and plotted against the months.

We conducted a correlation analysis between fire danger indices, fire frequency, and areas burned. First, fire frequency and areas burned across the province were summed for each month from January 1996 to December 2010 to produce a time series of 180 months. For each weather station, we also generated a similar time series for monthly averages of FFMC, DMC, DC, ISI, BUI, and FWI. Then the data from the 36 stations were pooled to generate a time series of monthly averages for the whole province. Correlation analysis was then conducted between monthly fire data and monthly fire danger index data. The results from such an analysis helped us evaluate if the fires and the indices are coupled and if these fire danger indices can be used as a proxy for the fire situation in the province for fire management purposes.

For each weather station, we calculated monthly averages of TEMP, RHUM, WIND and a monthly summation of PRCP for March, April, May, June, September, October, and November for each year from 1996 to 2010. Thus, for each weather variable at each station, we have a time series of 15 years. In the same fashion, we also created the same time series for FFMC, DMC, DC, ISI, BUI, and FWI. Then for each month, a simple linear regression $y = a + b \times t$ was fitted with weather variables or fire weather indices as the dependent variable y and years of 1996, 1997, …, 2010 as the independent variable t. The same analysis was done on a daily basis as well. For each weather station, we fitted the regression model to the daily weather observations and daily fire danger indices; the independent variable is the number of days from 1 to 5479 (the number of days from 1996 to 2010). The estimated b values should reveal the long-term trend of these variables. After estimated b values were derived for all 36 stations, the TSPLINE was used to convert the 36 data points into the grid format.

Results and discussion

Fire occurrence

Table 1 shows the distribution of fire size classes for the study period. The 894 forest fires over the 15 years burned an area of 4838.2 ha (1986.8 ha of forested land and the remainder either grasslands or swamps). The average gross area burned per ignition was 5.4 ha; the average forest area burned per ignition was 2.2 ha. Fires that burned areas greater than 100 ha accounted for 1% of all fires, but the areas burned by these fires totaled 39.5% of all gross areas burned and 28.8% of forest areas burned. No fire from 1996 to 2010 burned more than 93 ha of forest area. Fire frequency averaged approximately 60 ignitions/year during the 15 years; the highest frequency was 151 in 2008.

Figure 2 presents the spatial distributions of ignitions by year and fire season for the 15 years across the province and by month during the two seasons. Clearly, more fires occurred in the spring season than in the fall season, with 77.7 versus 22.3% in fire frequency, 86.3 versus 13.7% in gross area burned, and 82.3 versus 17.7% in forest area burned for the period. In the spring season, April was the worst month in terms of either fire frequency or areas burned. Specifically, the fire frequency, gross area burned, and forest area burned in April accounted for 46.2%, 62.3%, and 61.7% of annual frequency and areas burned, respectively. The monthly fire ignition showed that April, May, and October were the worst months.

Complementary to Fig. 2, Fig. 3 presents the plots of the summarized fire occurrences for Jilin Province over time. First, monthly fire frequency and areas burned were plotted against months (January 1996 is the first month, and December 2010 is the 180th month or the last month). Second, annual fire frequency and areas burned were plotted versus years 1996, 1997, …, 2010. Finally, 12 monthly sums of fire frequency and areas burned from 1996 to 2010 were plotted over 12 months from January to December. Generally, fire frequency showed an increasing pattern from 1996 to 2010, but areas burned showed an opposing pattern, indicating that the ability to control fires in Jilin Province is improving. Fire prevention agencies can mobilize a fire fighting force quickly as soon as fire is detected and can put down fires at the earliest stage to avoid further damage. As expected from the fire control experience in the province, April and May in spring were the worst months with the highest and second highest fire occurrences, confirming the fire patterns observed in Fig. 2.

Table 1 Statistics by fire size for Jilin Province (1996–2010)

Individual fire size class (ha)	Total no. of fires (% of total)	Total ha (% of total)	Total ha forested area (% of total)
<1.0	630 (70.5)	265.4 (5.5)	141.6 (7.1)
1.0–4.0	144 (16.1)	334.4 (6.9)	174.4 (8.8)
4.1–100.0	111 (12.4)	2326.7 (48.1)	1099.4 (55.3)
>100.0	9 (1.0)	1911.7 (39.5)	571.4 (28.8)
Total	894 (100.0)	4838.2 (100.0)	1986.8 (100.0)

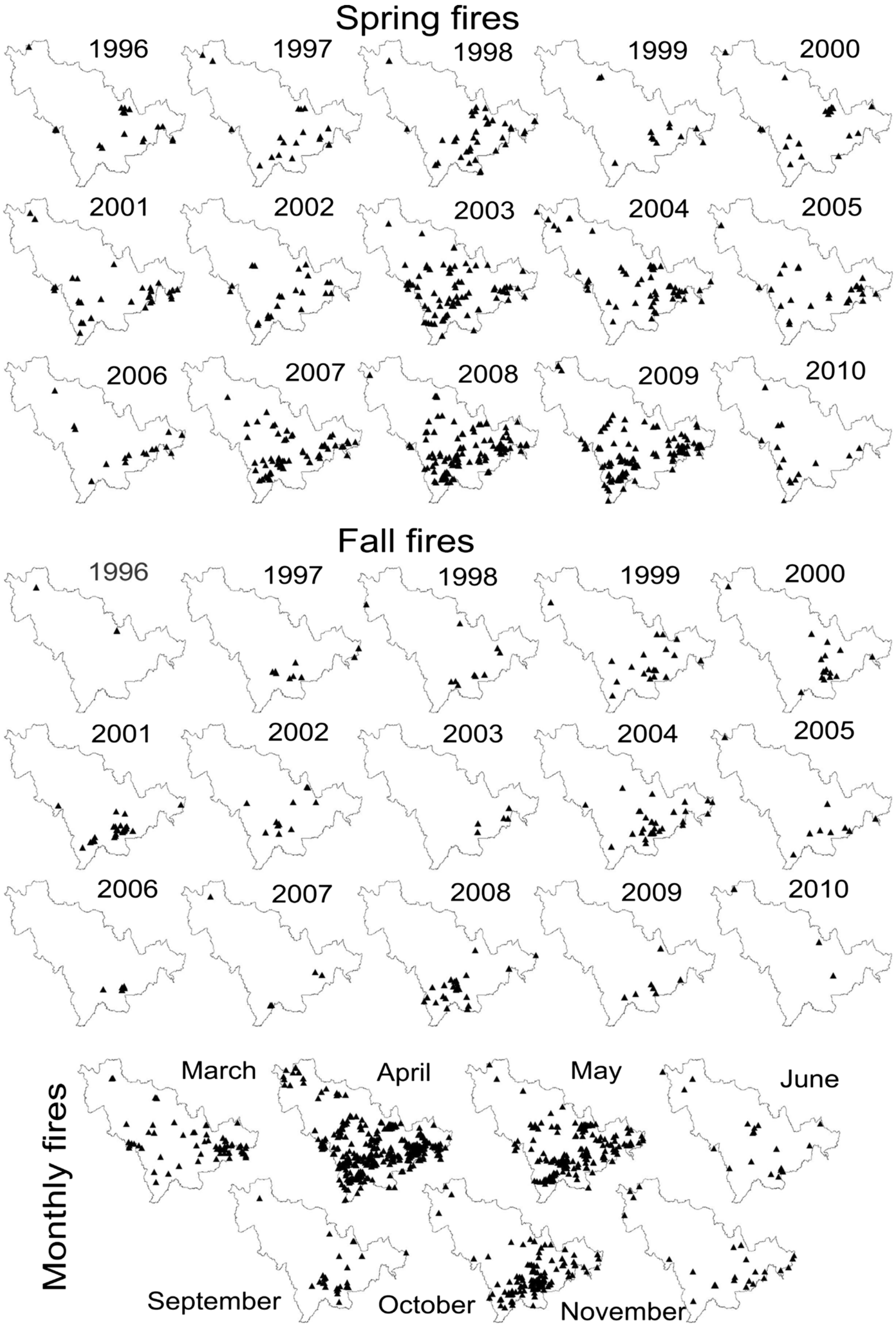


Fig. 2 Locations of annual forest fires from 1996 to 2010 for two fire seasons and by month for March, April, May, June, September, October, and November

Analyses of the FWI indices and fire occurrence

Correlation analyses were conducted between monthly fire danger indices, monthly sums of fire frequency, and areas burned based on 180 months (from January 1996 to December 2010); Table 2 presents the correlation coefficients between the indices, fire frequency, and areas burned; a significant correlation was found between all fire indices except for DC, fire frequency, and forest areas burned ($P = 0.01$). Also, gross areas burned were significantly correlated with danger indices except DC and BUI. Although the correlation between gross areas burned and BUI was not significant at $P = 0.01$ ($P = 0.019$), it was significant at $P = 0.05$. Real fire

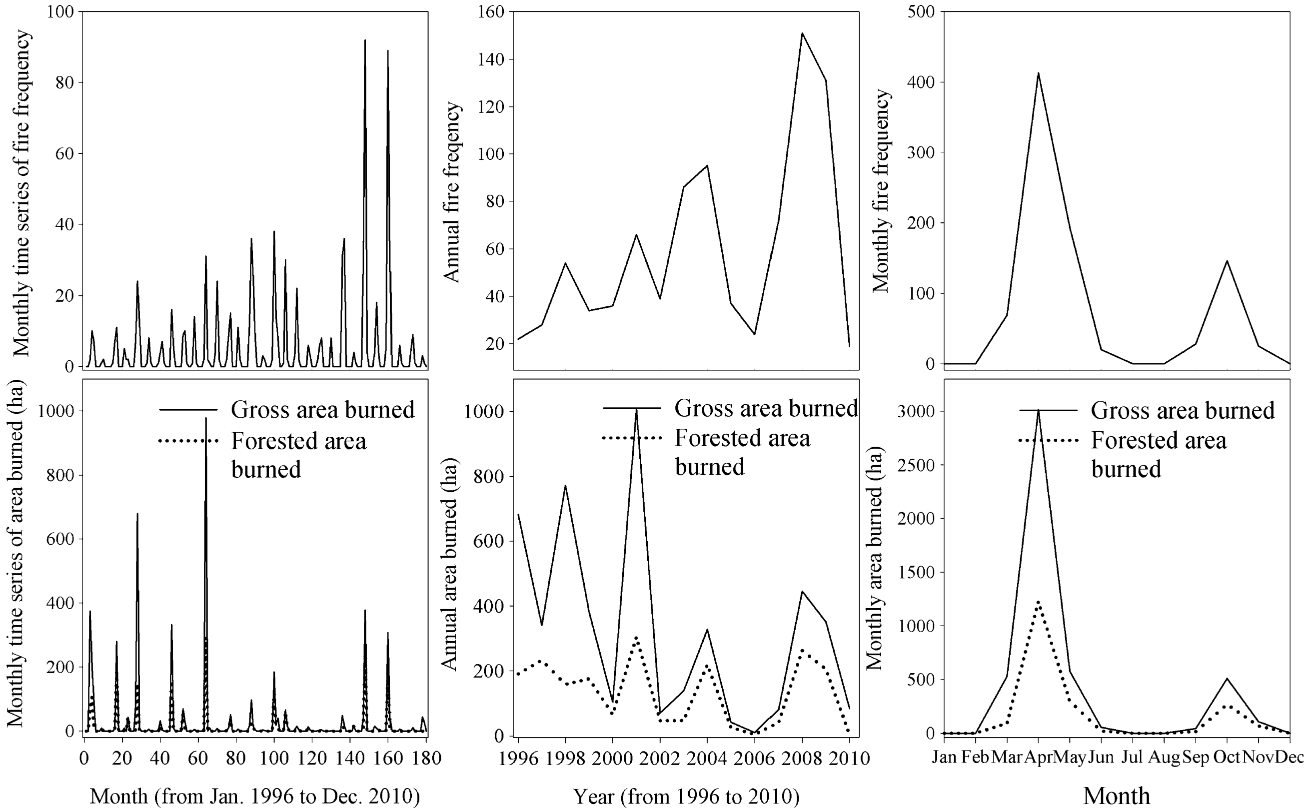


Fig. 3 Plots of monthly fire frequency and monthly area burned over time; plots of annual fire frequency and areas burned over time, and plots of monthly sums of fire frequency and areas burned over time for January to December

Table 2 Pearson correlation analysis among monthly fire frequency and areas burned and monthly average of Fire System indices for the period 1996–2010

Index	No. of fires	Total area burned	Total forest area burned
FFMC	0.375^A	0.283^A	0.280^A
DMC	0.378^A	0.222^A	0.256^A
DC	0.127	−0.050	0.011
BUI	0.350^A	0.175^B	0.217^A
ISI	0.553^A	0.494^A	0.507^A
FWI	0.532^A	0.397^A	0.424^A

^{A} Highly significant ($P = 0.01$)

^{B} Significant ($P = 0.05$)

danger was also affected by the state of the deeper organic layers, by concentrations of large downed wood, and even by the availability of water in small streams and swamps. All of these factors influencing fire danger are reflected in the DC (Van Wagner 1987). Since almost all fires in Jilin are human-caused, surface fires, it is reasonable that no significant correlation exists between fires and DC.

Fire danger classes

Based on the premise that extreme days should account for less than 3% of the total study period (Van Wagner 1987), we found that the FWI value of 96 was the lower limit for defining the extreme fire danger class. Then using a geometric approach, we classified the ranges for other FWI danger classes (Table 3). These FWI classes may be used by local fire managers as a guide to rate fire danger and understand potential fire behavior and suppression requirements. Statistics indicate that fire frequency, gross areas burned, and forest areas burned were maximized when the fire danger rating system (FDRS) class was "High". The cumulative percentage of fire frequency, total area burned, and forest area burned for the three classes of "High", "Very High", and "Extreme" was 68.2%, 78.0%, and 83.0%, respectively (Table 3). Table 3 showed that class "High" was associated with the highest fire frequency and areas burned, reflecting the reality of fire prevention in the province. As mentioned previously, almost all forest fires in the province are caused by humans, usually ignited by careless smoking (23.2%), agriculture residual burning (31.7%), paper-burning when visiting tombs (11.0%), camping fire (9.0%), arson (14.3%), and sometime by fires in Russia or North Korean (DPRK) burning across the

Table 3 Statistics for fires between 1996 and 2010 according to class in the fire danger rating system (FDRS) and fire weather index (FWI)

FDRS class	FWI	Occurrence (%)	No. of fires	Frequency (%)	Total area (ha)	Total area (%)	Total forested area (ha)	Total forested area (%)
Low	0–14	35	44	4.9	410	8.5	81	4.1
Moderate	15–33	30	240	26.9	653	13.5	255	12.8
High	34–70	27	429	48.0	2879	59.5	1125	56.7
Very high	71–95	5	119	13.3	547	11.3	294	14.8
Extreme	>95	3	62	6.9	349	7.2	231	11.6

border (2.6%). When fire danger class is “Low” or “Moderate”, fuel can hardly be ignited because of high moisture content in the fuel. When the danger class is “Very high” or “Extreme”, forest fire agencies at different government levels will be on highest alert; fire patrol will be intensified, and preventive measures will be strictly enforced. For example, ignition agents such as cigarette lighters and matches will be confiscated from people entering and working in forests when the possibility of a forest fire is very high. As a result, fire occurrence at the two highest danger levels will not reach the expected levels, since human activities in forest areas are under strictest control. At danger level “High”, fuel can be ignited relatively easily, but the alert is not as high as for classes “Very High” and “Extreme”. As a result, preventive measures are sometimes not fully carried out, and fire-fighting personals are not fully mobilized, which largely explains why danger level “High” is associated with the highest fire frequency and areas burned.

Spatial variation in fire danger in Jilin

Although all analyses were based on monthly or yearly data, we also created some daily grids of the six fire danger indices as an example to show how to assess fire danger spatiotemporally. Figure 4 represents the spatial distribution of FFMC, DMC, DC, ISI, BUI, and FWI on April 9, 2009 for the 16 ignition locations of forest fires that occurred that day in the province of Jilin. The maximum daily fire frequency during the study occurred on April 9, 2009 with a recorded 16 fires. Weather conditions at all 16 ignition locations were generally favorable for fire occurrence. The weather was clear for 13 ignition locations and clear to cloudy for the other three locations; the daily maximum temperatures for the 16 locations were above 22 °C, which was much higher than the daily normal. Of the 16 fires, 15 occurred in afternoon. FFMC on the day was relatively high for the province with most values greater than 95; the FFMC values at 13 ignition locations were greater than 96, showing a strong association between high FFMC value and fire occurrence.

Figure 5 presents the grids of estimated b value of regression $y = a + bt$. In the regression equation, t is an independent variable using values of 1996, 1997, …, 2010; y is one of the four monthly weather variables, and its values are the monthly averages (for TEMP, RHUM, and WIND) or the monthly sum (PRCP) over the 15 years from 1996 to 2010. Clearly, weather variables vary spatially and temporally. Temperatures tended to decrease in March and April and increase trend in October and November for the whole province. Both increasing and decreasing trends were found in May, June, and September in the province. RHUM appeared to decrease pattern across the province for all months but March and April, which was favorable for fire occurrence; wind speed also seemed to decrease. Precipitation in March and April showed a strong increasing trend province-wide, which would be beneficial for fire prevention. However, there was a drying trend in other months, especially in the eastern part of the province in June, September, and October.

Figure 6 presents the grids of estimated b values of the regression model as shown in Fig. 5. All fire danger indices except DC showed a decreasing trend for March and April, suggesting the chance of fire occurrence decreasing within those 2 months. Given that April is the worst month for fire occurrence, such a decreasing trend should be helpful for fire prevention in the spring fire season. DC showed a strong increasing trend in March and April, suggesting that any fires at this time would have high chance to become large fires because DC reflects the susceptibility of the deeper organic layer and downed wood to fire. The maps in Fig. 5 indicated that TEMP and wind speed decreased in March and April and PRCP increased. RHUM decreased in the western part of the province in March and showed a small increase across the province in April. Overall, such climatic changes in March and April were favorable for fire prevention, because most fires occurred in the spring fire season. In March, an increasing trend in FFMC dominated the northwestern part of the province; however, most forests grow in the province’s southeastern part and such an increasing trend should have minimal impact on fire

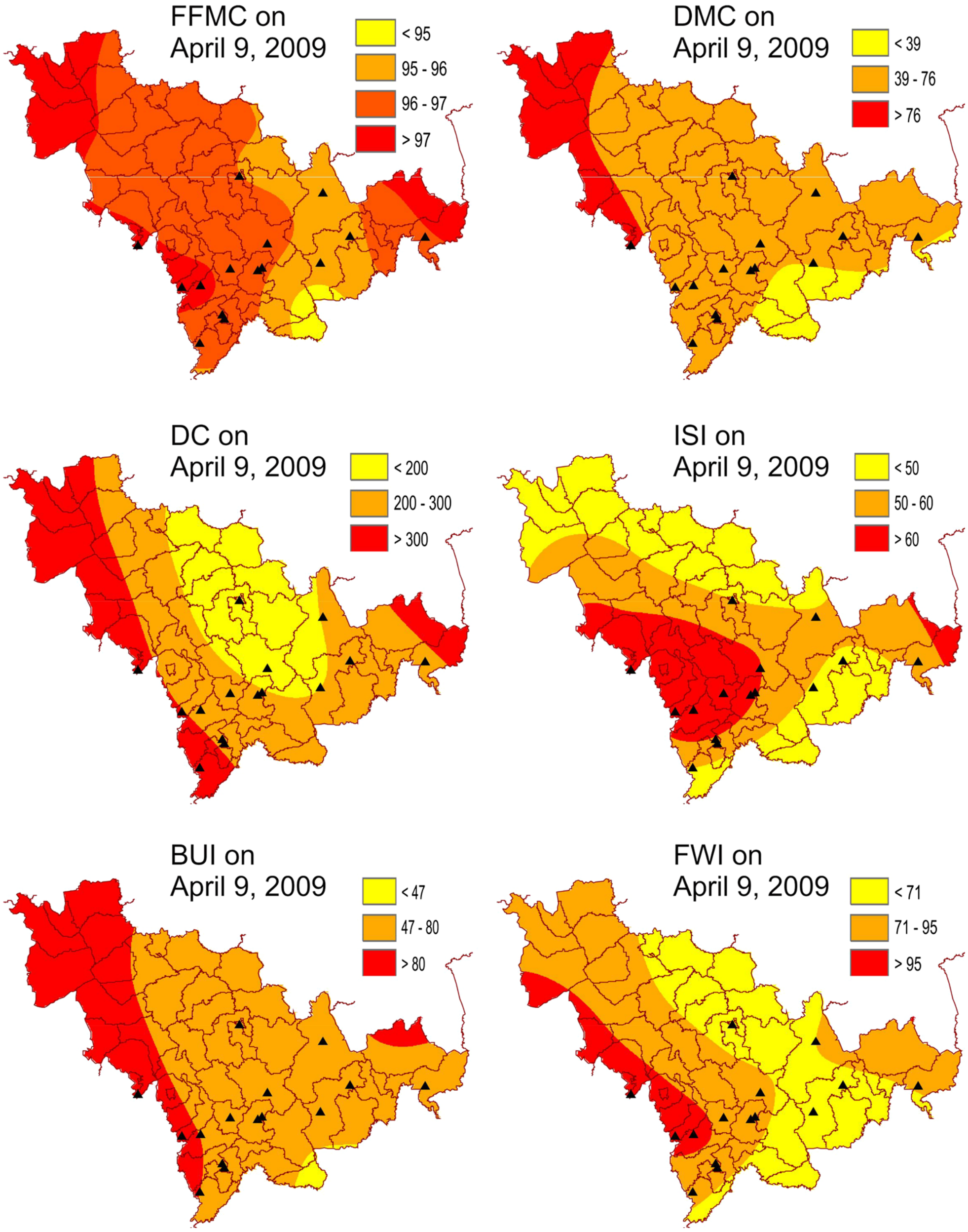


Fig. 4 Grids of FFMC, DMC, DC, ISI, BUI, and FWI for April 9, 2009 with the geographic locations (*triangles*) of the 16 forest fires on that day

occurrence. October is the worst month in the fall fire season as the most fall fires occurred during October. The FFMC, DMC, DC, and BUI maps of October indicated the fire situation was worsening that month from 1996 to 2010, corresponding to increased TEMP, decreased RHUM and PRCP in the southern part of the province.

Figure 7 presents the grids of estimated b values for regression on daily data. In the regression, t represents the values 1 (January 1, 1996), 2 (January 2, 1996), … 5479 (December 31, 2010), and y is one of the four daily weather variables and one of the six daily fire danger indices. Overall, daily TEMP and PRCP increased province-wide from 1996 to 2010, which largely agrees with the report that significant warming, generally accompanied by an increasing amount of precipitation, would occur globally (Intergovernmental Panel on Climate Change 2007, 2013).

However, Zoltai et al. (1991) and Hogg and Hurdle (1995) found that in a boreal forest in western Canada, even though annual precipitation generally increases, the

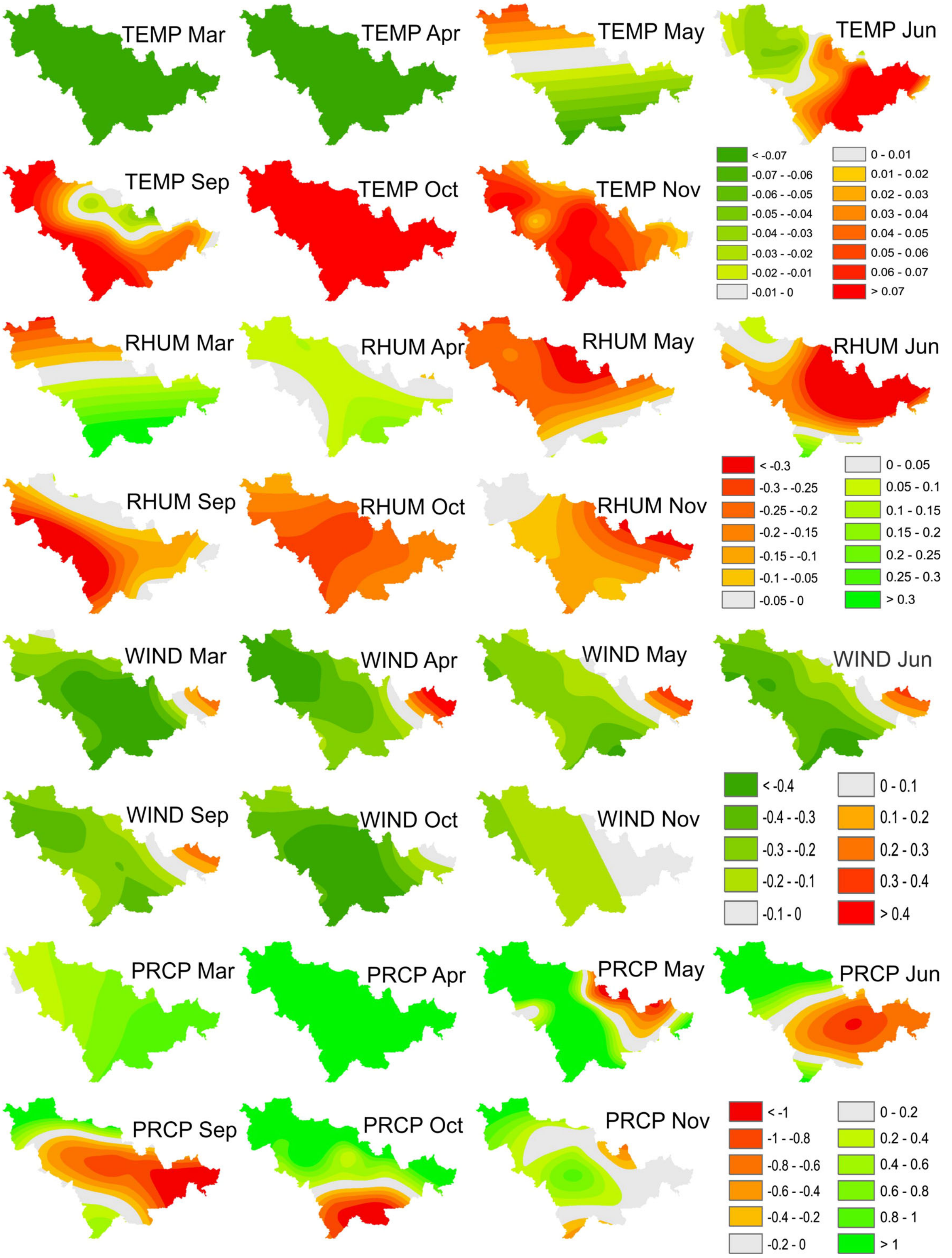


Fig. 5 Grids of the estimated *b* values based on monthly averages over 15 years (1996–2010) for weather variables TEMP, RHUM, and WIND, and grids of estimated *b* values based on monthly sum over 15 years (1996–2010) for weather variable PRCP

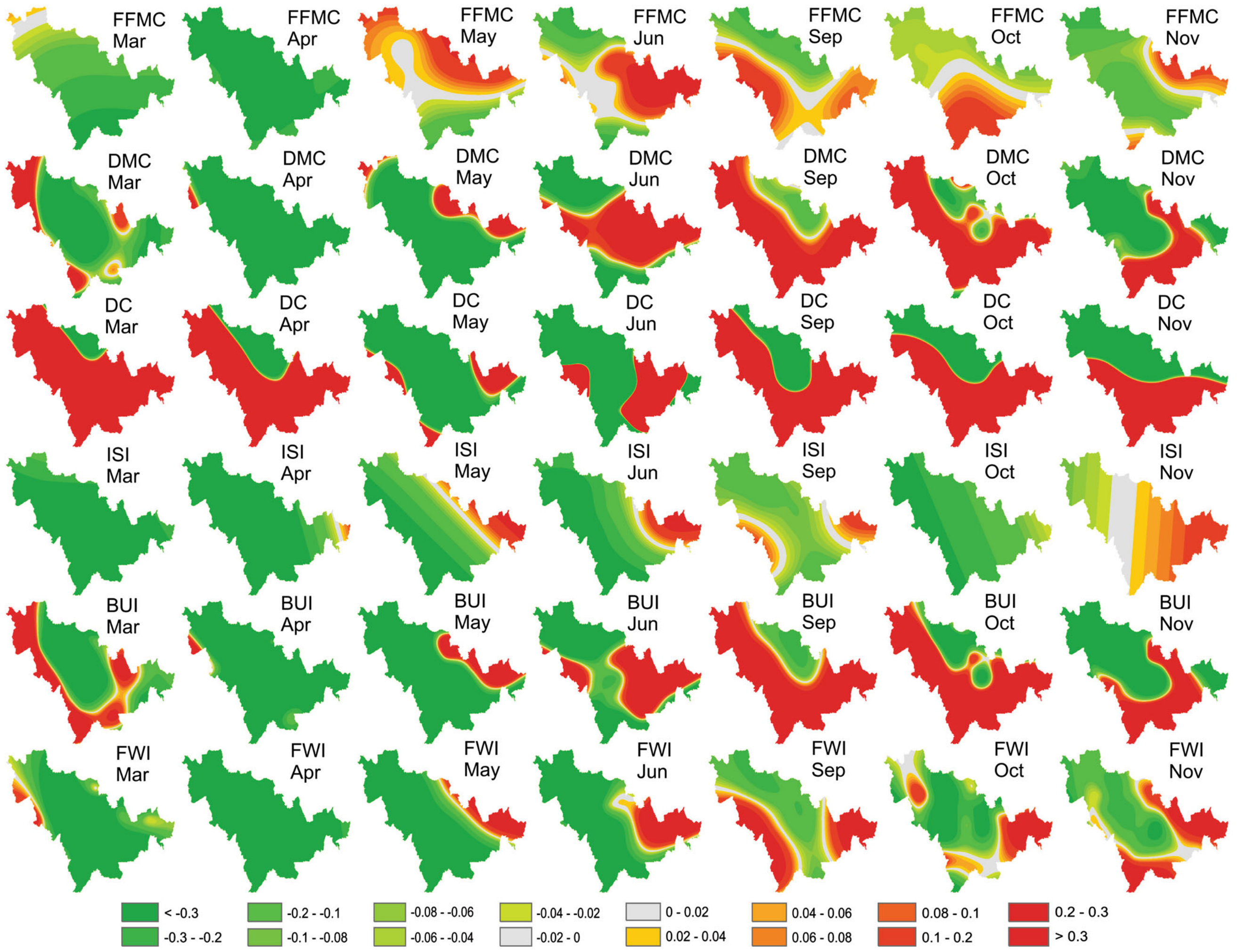
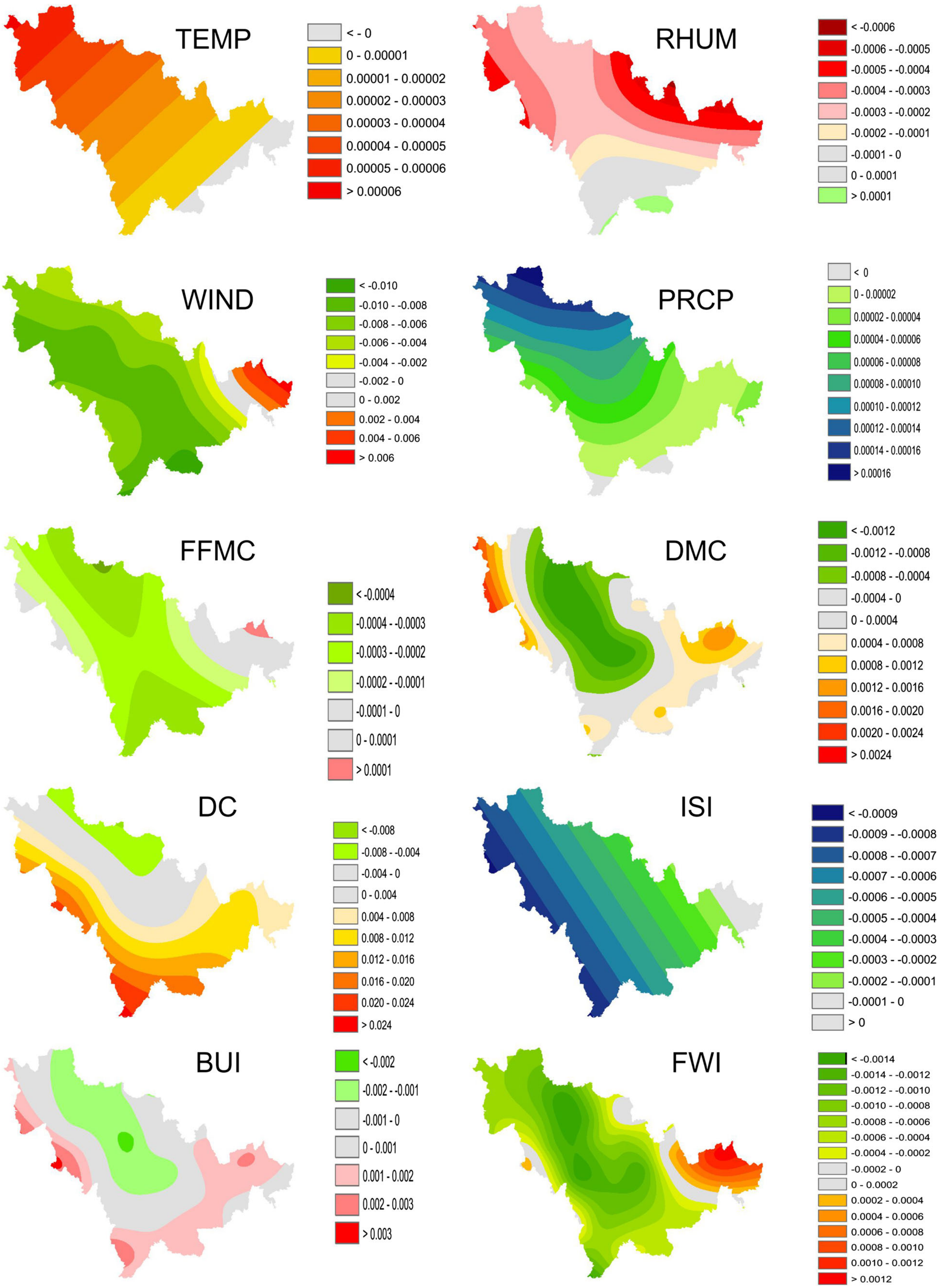


Fig. 6 Grids of estimated *b* value based on monthly averages over 15 years (1996–2010) for fire danger indices FFMC, DMC, DC, ISI, BUI, and FWI

increased temperatures drives increased evapotranspiration. They found a projected 11% increase in precipitation would be insufficient to offset the increase in potential evapotranspiration resulting from a projected warming of 4–5 °C in mean annual air temperature, and the forests would experience a greater moisture deficit that would reduce fuel moisture content. Because bioclimatic conditions in Jilin differ from those in the western Canadian boreal forests, we need time to observe whether the finding in Canada is applicable to Jilin's forests. RHUM showed a decreasing trend, which is unfavorable for fire prevention, and wind speed decreased spatiotemporally. When evaluated using daily data, FFMC in this period decreased, indicating that day-to-day fire susceptibility of the forest was decreasing. A similar trend was also found in the ISI and FWI for most of the province. The trend as shown by the DC map suggested that the chance of large fires occurring increased, although the general fire situation was easing.


TEMP
< - 0
0 - 0.00001
0.00001 - 0.00002
0.00002 - 0.00003
0.00003 - 0.00004
0.00004 - 0.00005
0.00005 - 0.00006
> 0.00006
RHUM
< -0.0006
-0.0006 - -0.0005
-0.0005 - -0.0004
-0.0004 - -0.0003
-0.0003 - -0.0002
-0.0002 - -0.0001
-0.0001 - 0
0 - 0.0001
> 0.0001
WIND
< -0.010
-0.010 - -0.008
-0.008 - -0.006
-0.006 - -0.004
-0.004 - -0.002
-0.002 - 0
0 - 0.002
0.002 - 0.004
0.004 - 0.006
> 0.006
PRCP
< 0
0 - 0.00002
0.00002 - 0.00004
0.00004 - 0.00006
0.00006 - 0.00008
0.00008 - 0.00010
0.00010 - 0.00012
0.00012 - 0.00014
0.00014 - 0.00016
> 0.00016
FFMC
< -0.0004
-0.0004 - -0.0003
-0.0003 - -0.0002
-0.0002 - -0.0001
-0.0001 - 0
0 - 0.0001
> 0.0001
DMC
< -0.0012
-0.0012 - -0.0008
-0.0008 - -0.0004
-0.0004 - 0
0 - 0.0004
0.0004 - 0.0008
0.0008 - 0.0012
0.0012 - 0.0016
0.0016 - 0.0020
0.0020 - 0.0024
> 0.0024
DC
< -0.008
-0.008 - -0.004
-0.004 - 0
0 - 0.004
0.004 - 0.008
0.008 - 0.012
0.012 - 0.016
0.016 - 0.020
0.020 - 0.024
> 0.024
ISI
< -0.0009
-0.0009 - -0.0008
-0.0008 - -0.0007
-0.0007 - -0.0006
-0.0006 - -0.0005
-0.0005 - -0.0004
-0.0004 - -0.0003
-0.0003 - -0.0002
-0.0002 - -0.0001
-0.0001 - 0
> 0
BUI
< -0.002
-0.002 - -0.001
-0.001 - 0
0 - 0.001
0.001 - 0.002
0.002 - 0.003
> 0.003
FWI
< -0.0014
-0.0014 - -0.0012
-0.0012 - -0.0010
-0.0010 - -0.0008
-0.0008 - -0.0006
-0.0006 - -0.0004
-0.0004 - -0.0002
-0.0002 - 0
0 - 0.0002
0.0002 - 0.0004
0.0004 - 0.0006
0.0006 - 0.0008
0.0008 - 0.0010
0.0010 - 0.0012
> 0.0012

◀**Fig. 7** Grids of estimated *b* values based on daily data over 5479 days (from January 1, 1996 to December 31, 2010) for weather variables TEMP, RHUM, WIND, and PRCP, and for fire danger indices FFMC, DMC, DC, ISI, BUI, and FWI

Conclusions

Fire frequency and forest areas burned were significantly correlated with fire danger indices, with the exception of DC from 1996 to 2010 for Jilin Province. Gross areas burned were significantly correlated with the fire danger indices with the exceptions of DC and BUI. Overall, the FWI System appeared to work well for rating fire danger in Jilin Province. Compared with the values of the FWI index obtained by Tian et al. (2011), our FWI values are relatively high. This difference can be attributed to the fact that we used the daily maximum for temperature and wind speed and the daily minimum for relative humidity. Otherwise, the values of the six danger rating indices calculated for Jilin all fall within reasonable ranges, and the spatiotemporal patterns of fires obtained using the maxima and the minima would be the same as those based on the daily measurements recorded at noon LST.

Our analyses indicate that in the coming decades, the fire danger in March and April will decrease across the province, but the chance of large fire occurrence will increase, as reflected through increasing DC values. The fire danger in May will decrease for most parts of the province, and the fire danger in June will increase for the eastern part of the province only. Although the fire danger rating is high in June, the fire situation in June should not be serious because the vegetation across the province will be green, inhibiting fire occurrence. This phenomenon is also confirmed by historical fire data (see Fig. 3). The fire danger in the fall will increase in the future, and the chance of large fire occurrence will also increase in the fall.

According to our analyses, the future fire trend in the province can be summarized as follows: the fire danger in the spring fire season will decrease, and fire danger in the fall fire season will increase. Because most fires historically have occurred in the spring fire season, a shift in the future fire danger between the two fire seasons will be beneficial for fire management in the province. Our analyses also indicated that, in future decades, the decreased values of FFMC, ISI and FWI suggest that the day-to-day susceptibility of the forest to fire will decrease, and the trend as shown by the DC grid suggests that the chance of large fire occurrence will increase.

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