Fire danger assessment with remote sensing: a case study in Northern China

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Received: 9 January 2012 / Accepted: 9 September 2012 / Published online: 21 September 2012
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Abstract Every year several million hectares of forest and grassland in China are affected by wildfires. The majority of wildfires occur in the northern part of China, where grasslands and forests are ubiquitous. A critical step toward the protection of life, property, and natural resources from wildfires is the development of a fire danger rating system. This paper presents a new method to assess fire danger that capitalizes on the abundance of environmental data available via remote sensing and applies this new method to the northern part of China. Using an analytical hierarchy process, a fire danger index was developed based on five environmental factors that are known to affect fire frequency and severity, including land surface temperature, vegetation curing, equivalent water thickness, vegetation continuity degree, and fuel weight. Data for these five factors were derived from satellite imagery, instead of point data, allowing for predictions to be made over a large geographic area. Fire danger ratings were then mapped for the region based on the fire danger index. In addition, the accuracy of the fire danger index was evaluated by statistical analyses. The fire danger index was significantly correlated with air temperature and precipitation, suggesting that changes in these two environmental variables will affect the predictions of the index.

Keywords Fire danger assessment · Remote sensing · Northern China

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1 Introduction

Globally wildfires affect several hundred million hectares of forest and grassland each year. In 2008, China experienced 14,144 forest fires resulting in over 184,000 ha of burned land and an economic loss of 125.93 million Yuan (NBS 2008). While wildfires may be recognized as important ecological processes in some ecosystems, in many areas of the world, wildfires are considered a threat to natural resources, property, and public safety (Goldammer 1998; Taylor and Alexander 2006).

Fire danger rating has long been used as a tool to assess several aspects of wildfires including the ease of ignition, rate of spread, difficulty of control, and impact of wildfires (Merrill and Alexander 1987; Taylor and Alexander 2006). In fact, fire danger rating systems are a major component of fire prevention and management (Forestry Canada Fire Danger Group 1992; Taylor and Alexander 2006). Many fire danger rating systems have been developed throughout the world, such as the Canadian Forest Fire Danger Rating System (CFFDRS) (Forestry Canada Fire Danger Group 1992), the US National Fire Danger Rating System (NFDRS) (Deeming et al. 1977), and the McArthur fire danger rating meter used in Australia (Luke and McArthur 1978). Most of the fire danger rating systems provide one or more qualitative and numerical indices of ignition potential and probable fire behavior (Taylor and Alexander 2006).

Assessing fire danger requires information regarding fuel, weather, and topography (Merrill and Alexander 1987; Carlson and Burgan 2003; Leblon 2005). Weather variables are the most dynamic and are used in all operational fire danger systems (Carlson and Burgan 2003). Topography, the least dynamic variable, is used in some fire danger systems, but not all (Carlson and Burgan 2003). Fire danger ratings are commonly calculated from point data for weather and fuels that are typically collected at weather stations (Merrill and Alexander 1987; Forestry Canada Fire Danger Group 1992; Leblon 2005). Point data can be used to calculate fire danger ratings for locations where observations were collected; however, in order to predict fire danger ratings over large geographic regions point data must be interpolated (Leblon 2005). The accuracy of ratings may be limited by the density of point data, as well as the interpolation methods, which generally does not account for the fine-scale variations in environmental conditions (Leblon 2005).

Remote sensing can provide the potential to address these limitations (Leblon 2005; Gillespie et al. 2007). In addition, we now have the ability to evaluate fire danger and monitor wildfires using satellite imagery (Aguado et al. 2003; Gillespie et al. 2007). Recent spaceborne sensors, such as MODIS, can provide near real-time data on variables that are commonly used to evaluate and predict fire danger ratings (Zhou et al. 2003). For example, characteristics of fuels, such as fuel moisture and biomass across large areas, can be well derived from satellite systems (Fuller 2000; Leblon 2005; Gillespie et al. 2007). Indicators of weather conditions, such as land surface temperature, can be generated from the thermal bands of satellite imagery (Wan and Dozier 1989; Wan and Li 1997; Wan 1999). In addition, remote sensing has a very useful advantage in predicting fire danger, as it can explicitly reveal spatial patterns of fire danger in a recurrent and consistent way over a large geographic area, even for those remote regions where weather stations are sparse and ground measurements are difficult to acquire (Leblon 2005).

This paper presents a new fire danger assessment method using variables derived via remote sensing. We apply this new method of fire danger assessment to Northern China. This region serves as an ideal test site because forest and grassland are widely distributed and wildfires frequently occur. Very few weather stations, however, are located in forested areas and grasslands. The majority of the weather stations are located in urban areas, far

away from those forests and grassland. The overall objective of this study was to investigate the potential of remote sensing data in evaluating fire danger. Rather than using point data from weather stations and ground measurements, we assessed the fire danger based on the fire environmental factors that were derived from remote sensing data alone. Statistical analyses were conducted to assess the effectiveness of the fire danger index in fire danger rating.

2 Study area

We focused on four provinces in Northern China: Inner Mongolia, Liaoning, Jilin, and Heilongjiang (Fig. 1), where grasslands and forests are widely distributed and wildfires frequently occur. Most of the grasslands are in the middle and west of Inner Mongolia arid and semi-arid cold zones, as well as the cold temperate zone in Jilin, Heilongjiang, and east of Inner Mongolia. Forests in this region are distributed in mountainous areas near Daxinganling Mountain, Xiaoxinganling Mountain, and Changbaishan Mountain. Wildfires frequently occur in this region, particularly in areas near the border. For example, over half of the 140 major forest fires in China from 1951 to 2000 occurred in this area (CFSDC 2000).

Fig. 1 The study area is located in the east-north region of China, including four provinces: Inner Mongolia, Liaoning, Jilin, and Heilongjiang. Forests in this region are distributed in the Daxinganling, Xiaoxinganling, and Changbaishan mountainous areas. The map shows the distribution of the degree of vegetation continuity in the study area, with lighter areas corresponding to a higher degree of vegetation continuity

3 Methods

Fire danger ratings can be assessed both qualitatively and quantitatively (Chuvieco et al. 1997). With a qualitative approach, fire danger is generally determined by a set of evaluation criteria based on expert knowledge (e.g., Brass et al. 1983). This approach has been criticized because criteria selection is somewhat subjective. In addition, criteria selected in one region might not be relevant to other regions (Chuvieco et al. 1997). A quantitative approach generally begins with building a model to compute the numerical value of the fire danger index, which is later divided into different fire danger ratings. In this study, we used a quantitative method to assess fire danger ratings that can be summarized in three steps: (1) identify variables that determine fire danger in the study area; (2) construct a fire danger index model based on the selected variables, and calculate the fire danger index; and (3) determine the fire danger ratings based on the fire danger index. In addition, the effectiveness of the fire danger index was evaluated by statistical analyses.

3.1 Selection and calculation of fire danger indicators

The occurrence and behavior of wildfires is influenced by many factors, including constant topographic factors such as slope of the land, semi-constant factors such as fuel type, fuel moisture, and amount of fuel, and variable weather factors such as wind and relative humidity (Goldammer 1998). We selected five variables to construct the fire danger index (FDI): land surface temperature (LST), degree of vegetation curing (DVC), equivalent water thickness (EWT), vegetation continuity degree (VCD), and fuel weight. These variables were obtained from satellite imagery, which we discuss in detail below. We selected these five variables because (1) they greatly influence the fire occurrence and behavior in our study area (e.g., Carlson and Burgan 2003; Mbow et al. 2004; Zhou et al. 2003) and (2) they can be directly derived from remote sensing data.

3.1.1 Land surface temperature

We used LST derived from MODIS imagery as a proxy for fuel temperature, which is one of the primary factors leading to fire ignition (Rothermel 1972; Dasgupta et al. 2006). In addition, satellite-derived LST is an indirect indicator of fuel moisture content, as LST increases in drier areas due to reduced evapotranspiration (Chuvieco et al. 1999; Dasgupta et al. 2006). LST for the study area was derived from MODIS data using a split window method (Wan 1999). The equation to calculate LST is given below:

$$T_s = A_0 + A_1 T_{31} - A_2 T_{32}, \quad (1)$$

where T_s is LST, and T_{31} and T_{32} are the brightness temperature of band 31 and band 32 of MODIS data, respectively. The MODIS data used for LST calculation were daytime images (mainly from Terra). The indicator of LST was synthesized using 10 days' images with grid cell size of 1 km. There would be some invalid pixels in every LST images for some reasons, such as cloud cover and raw data anomalies. In the synthesis process, the validation-mean method (Eq. 2) was used to avoid the effect of the invalidation values (i.e., pixels under cloud cover).

$$\text{mean} = \frac{\sum_{i=1}^N V_i}{N}, \quad (2)$$

where mean is the synthesized value in a 1-km grid cell, and V_i and N are the validation values and the amount of the 10 days in a 1-km grid cell, respectively.

3.1.2 Degree of vegetation curing

Degree of vegetation curing is one of the key determinants of fire ignition and behavior (Brooks 1999). It is a measure of vegetation “greenness” and is defined as the percentage of vegetation (e.g., grass) material that is dead in the sward. Vegetation curing can be estimated by field observation or derived from satellite imagery. The vegetation index, such as normalized difference vegetation index (NDVI) derived from satellite images, is thought as a good indicator to the greenness of vegetation, water stress, and other vegetation parameters (Huete et al. 1999). “The NDVI profile shows annual patterns of vegetation development from green-up to senescence” (Burgan et al. 1996). NDVI has been typically used to assess fuel greenness or curing (Burgan and Hartford 1993; Brooks 1999; Zhou et al. 2003). Annual maximum NDVI value using maximum-value composite (MVC) can reflect the highest amount of fresh vegetation at a pixel. The increasing of dead vegetation will decrease the NDVI value at the pixel. So, we used the ratio between the current NDVI and annual maximum NDVI value to retrieve the degree of vegetation curing. And what is more the MVC method will minimize the effect of clouds, haze, off-nadir view angles, and other factors (Burgan et al. 1996). In this study, the degree of vegetation curing was calculated by:

$$P_{\text{curing}} = (1 - \text{NDVI}_i / \text{NDVI}_{\text{max}}) * 100\%, \quad (3)$$

where NDVI_i is the NDVI value of day i , and NDVI_{max} is the annual maximum NDVI value. We used the same MODIS image data and synthesis method that were used for LST to calculate the degree of vegetation curing.

3.1.3 Equivalent water thickness

Fuel moisture content is a key factor leading to fire ignition and has important implications regarding how far a fire will spread (Carlson and Burgan 2003; Maki et al. 2004). Remote sensing techniques provide an effective way to measure the temporal and spatial variation in fuel moisture content. Several metrics have been developed to measure fuel moisture content, such as fuel moisture content (FMC) (Mbow 1999), equivalent water thickness (EWT) (Danson et al. 1992), and relative water content (RWC) (Bowman 1989). EWT is defined as the ratio of the quantity of water to the leaf area (Danson et al. 1992):

$$\text{EWT} = \frac{\text{FW} - \text{DW}}{A} (\text{g}^{-1} \text{cm}^2), \quad (4)$$

where FW is the fresh weight of sampled vegetation, DW is the dried weight, and A is the total leaf area of the vegetation. Through the analysis of the spectral data and field data, EWT has a logarithmic relationship with the spectral reflectance of species of vegetations in the shortwave-infrared (SWIR) and the near-infrared (NIR) channels (Ceccato et al. 2001; Du 2006; Yu 2008). Those channels are the water absorption channels and account for variations in reflectance due to other biophysical factors (Zarco-Tejada et al. 2003). Ceccato et al. (2002b) used a regression line derived from model simulations to construct

Eq. (5) to calculate EWT by the satellite-derived index—global vegetation moisture index (GVMI).

$$\text{EWT} = \frac{-(ad + c - d(\text{GVMI} + 0.13)) + \sqrt{(ad + c - d(\text{GVMI} + 0.13))^2 - (4cd(a + b - \text{GVMI} - 0.13))}}{2cd}, \quad (5)$$

where a , b , c , and d are constant, with $a = 1.53$, $b = -1.40$, $c = -0.000099$, $d = 0.000517$. GVMI is defined as (Ceccato et al. 2002a):

$$\text{GVMI} = \frac{(\text{NIR} + 0.1) - (\text{SWIR} + 0.02)}{(\text{NIR} + 0.1) + (\text{SWIR} + 0.02)}, \quad (6)$$

where NIR is near-infrared channel, and SWIR is the shortwave-infrared channel. The GVMI is an index that “optimizes the retrieval of vegetation water content expressed in terms of quantity of water in the canopy per unit area and minimizes the perturbing effects of geophysical and atmospheric effects” (Ceccato et al. 2002a). Some studies have shown that GVMI is not influenced by species composition and therefore can be used to estimate many types of vegetation EWT with high precision, such as grass EWT and EWT for both deciduous and coniferous forests (e.g., Ceccato et al. 2002a, b; Du 2006; Yu 2008). In this study, the same MODIS image data and synthesis method that were used for LST and DVC were used to calculate GVMI and to estimate EWT.

3.1.4 Fuel weight

Fuel type and quantity can play an important role in determining fire type and intensity. Remote sensing has typically been used to map fuel load at the landscape scale (Carlson and Burgan 2003; Brandis and Jacobson 2003). Fuel weight is the dry weight of combustible materials (mainly vegetation) per unit area (kg m^{-2}), which can be estimated in three steps: (1) Remote sensing data such as Landsat TM data with pixel sizes of 30 m can be used to provide the information on the vegetation type and distribution in the study area; (2) The weight of fresh vegetation can be estimated combining the information on the vegetation type and distribution with the vegetation survey and previous studies (e.g., Piao et al. 2004; Zhao and Zhou 2004); and (3) The fuel weight can then be calculated based on the ratio of fresh vegetation weight to dry weight:

$$W_{\text{fuel}} = W_{\text{fresh}}/C, \quad (7)$$

where W_{fuel} is the fuel weight (kg m^{-2}), W_{fresh} is the weight of fresh vegetation, and C is a constant that respects the ratio of fresh weight to dry weight. Based on the vegetation survey and previous studies, the value of C was set corresponding to the main vegetation types (e.g., grass vs. shrubs) in the study area.

3.1.5 Degree of vegetation continuity

We included the degree of vegetation continuity in the assessment of fire danger rating because a higher degree of vegetation continuity may influence fire intensity and determine how far a fire spreads (Brooks 1999; Baeza et al. 2006). The degree of vegetation continuity was defined as (Zhou et al. 2003):

$$C_g = \left(\frac{\sum_{i=1}^N S_i}{N * S_T} \right) * 100 \%, \quad (8)$$

where S_i is the area of the vegetation patches i within a specific region (i.e., a grid cell with area of 100 ha), S_T is the total area of this region (i.e., 100 ha), and N is the number of the vegetation patches. Vegetation patches were derived from the same national vegetation yields data set that was used for fuel weights measurement.

3.2 Fire danger index model

Different methods have been used to construct fire danger index models, such as expert scoring (Zhou et al. 2003), principal component analysis (Mbow et al. 2004), analytical hierarchy process (Yin et al. 2005), fuzzy comprehensive judgment (Yu et al. 2002), multiple regression (Castro and Chuvieco 1998), and neural networks (Zeng et al. 2005). Following the selection of indicators for fire danger rating, we chose the analytical hierarchy process (AHP) to construct our fire danger index model. AHP is a decision-making method that can effectively transform semi-qualitative or semi-quantitative problems into quantitative problems (Saaty 1991, 1999, 2008). It provides a comprehensive and rational framework to structure a decision problem, to represent and quantify its elements and relate them to overall goals, and to evaluate alternative solutions (Saaty 2008). In addition, AHP allows more expert knowledge to be integrated into the modeling process and requires less data (Saaty 1999, 2008).

The procedure for using the AHP could be summarized as five steps: (1) model the problem as a hierarchy containing the decision goal; (2) establish priorities among the elements of the hierarchy by making a series of judgments based on pairwise comparisons of the elements; (3) synthesize these judgments to yield a set of overall priorities for the hierarchy; (4) check the consistency of the judgments; (5) come to a final decision based on the results of this process (Saaty 1999). Based on the previous research and expert knowledge, we established a two-hierarchy structure, priorities judgments for pairwise comparisons, and the judgment matrix A–C (Eq. 9).

$$\begin{pmatrix} A & C_1 & C_2 & C_3 & C_4 & C_5 \\ C_1 & 1 & 1/3 & 1/4 & 1/5 & 1/3 \\ C_2 & 3 & 1 & 1/2 & 1/3 & 1 \\ C_3 & 4 & 2 & 1 & 1/2 & 2 \\ C_4 & 5 & 3 & 2 & 1 & 3 \\ C_5 & 3 & 1 & 1/2 & 1/3 & 1 \end{pmatrix}, \quad (9)$$

where A was the fire danger index, C_1 was the degree of vegetation continuity, C_2 was the fuel weights, C_3 was the degree of vegetation curing, C_4 was land surface temperature, and C_5 was equivalent water thickness. The characteristic roots and vector for the judgment matrix A–C were found that the maximum of the characteristic roots is 5.057 and the corresponding characteristic vector was $W = [0.06, 0.14, 0.25, 0.41, 0.14]^T$. And then the consistency of the judgments was checked:

$$CR = \lambda_{\text{Max}} - n / RI(n - 1) = \frac{5.057 - 5}{1.12 * (5 - 1)} = 0.013 < 0.1, \quad (10)$$

where $CR < 0.1$ showed that the judgment matrix A–C had good compatibility and a reasonable level of consistency. Finally, the fire index model was constructed as the following:

$$\text{FDI} = 0.41 * \text{LST} + 0.14 * \text{EWT} + 0.25 * \text{DVC} + 0.06 * \text{VCD} + 0.14 * \text{FW}, \quad (11)$$

where FDI was the fire danger index, LST was land surface temperature, EWT was equivalent water thickness, DVC was the degree of vegetation curing, VCD was the degree of vegetation continuity, and FW was the fuel weights.

3.3 Fire danger classes

Using remote sensing data (e.g., MODIS and TM) and auxiliary information, the five fire danger indicators of LST, DVC, EWT, VCD, and fuel weight were retrieved and normalized to the range [0, 100], based on their maximum and minimum. The fire danger index data were calculated according to Eq. (11), and the range of its value was theoretically between 0 and 100. And then referring to the fire danger classification system of the PRC forest industry standard LY/T 1172–1195 (SFAC 1995), five fire danger classes, ranging from low to extremely high, were defined using the value of the FDI (Table 1). The fire danger classes were mapped for the study area (Fig. 2).

3.4 Statistical analyses

Fire danger indices are typically validated by (1) fire events, (2) meteorological data, and (3) fuel moisture content (Desbois et al. 1997). We used meteorological data to evaluate the effectiveness of the index. We chose meteorological data rather than fire events or fuel moisture content because (1) meteorological data are readily available and accessible to managers and (2) meteorological data were not used in the development of the index. In contrast, vegetation moisture content was used as a variable in the index and therefore is not appropriate for validation. While the best way to evaluate the effectiveness of the proposed index may be to use data representing previous fires (Desbois et al. 1997), it is very difficult, if not impossible for us to obtain accurate data of the fire events for our study area.

Statistical analyses were conducted to evaluate the effectiveness of the fire danger index. This was done by analyzing the relationships between the fire danger index and two meteorological variables from the weather stations, 10-day averaged air temperature and precipitation. Air temperature and precipitation are two important indicators in fire meteorological environment that are highly correlated with the occurrence of wildfires (Deeming et al. 1977; Forestry Canada Fire Danger Group 1992; Carlson and Burgan 2003). Higher air temperatures not only accelerate the process of desiccating fuel, but also increase fuel temperature, increasing the probability of fire ignition. In contrast, increases in precipitation can reduce the possibility of wildfires by increasing air humidity and fuel moisture content.

Table 1 The fire danger is classified into five categories and their descriptions are as follows

FDI value	Fire danger class
0–20	Low
20–35	Moderate
35–50	High
50–70	Very high
70–100	Extreme

Fig. 2 The fire danger rating maps for the study region from 2003 to 2004. Those maps are produced by the fire danger rating assessment, which show the distribution of fire danger in the study region. **a** Map of fire danger categories for the last 10 days of April 2003, **b** Map of fire danger categories in last 10 days of October 2003, **c** Map of fire danger categories in middle 10 days of January 2004, **d** Map of fire danger categories in last 10 days of January 2004, **e** Map of fire danger categories in first 10 days of February 2004, **f** Map of fire danger categories in middle 10 days of February 2004

Data of air temperature and precipitation collected at 21 weather stations in our study region were used in the statistical analyses (Fig. 3). In the selection of weather stations, we took into account: the representativeness of the data and trying to ensure that the stations could cover the entire region; and more stations in two fire-prone regions of eastern Inner Mongolia grassland area and Heilongjiang forest area. Fourteen fire danger rating maps from April 2003 to March 2004 were used in the statistical analyses. Based on the locations of 21 weather stations (i.e., longitude and latitude), the FDI values were extracted and combined with the corresponding meteorological data. The FDI values were combined with the corresponding meteorological data (10-day averaged air temperature and precipitation) to provide 294 data points for the following statistical analyses.

Two approaches, distribution analysis and correlation analysis, were used to analyze the relationship between FDI and each of the two meteorological variables. The distribution analysis was used to examine the distribution trend of FDI under different air temperature and precipitation conditions, while the correlation analysis was used to assess the correlation between FDI and the two meteorological variables. A Pearson's correlation analysis

Fig. 3 The distribution of selected weather stations. (The base map shows the degree of vegetation continuity in the study area, with lighter areas corresponding to a higher degree of vegetation continuity)

was developed to examine the relative strengths of correlations between FDI and the two meteorological variables.

With the distribution analysis, we first used the histograms of FDI, air temperature and precipitation to examine their overall distributions (Fig. 4a). We then investigated the distributions of FDI under the following air temperature and precipitation conditions: air temperature greater than (a) 0 °C and (b) 10 °C (where 0 °C was the value of the first peak in the histogram, and 10 °C was the value at the valley between the two peaks); and precipitation greater than (c) 25 mm, and (d) 35 mm. In addition, we examined the distribution of FDI under the condition of air temperature greater than 0 °C and precipitation <35 mm.

4 Results and discussions

4.1 Fire danger index and rating in the region

Using the fire danger index, fire danger rating maps with a frequency of 10 days were created from April 2003 to March 2004 for the study area (Fig. 2). Our results show that during this time period, the two fire danger ratings, “extreme” and “very high,” were most frequently observed from April to May 2003, as well as from September to October 2003. These two time periods coincide with peaks in forest fires (i.e., mid-March through mid-

Fig. 4 The distribution maps of FDI values in the different range of meteorological variables: **a** all; **b** air temperature was higher than 0 °C; **c** air temperature was higher than 10 °C; **d** precipitation was lower than 35 mm; **e** precipitation was lower than 20 mm; **f** air temperature was higher than 0 °C, and precipitation was lower than 35 mm

Table 2 Descriptive statistics value in the distribution analysis

Groups	Mean	Median	Max	Min	Std	Number
All	38.75	37.40	70.75	10.39	12.85	294
High temperature ($>0^{\circ}\text{C}$)	41.64	41.59	70.75	14.46	13.61	156
High temperature ($>10^{\circ}\text{C}$)	48.48	51.74	70.75	21.59	10.95	80
Low precipitation ($<35\text{ mm}$)	41.47	42.02	70.75	14.39	11.95	198
Low precipitation ($<20\text{ mm}$)	43.86	44.41	70.75	25.29	10.04	108
High temperature ($>0^{\circ}\text{C}$) and low precipitation ($<35\text{ mm}$)	42.58	42.27	70.75	15.56	10.59	90

June, and mid-September through mid-November) that have been recognized by the fire prevention department in Northern China (Ma 2003).

4.2 Statistical analyses

4.2.1 The distribution analysis

The histogram shows that the distribution of all FDI values followed a nearly normal distribution, with mean and standard deviation of 38.75 and 12.85, respectively (Fig. 4a; Table 2). For the group with air temperatures higher than 0°C , the mean of FDI was 41.64, with a standard deviation of 13.61; while the group with air temperatures higher than 10°C had a mean FDI of 51.72, with a standard deviation of 10.95. These results indicate that the FDI developed in this study is sensitive to changes in air temperature with higher air temperatures leading to higher fire danger ratings.

For the FDI group with precipitation $<35\text{ mm}$, the mean, median, and standard deviation were 41.47, 42.02, and 11.95, respectively (Table 2). For the FDI group with precipitation $<20\text{ mm}$, the mean, median, and standard deviation were 43.86, 44.41, and 10.04, respectively (Table 2). These results indicate that higher precipitation results in lower FDI values, suggesting an association between FDI and precipitation.

Figure 4f shows the distribution of FDI under the combined conditions of air temperature higher than 0°C and precipitation $<35\text{ mm}$ (i.e., a scenario where temperatures are high and precipitation is low). We compared this scenario to the FDI group with air temperature higher than 0°C (Fig. 4b) and the FDI group with precipitation $<35\text{ mm}$ (Fig. 4d) and found that the combination of high temperatures and low precipitation had a higher mean (42.58), median (42.27), and minimum (15.56). In addition, the FDI values were more concentratedly distributed.

4.2.2 The correlation analysis

The correlation analyses show that FDI was strongly correlated with both air temperature and precipitation (Table 3), suggesting the sensitivity of FDI to changes in air temperature and precipitation. Those correlations, however, are only moderately strong, with the correlation coefficients generally in the range of 0.4–0.6. This may be partly due to the fact that the five indicators that were used to calculate the FDI included not only meteorological variables, but also vegetation factors. In addition, correlation coefficients between FDI and the two meteorological factors varied by weather stations. A further analysis revealed a general pattern between those correlation coefficients and the degree of vegetation

Table 3 The absolute values of correlation coefficients between FDI and two meteorological variables for each of the 21 weather stations

Station ID	Station name	Air temperature	Precipitation	The value of degree of vegetation continuity
50136	Mohe	0.434	0.682	71
50246	Tahe	0.512	0.671	73.4
50442	Daxinganling	0.447	0.625	18
50557	Nenjiang	0.591	0.317	8
50564	Sunwu	0.614	0.352	6
50774	Yichun	0.525	0.219	9
50853	Beilin	0.533	0.348	4
50888	Baoqing	0.527	0.457	15
54094	Mudanjiang	0.518	0.461	11
54157	Siping	0.540	0.512	13
54181	Jiaohe	0.581	0.403	2
50434	Tulihe	0.537	0.397	35
50527	Hailaer	0.496	0.546	21
50639	Zhalantun	0.508	0.518	0
50727	Aershan	0.464	0.492	22.4
50838	Wulanhaote	0.431	0.473	55.6
50915	Dongwuzhumuqinqi	0.478	0.418	21
52378	Guaizihu	0.332	0.612	15
53192	Abagaqi	0.381	0.630	16
53336	Wulatezhongqi	0.296	0.624	31.2
54115	Linxi	0.317	0.535	15

The degree of vegetation curing for each station is also included ($n = 14$, $p \leq 0.05$)

continuity (VCD) at different stations (Fig. 5). The correlation coefficients between FDI and precipitation were larger than those between FDI and air temperature when the corresponding VCD was greater than 15, whereas the correlation coefficients between FDI and precipitation were smaller than those between FDI and air temperature when the corresponding VCD was <15 . These results suggest that precipitation has more influence on fire danger than air temperature in locations with greater vegetation cover (i.e., the VCD greater than 15). In areas with less vegetation cover, indicators of vegetation cover (e.g., DVC, EWT) had less influence on FDI values, while air temperature had stronger relationship with FDI. Previous studies (e.g., Ke et al. 2011) have showed that LST has a certain correlation with air temperature despite the effect from elevation, land cover, and season.

5 Summary and conclusions

Wildfires affect several million hectares of forest and grassland in China annually. To protect life, property, and natural resources from wildfires, a fire danger rating system is required for effective forest and grassland fire management. This paper presents the methods and results of using remote sensing to assess fire danger in Northern China, where

Fig. 5 The scatter diagram shows the relationship between the correlation coefficients and VCD at each weather station. X-axis shows the values of VCD, and y-axis shows the absolute values of correlation coefficients between FDI and air temperature or precipitation

grassland and forests are widely distributed and wildfires frequently occur. Using an analytical hierarchy process, a fire danger index was first developed based on five fire environmental factors, including land surface temperature, vegetation curing, equivalent water thickness, vegetation continuity degree, and fuel weight. Fire danger ratings were then mapped for the region based on the fire danger index. Data of these five factors were derived from satellite imagery, instead of point data from weather stations and ground measurements. Therefore, the fire danger index developed in this study can be used to explicitly reveal the spatial patterns of fire danger in a recurrent and consistent way over the large geographic areas. This is critical because of the very limited number of weather stations located in forests and grasslands, and the difficulty in ground measurements of fuel characteristics. The statistical analyses reveal the fire danger index was in strong relationship with air temperature and precipitation, suggesting the index is suitable for assessing the fire danger of forest and grassland in North China.

Acknowledgments This work was supported by the Special Foundation for Free Exploration of State Laboratory of Remote Sensing Science and Forestry Scientific and Technological Special Program of Commonweal industry (201304416). The meteorological data were acquired from China Meteorological Data Sharing Service System. Many thanks to Dr. Kirsten Schwarz at the University of California, Davis, whose careful review has greatly improved the language of the manuscript. We also thank Emilio Chuvieco, Marty Alexander, and Patricia L. Andrews, USDA, for sharing their papers and working documents. Finally, we wish to thank the two anonymous reviewers for valuable comments to the earlier version of the manuscript.

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