Spatial-temporal distribution of forest fires and fire weather index calculation from 2000 to 2009 in China

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ABSTRACT: This paper describes the forest fire dynamics in the city of Sanming in Fujian province, China, from 2000 to 2009 with a view to understand the number of fires and burned areas in different counties. It also includes the spatial-temporal distribution of fires and application of the Canadian Forest Fire Danger Rating System (CFFDRS). Daily forest fire data was provided by the Department of Wildfire Prevention of Sanming Forestry Bureau. FWI calculator v.7.0.2.76 was used in this study for analysing the weather parameter data. The results showed that a total of 818 fires and burned areas of 8721.16 ha were found during the study period of 10 years. However, the highest and lowest forest fires were found in Youxi county and Sanming district, respectively. Most of the fires with large burned areas occurred at 2 p.m. Moreover, occurrences of fires were found the highest and lowest in March and June, respectively. Based on FWI calculation, the highest danger rating value was found in March, 2009. This study proposes that it would be possible to manage regular forest fire occurrences through the application of CFFDRS. Finally, to plan the fire prevention and management in southern China and other tropical countries, this system has a great opportunity for further implementations.

Keywords: Sanming; spatial-temporal distribution; CFFDRS

Abbreviations: CFFDRS – Canadian Forest Fire Danger Rating System, FWI – Fire Weather Index, FFMC – Fine Fuel Moisture Code, DMC – Duff Moisture Code, DC – Drought Code, BUI – Build-Up Index, ISI – Initial Spread Index, DT – Datian, JL – Jiangle, JN – Jianning, MX – Mingxi, NH – Ninghua, SM – Sanming, SX – Shaxian, TN – Taining, QL – Qingliu, YA – Yongan, YX – Youxi

Forest fire becomes a major concern in the forestry of China after serious fire that occurred in Daxing'anling Mountain in May 1987. It caused great damage – 213 persons died and 1330 ha of areas were burned (Shu et al. 2003). However, in China, 13,600 forest fires with average burned areas of 758,000 ha per year have been recorded during the last 55 decades (Zhang, Qingwen 2008). Zhao (2003) mentioned that the annual fire area is about 0.8% of the whole forest area, which is eight times more compared to the world average level.

Understanding of the spatial and temporal variation of forest fires contributes to efficient forest fire management (Gonzalez 2005; Nonaka, Spies 2005). Kasischke et al. (2002) stated that the application of forest fire statistics including the number of fires and burn area is an effective method to understand forest fire characteristics. However, these perspectives have already been practiced in Canada (Asgary 2010), Israel (Wittenberg, Malkinson 2009), India (Kodandapani et al. 2008) and South Korea (Lee et al. 2006).

Liu et al. (2010) found that the variability of climate and weather influences not only the fire occurrence and spread behaviour but also fire severity at different time scales. Drought and rising temperature both are responsible for fire season lengthening, spreading and igniting. Several researchers remarked that the long-term atmospheric anomalies and forest fire activities have a close relationship (e.g. Swetnam, Betancourt 1990; Chu et al. 2002; Skinner et al. 2002; Hoinka et al. 2009).

Forest Fire Danger Rating System (FFDRS) is a well-developed and widely applied system that has been

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Table 1. Fire weather indexes according to the Canadian forest fire danger rating system (http://www.dnr.state.mn.us/forestry/fire/reports/canadian_indexes_f.html)

Danger rating	FFMC	DMC	DC	ISI	BUI	FWI
Low	0–81	0–13	0–80	0–4	0–19	0–5
Moderate	81–88	13–28	80–210	4–8	19–34	5–14
High	88–90.5	28–42	210–274	8–11	34–54	14–21
Very High	90.5–92.5	42–63	274–360	11–19	54–77	21–33
Extreme	92.5+	63+	360+	19+	77+	33+

practiced in Canada, Australia and United States for about 75 years (Stocks et al. 1989). Moreover, it is applied now mostly in Russia (Stocks et al. 1998), Mexico (Lee et al. 2002), New Zealand (National Rural Fire Authority 1993), Indonesia and Malaysia (William et al. 2006), and in European countries (San-Miguel-Ayanz et al. 2003). This system addresses several fire management problems such as occurrence time, spread and damage to resources.

In the 1980s, CFFDRS was introduced in China to control and manage forest fires (Taylor 2001). It has already been practiced in some provinces of Heilongjiang, Jilin, Inner Mongolia, Liaoning, and Yunnan to understand the fire danger ratings and fire prone seasons.

A set of customizable codes makes Canada's Spatial Fire Management System the only one in the world capable of being adapting to any scale, from local to global. The FWI System is based on weather parameters such as surface temperature, precipitation, relative humidity, and wind speed to show fire danger (van Wagner 1987).

All of these codes have numerical ratings like the Fine Fuel Moisture Code (FFMC) that measures the moisture content of the smallest forest fuels. The Duff Moisture Code (DMC) and Drought Code (DC) both indicate the average moisture content of loosely (2–10 cm) and deeply compacted (> 10 cm) organic layers on the forest floor, respectively. The Initial Spread Index (ISI) shows the expected rate of fire spread, the Build-Up Index (BUI) indicates the total amount of fuel available for combustion. The Fire Weather Index (FWI) shows the fire intensity that is used as a general indicator of fire danger. Maximum value of the FFMC is 101, but the DMC and DC both are 'open ended'. The values of fire behaviour indexes such as ISI, BUI increase as fire weather severity worsens (Tian et al. 2011). The fire weather codes and indexes with ranges are shown in Table 1.

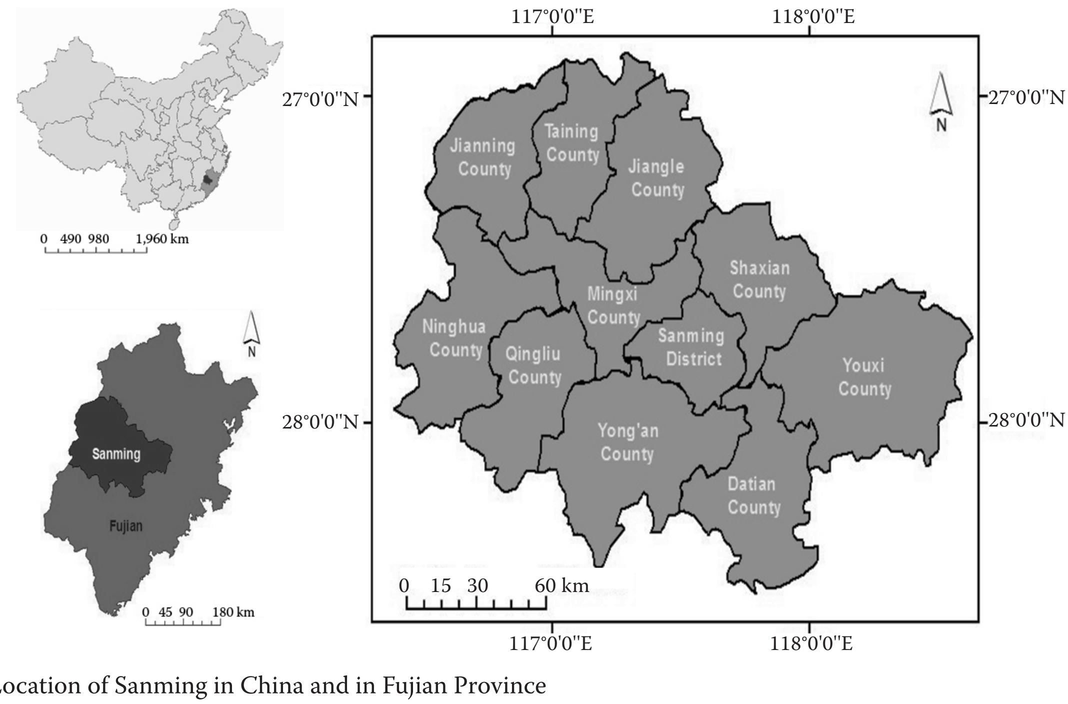

Fig. 1. Location of Sanming in China and in Fujian Province

Since the Fujian province of southern China is rich in biological diversity, every year it faces small to large fires due to availability of more combustible fuels on the forest ground. The objectives of this study are to identify a fire prone county in Sanming, and to compare the spatial-temporal distribution of forest fires. Moreover, it includes the calculation of CFFDRS codes and indexes.

MATERIAL AND METHODS

Study area

Sanming is situated in the northwest of the Fujian province, located at 116.22–118.39°E longitude and 25.30–27.07°N latitude (Fig. 1), and the total area of 2.31 mill. ha. It belongs to subtropical monsoon climate with high rainfall, mild climate, and long non-frost period with clear distinction of the four seasons. Annual average temperature is 17–19.4°C, average annual rainfall of 1,565–1,795 mm, maximum annual rainfall of 2,255 mm, and minimum annual rainfall of 1,131 mm as well as an average relative humidity of 79–94%. The forest area of the whole city is 1.90 mill. ha, and by 2000, forest cover in the city had already approached its upper limit with 71% of available lands being forested (Ying et al. 2010). About 76% of forest land is covered only by Chinese fir (*Cunninghamia lanceolata*) and Masson pine (*Pinus massoniana*). Low biological diversity hampers the ecological health of the Sanming forests (Song et al. 2004).

Data collection

The forest fire data from 2000 to 2009 was provided by the Department of Wildfire Prevention of Sanming Forestry Bureau. Each fire event record comes with a list of attributes such as fire location, fire classes and occurrence time (i.e. fire starting time). Weather parameters data which include temperature, humidity, rainfall and wind speed was collected from Taining (26°54'N, 117°10'E) and Yongan (25°58'N, 117°21'E) meteorological stations. Weather observation at noon every day is the input of the FWI system, and the temperature was estimated by subtracting 2°C from the daily maximum temperature (Williams et al. 2001). Rainfall, humidity and wind speed data was collected from these local weather stations.

Calculations for each code and index in this study using the initial value 85 for FFMC, 6 for DMC, and 15 for DC, are done because of the unavailability of initial values for all counties of Sanming. Regardless of the numbers that serve as the initial value it will not affect the final results of the calculation, therefore, this study will use the same initial values as a previous study conducted by van Wagner (1987).

Collected spatial-temporal data was calculated and presented in graphs using the SigmaPlot v.8.02 software. Fire Weather Index was calculated using FWI Calculator v.7.0.2.76 (SoftRock, Auckland, New Zealand). Moreover, the FFMC, DMC, DC, ISI and BUI were also calculated using this calculator.

FWI calculator v.7.0.2.76

SoftRock is the producer of this software, and currently freeware at this version. This application is useful to solve an immediate need, and in doing so developed well beyond its initial scope. FWI calculator provides several facilities such as forest type. It has been added so that the user can better select the closest match. Besides, this enhances FFDC (Forest Fire Danger Code) accuracy. Moreover, it manually accepts weather and environment data, and then calculates daily FWI, BUI, ISI, DC, DMC and FFMC. It saves weather data and FWI indexes in a recoverable data file, and displays charted data for FWI, FFMC, DMC, DC, ISI, BUI, and allows them to be saved to file.

RESULTS

Distribution of three classes of forest fires

Three classes of forest fires mostly occur in China, and these are Class I (burn area of < 1 ha), Class II (burn area of 1–100 ha) and Class III (i.e. serious fire, burn area of > 100 ha). In Sanming, from 2000 to 2009, there was a total of 818 forest fires. All classes of fire occurred in this period – 133, 674 and 11 fires for Class I, Class II and Class III fires, respectively (Table 2). Both Class I and II fires occurred in all counties except the Sanming district. Most of the fires occurred in Youxi and Datian counties. Among all counties, the highest number of serious fires with large burned areas was found in Datian. There were 6 fires and the total burned area was 2350.50 ha (Table 2). Moreover, the highest number of fires was recorded in Youxi followed by Datian, Yongan, Mingxi and Ninghua. On the contrary, the lowest number of fires and the smallest burned area were found in Sanming district.

Comparative analysis of forest fires

The forest fire data were grouped in two periods (i.e. either of the periods is 5 years, one is 2000 to 2004 and the other is 2005–2009). It was considered separately at a 5-year fire cycle to realize the changing pattern of total forest fires and burned areas.

In all counties, the number of fires and burned areas were increasing in the next 5-year period of 2005–2009 compared to the first period 2000–2004 (Fig. 2). However, within these 10 years, a remarkable number of fires and large burned areas were found in Datian, Mingxi, Qingliu, Shaxian, Yongan and Youxi counties. In the rest of the counties, there were few fires with small burned areas in this period. Although, within this period, the forest areas were burned in all counties but most of the areas were burned in Datian and Youxi counties from 2005 to 2009. However, closely similar burned areas in both periods were found in Jiangle, Jianning, Ninghua and Taining counties. Very small burned areas (only 2.70 ha) were found in Sanming district (Table 2).

Table 2. Forest fire statistics in the city of Sanming from 2000 to 2009

County	Total fire	Class			Burn area (ha)
		I	II	III	
DT	146	13	127	6	2,350.50
JL	42	4	38	0	438.40
JN	51	10	41	0	374.90
MX	85	13	72	0	524.32
NH	59	10	49	0	269.84
SM	12	12	0	0	2.70
SX	58	5	52	1	779.70
TN	52	9	43	0	305.80
QL	46	11	34	1	832.20
YA	95	12	82	1	1,139.10
YX	172	34	136	2	1,703.70
Total	818	133	674	11	8,721.16

DT – Datian, JL – Jiangle, JN – Jianning, MX – Mingxi, NH – Ninghua, SM – Sanming, SX – Shaxian, TN – Taining, QL – Qingliu, YA – Yongan, YX – Youxi

Spatial-temporal distribution of forest fires

Daily variation

In both periods, most of the forest fires occurred from 10 a.m. (i.e. starting time) to 5 p.m. It was mainly due to favourable weather conditions and continuous human activities. In Sanming, the highest number of fires occurred at 2 p.m., which was 78 and 86 fires in these periods of 2000–2004 and 2005–2009, respectively (Fig. 3). Considering the total burned areas, from 10 a.m. to 5 p.m., it was found 3105.78 ha for the first period and 4,490.50 ha for the second (Fig. 3). Within these periods, at 2 p.m., large burned areas of 982.80 ha were found in 2005–2009 whereas 807.60 ha in 2000–2004. Very small burned areas for both periods were found in the early morning from 12 a.m. to 6 p.m.

Monthly changes

Occurrences of fires were found higher in late spring and summer (January–April) compared to the other seasons in both periods. Moreover, few fires and small burned areas occurred in autumn (i.e. July–September) (Fig. 4). In winter (i.e. October to December), fire numbers and burned areas were found higher than in the rainy season (from May to June). In March, most of the fires occurred

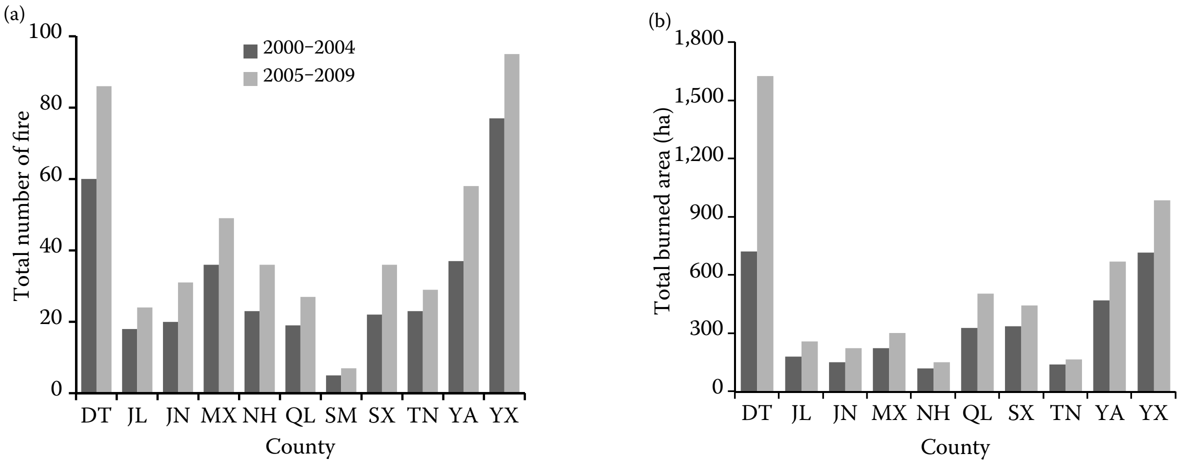

Fig. 2. Fire number (a) and burned areas (b) in two study periods

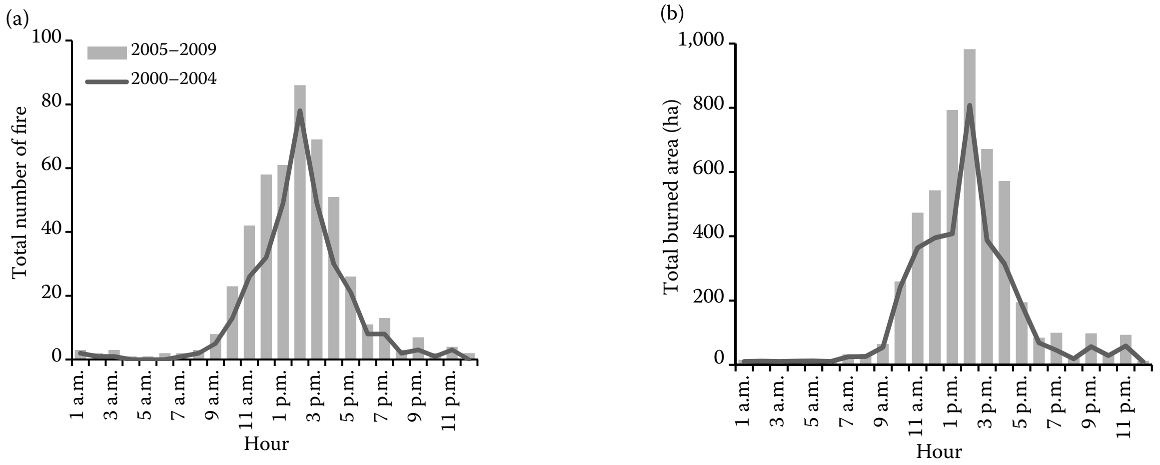

Fig. 3. Total number of forest fires (a), burned areas per day (b)

with large burned areas and it is followed by February and January. Moreover, the lowest number of fires and small burned areas was found in June. In March, there were a total of 102 fires and 1,407 ha burned areas in 2000–2004 and 167 fires with 1,669.40 ha in 2005–2009. The second and the third largest burned areas were found in February and January for both study periods. There were few forest fires and small burned areas in the rest of the months in these periods.

Annual distributions

In 2000, 124 forest fires and 1,922.20 ha burned areas were found in the first 5 years. In the following year, there was a decreasing trend of fire occurrences. From that year till 2004, fire numbers and burned areas were both increasing very sharply. The lowest number of fires and the smallest burned areas were found in 2006 during this 10-year period, which was only 15 fires and 102.20 ha (Fig. 5). However, fire number and burned areas were both increasing rapidly from 2007 to 2009. In 2009, fire numbers increased 4 times and burned areas increased 10 times compared to fire occurrences in 2007. Overall, in Sanming, it was observed that occurrences of fires were increasing regularly at a 5-year interval. Moreover, in this 5-year fire cycle, it is clear that if the fire occurrence rate is low in the first 2 years, it becomes high in the next 3 years.

FFMC, DMC, DC, ISI and BUI calculation

Calculating different codes and indexes, it was identified that March and June are the highest and the lowest fire danger months. According to danger rating, the extreme danger rating was found in March from 2005 to 2009, and the value range was 92.5+ for FFMC, 63+ for DMC, 360+ for DC, 19+ for ISI and 77+ for BUI (Table 3). In March, between 2000 and 2001, the danger rating was high, and the value range was 85–90.5 for FFMC, 28–42 for DMC, 210–274 for DC, 8–11 for ISI and 34-54 for BUI. Very high fire danger rating was found in March from 2002 to 2004. It amounted to 91.21, 90.20 and 88.18 for FFMC;

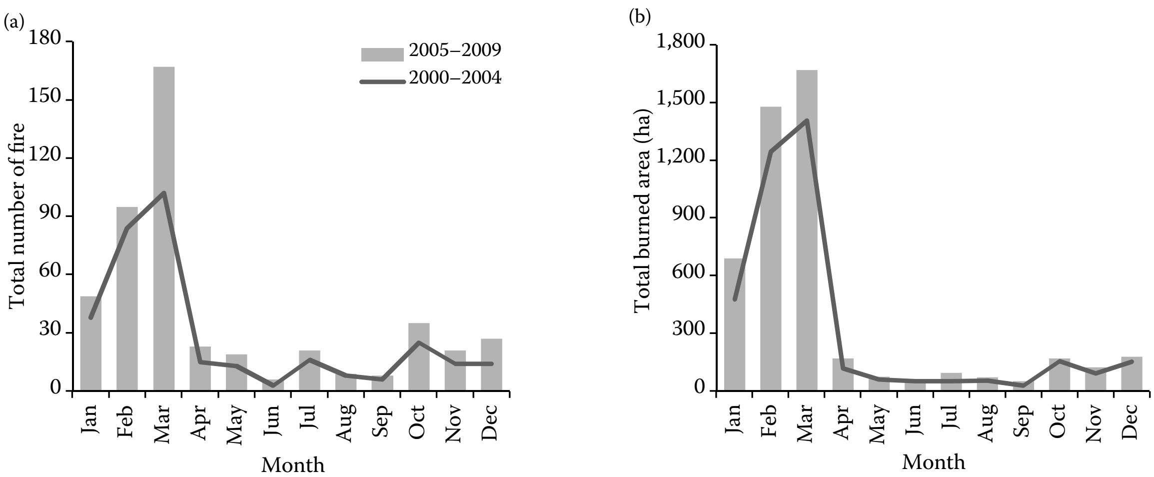

Fig. 4. Forest fire distribution with burned areas during twelve months

Table 3. FFMC, DMC, DC, ISI and BUI calculation

Year	Month	Codes and indexes				
		FFMC	DMC	DC	ISI	BUI
2009	March	97.06	68.55	408.55	22.45	114.03
2008		96.94	68.06	405.45	21.88	105.58
2007		96.76	67.03	390.06	21.79	100.74
2006		96.45	66.61	387.03	20.16	98.81
2005		93.36	63.39	384.23	20.01	90.23
2004		91.21	61.10	359.32	18.59	76.03
2003		90.20	57.29	355.65	18.50	72.81
2002		88.18	55.61	350.74	18.76	70.48
2001		87.61	41.23	248.45	10.35	51.26
2000		85.05	40.87	245.35	9.56	51.06
2009	June	73.16	19.63	73.60	1.57	23.37
2008		73.12	18.40	72.70	1.28	20.50
2007		72.22	18.30	71.93	1.25	20.37
2006		71.88	16.27	62.43	1.13	20.30
2005		69.95	16.23	61.83	1.11	19.00
2004		69.20	15.03	61.63	1.10	17.63
2003		68.03	14.90	57.10	1.09	17.57
2002		65.60	13.33	52.00	1.06	16.90
2001		64.18	13.23	45.17	0.98	15.80
2000		60.86	12.53	43.33	0.78	13.20

61.10, 57.29 and 55.61 for DMC; and 359.32, 355.65 and 350.74 for DC in 2004, 2003 and 2002, respectively. Moreover, for March, the ISI was 18.59, 18.50 and 18.76; and BUI was 76.03, 72.81 and 70.48 in 2004, 2003 and 2002, respectively. From 2000 to 2009, the lowest fire danger rating was found in June. Low danger rating was categorized as the value ranges 0 to 81 for FFMC, 0–13 for DMC, 0–80 for DC, 0–4 for ISI and 0–19 for BUI. However, in June 2000–2009, the FFMC value was increasing from 60.86 to 73.16, DMC from 12.53 to 19.63, DC from 43.33 to 73.60, ISI from 0.78 to 1.57, and BUI from 13.20 to 23.37.

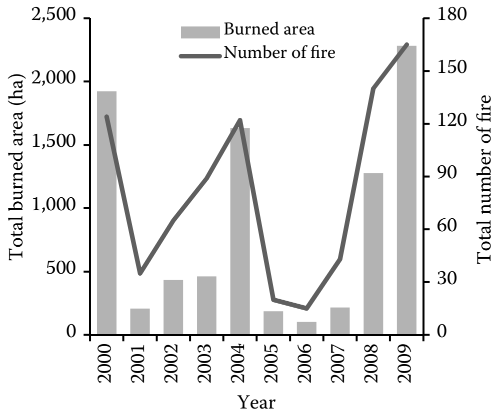

Fig. 5. Distribution of forest fires and burn areas from 2000 to 2009

FWI calculation

FWI calculations using four weather parameters from 2000 to 2009 are shown in Table 4. From 2000 to 2009, average FWI in January, February, March, June, November and December were found to be 50.64, 52.20, 56.02, 18.08, 25.74 and 25.15, respectively. March had the highest FWI, increasing from 2000 to 2009 (average value increased from 44.44 to 61.75). In this month, most of the fires during the 10-year period occurred. However, fire danger rating was extremely high at the beginning of the year, mainly in January, February and March. In 2000 and 2001, from April to December, the fire danger ratings were

Table 4. Fire Weather Index calculation in years

Month	2009	2008	2007	2006	2005	2004	2003	2002	2001	2000
January	57.90	55.02	54.64	53.49	51.67	51.52	49.88	46.94	43.96	41.38
February	59.27	57.36	56.38	54.45	53.45	53.38	50.84	49.58	45.90	41.42
March	61.75	60.54	60.48	59.16	57.85	55.65	54.82	53.18	52.29	44.44
April	45.20	39.17	34.25	30.80	27.83	25.25	25.10	24.14	16.94	15.49
May	38.65	37.34	31.45	30.13	21.66	18.97	13.71	13.31	12.64	11.63
June	26.62	24.28	23.39	21.15	20.80	18.16	13.53	11.40	10.84	10.60
July	32.50	30.76	30.68	23.31	22.95	21.43	19.11	17.00	16.23	10.97
August	32.21	30.47	29.96	23.30	21.61	21.40	19.09	16.94	15.86	10.45
September	23.70	22.70	22.53	20.41	20.91	17.88	12.08	11.20	10.18	10.12
October	41.31	37.28	32.94	30.89	21.51	17.95	17.71	14.92	13.82	12.66
November	35.26	34.83	34.44	32.35	22.70	21.15	20.67	20.27	18.46	17.28
December	37.55	36.11	32.78	24.84	23.87	23.48	23.39	19.69	18.36	11.41

high to moderate, and FWI value ranged from 10.12 to 18.46. However, from 2002 to 2009, the fire danger ratings for April, November and December were becoming very high to extreme (FWI value > 18.5).

During the ten-year study period, FWI value was found very high in the first three months. It was low between April and September, and it was also high between October and December. From January to April, high temperature and low rainfall were mainly responsible for high fire danger ratings. High rainfall with humidity from May to September caused low to moderate fire danger ratings in these months. The winter season with low humidity and heavy wind speed caused severe fires from October to December resulting in very high fire danger ratings with high FWI value.

DISCUSSION AND CONCLUSIONS

Understanding of forest fire distribution

Classification of fire danger rating area all over the country is considered very important to better understand fire occurrences and dangers. More attention to this classification was given by many countries. However, China started to practice it in 1950. In 1991, the Forest Inventory Design Institute under Ministry of Forestry classified three fire danger ratings based on the theory of the forest burning link (Zheng, Yao 1993). This classification depends on the following four factors: forest fire behaviour (fire occurrence and burn area), distribution and type of forest (dominant trees and forest cover), climate, and fire resource (population density and fire management). In Sanming, this classification was considered properly to understand the fire behaviour. Evergreen broadleaved forest and high combustible fuels were mainly responsible for regular fire occurrences in Youxi and Datian counties. High temperature and low rainfall in summer, and low humidity and high wind speed in winter during the last decade also caused large fires in Sanming. Moreover, highly populated and poor fire management system in this city was responsible for most of the fires. In Sanming, most of the forest fires occurred between 10 a.m. and 5 p.m. Huang (2009) and Liu et al. (2009) cited that most of the forest fires in the city of Wuyishan in Fujian province occurred from 11 a.m. to 2 p.m. A study conducted in Toronto, Canada, showed that the density of fire incidents is often changed by time (h), and afternoon and early evening hours seem to have the densest patterns of forest fire occurrences (Asgary et al. 2010). This study also revealed that the highest number of forest fires occurs in late spring and summer while the lowest number of incidents occurs in autumn. From our findings in Sanming, the late spring and summer season had a higher incidence of forest fires. In addition, dry weather, heavy sunshine, low humidity and high wind speed from January to April responded for this distinct difference of spatial-temporal forest fire characteristics.

CFFDRS and FWI

There is a close relationship between the forest fire occurrences and changes in weather parameters. The large forest fire results from dry conditions due to changes in humidity and temperature. Mike Flannigan, a Canadian Forest Service researcher, found out a positive relationship between the rising temperature and the increase in forest fires in Canada, and it is the same worldwide (Mukhopadhyay 2009). Valdiya (2006) reported that the increase in temperature increases the chance of fire occurrences whereas rainfall and humidity have the opposite relationship with fire.

The FFMC is commonly used as an indicator of fire starts (Martell et al. 1987; Anderson, Englefield 2001). The FFMC scale ranges 0–99 with higher values indicating drier fine fuels and greater fire danger. The data showed a general increasing trend of FFMC to the highest 97.06 in March, 2009 (Table 3). It was reflected by the progressive drying of fine fuels resulting in the large number of forest fires during that time in Sanming. A gradual increase in FFMC value 2000–2009 appears to indicate large fire occurrences with fine fuels on the landscape leaving a potential to burn.

FWI is usually used to indicate the fire intensity for most of the fuel types. It is a combination of the fire spread rate of ISI input and the total fuel consumption rate of BUI input (William et al. 2006). Results showed that forest fires and burned area increased from 2000 to 2009 when average FWI > 50. When average FWI < 27 during the ten-year study period, there were very few forest fires occurring in Sanming. To provide early warning, the CFFDRS identifies classes of increasing fire danger as the FFMC, DC, and ISI approach these key threshold values.

Recommendations

Based on this research it is recommended to set up more weather stations at different elevations and slopes, and to collect weather and forest fire data daily. To estimate the burn area and forest volume, use the FWI calculator at weather stations to calculate the fire codes and indexes, also save the fire data electronically.

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