ASSESSING THE TEMPORAL AND SPATIAL DYNAMICS OF THE FOREST FIRES IN SOUTHEASTERN CHINA

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Abstract. This study presented the distribution of the largest forest fires in the area of Sanming, Fujian province of China from 2000 to 2009 and focused on the spatial and temporal dynamics of forest fire occurrences. The fire location distribution, occurrence causes, and daily, monthly and annual distribution of fires influenced by weather were examined. The weather data was analyzed using the software FWI Calc. v.10.3.1.106. There were a total of 818 forest fires occurred in the period 2000-2009 that burned 87 million m^2 of forests; the fires have been detected during the fieldwork. The time distribution of forest fire occurrence had a regular pattern daily, and most forest fires occurred between 9 a.m. and 5 p.m., accounting for 92.42% of total fires. It was found that drier and warmer weathers provided favorable conditions for forest fire occurrences, and the majority of serious fires were occurred between 2008 and 2009, which was a period with relatively dry and warm weather. Significant relationships between forest fire occurrence and weather were determined in the study. Because of human activities and more combustible species in Youxi and Datian counties in the Sanming area, the two counties had the highest fire risks.
Keywords: *fire dynamics, forest meteorology, weather parameters, Fire Weather Index (FWI), Canadian Forest Fire Danger Rating System (CFFDRS), Sanming*

Introduction

Over the last decades, scientists and forest managers have begun to explore the emulation of forest fire disturbance in managing forest landscape (Seymour et al., 2002; Cleland et al., 2004; Nitschke, 2005; Ekoungoulou et al., 2017) because forest fire is a key process in regulating vegetation succession, plant regeneration, and maintaining biodiversity in many forest ecosystems (Rollins et al., 2004; Ekoungoulou et al., 2018b). Trees, the major components of forests (Ekoungoulou et al., 2014a and 2014b), absorb large amounts of atmospheric carbon dioxide by photosynthesis (Ekoungoulou et al., 2015), and forests return an almost equal amount to the atmosphere (Ekoungoulou et al., 2018c) by auto-and heterotrophic respiration (Ekoungoulou et al., 2014b and 2014c). Understanding the spatial and temporal variation of forest fire provides a long-term perspective of dynamics of ecosystem processes and vegetation patterns (Gonzalez, 2005; Nonaka and Spies, 2005). Use of forest fire statistics, including records of ignition sources, number of forest fire occurrences, and burnt area, is an effectual method to understand the spatial and temporal characteristics of forest fire (Kasischke et al., 2002; Liu et al., 2015). Variability of climate and fire weather also influences forest fire behaviors and the fire severity at various time scales (Liu et al., 2010).

Different geographical, topographical, and climatic characteristics exist across the vast landmass of China; as a result, forest fire regimes would vary spatially in the

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country. Forest fire has been a serious issue in China's forest management; in the period 1950-2000, there were 13,600 fire occurrences per year in China. The yearly average of burned area in the period was approximately 758,000 ha, according to the official report from the China's forestry bureau (Zhang and Qingwen, 2008). Because of climatic differences across China, fire season varies in major forest regions. In the Northeastern China and Inner Mongolia, fire season lasts from spring to autumn. Fire season is from winter to spring in the southern and southwestern China and from summer to autumn in the northwestern China. In China, wildland fires are not distributed uniformly over the country; most of the fires occurred in approximately 100 key counties from 16 main forestry regions (Guo and Fu, 2007). Also, the number of forest fires in China and the burnt area fluctuated largely annually, and the burnt area was over 1 million ha in years 1951, 1955, 1956, 1961, 1962, 1972, 1977, 1987 and 1996 (Zhong et al., 2003).

The increase of human population and human activities has resulted in an increase in forest fire frequency (Guo and Fu, 2007). As modern society has encroached on forests and thereby forest fires threaten the regional economy and the safety of residents, forest fires have become an important issue socially as well as scientifically (Kalabokidis et al., 2002). From the statistical data reported by the Ministry of Forestry, China in 1999, most wildland fires are caused by non-productive fire utilizations such as smoking (accounting for 40.6%). The rest were caused by productive fire utilizations such as prescribed fires for land reclamation (30.9%), lightning and other natural disasters (0.38%), arson (1.52%), and others (21.18%) (Anon, 1999). There is no doubt that much progress has been achieved in forest fire prevention and protection in China since the foundation of the new China (Lifu et al., 2003). However, with the fast growing economy in China, the present situation of forest fire protection is becoming even more urgent. Therefore, the forest fire study in Sanming becomes important. The study focused on spatial and temporal fire distribution, ignition causes, and the influence of temperature, humidity, precipitation and wind speed on forest fire occurrence. The study can help develop local fire management and forest fire prevention projects.

Materials and Methods

Study site

Sanming is located in the northwest of Fujian Province, between 116.22 to 118.39 °E and 25.30 to 27.07 °N, with ~230 km from east to west and ~180 km from south to north (*Fig. 1*). The total area of Sanming is approximately 22,900 km^2, including the urban area of 1,178 km^2. Mountainous area farm land, river and others account for 82%, 7.3%, 8.7%, and 2% of Sanming city, excluding the urban area. Sanming belongs to a sub-tropical climate of monsoon with considerable precipitation and clear presence of four seasons. Annual mean temperature is between 17-19.4°C; average annual precipitation is from 1,565 to 1,795 mm with the maximum annual precipitation 2,255 mm and the minimum annual precipitation 1,131 mm, and average relative humidity is between 79 to 94%.

The forest cover of the city is around 28.26 million hm^2, and by the year of 2000, the forested area in the city had already reached its upper limit with 71% of available lands being forested (Guo and Fu, 2007). Chinese fire (*Cunninghamia lanceolata* (Lamb.) Hook) and Masson pine (*Pinus massoniana* D. Don) account for 76% of the forested area. The dominance of the two species resulted in an overall lack of bio-diversity and

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an increasing challenge to the ecological health of the forest in the city (Huang, 2009; Song et al., 2004).

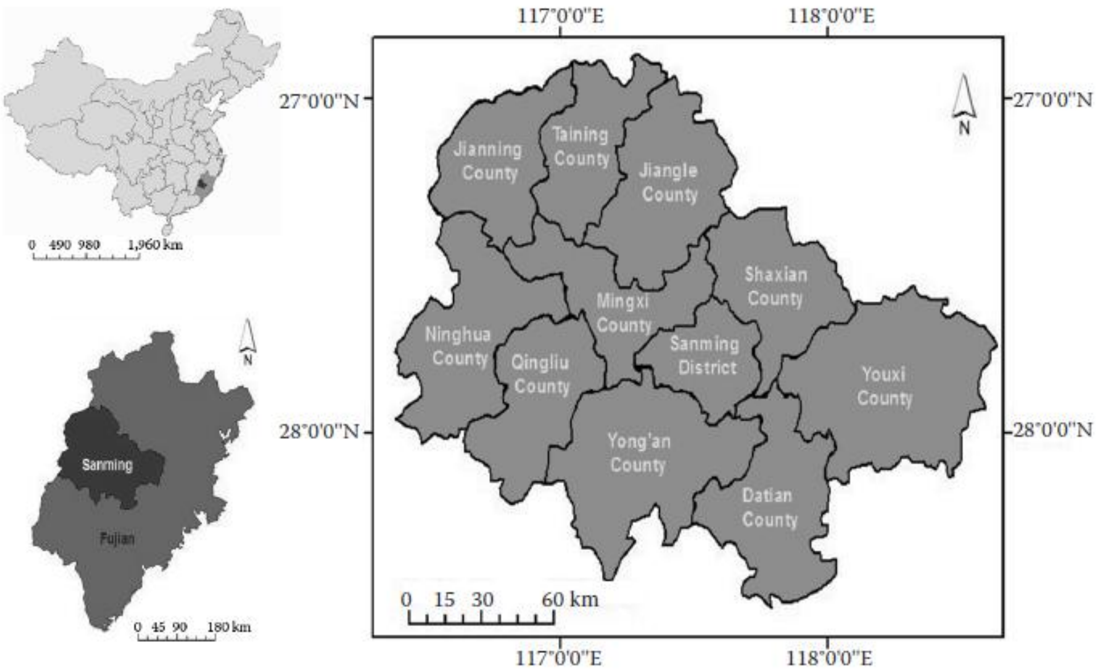

***Figure 1.** Location of Sanming city and Fujian Province in Southeast China*

Data collection

In this study we used fire occurrence records provided by the Administrative Divisions of Fujian Province from 2000 - 2009. Each record consists of fire information such as fire locations, fire severity classes, ignition causes and the date of fires. Weather data of temperature, relative humidity, precipitation and wind speed were collected from the Yong'an Meteorological Station, which is located at 117.21 °E longitude and 25.58 °N latitude with the elevation of 206 m. Both fire dandy weather data were analyzed using statistical software Minitab 2002 to find out relationship between forest fire occurrence and weather conditions. The spatial and temporal analyses were conducted using the software FWI Calculator v.10.3.1.106 and the graphic results were prepared using the software SigmaPlot v.10.0.

Data analysis

The Fire Weather Index (FWI) system is the first part of Canadian Forest Fire Danger Rating System (CFFDRS) introduced into New Zealand in 1980. It has proved to be a suitable fire danger rating system for the country. The FWI was evaluated for several seasons before it was introduced for the 1980-81 fire season. FWI is based on weather readings taken at noon standard time and it rates fire danger at the midafternoon peak from 2:00 - 4:00pm. Weather readings required include the air temperature in the shade, relative humidity in the shade, wind speed at 10 meters aboveground level for a mean over 10 minutes; rainfall for the previous 24 hours. FWI calculator v.10.3.1.106 can read the weather input file every 15 minutes after the initial midday reading. If the

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weather station software keep updating this file (e.g., every 10-15 min), FWI Calculator will record the peak temperature and other relevant weather values. The FWI System outputs three moisture codes: the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC), with higher values indicating drier conditions and greater fire danger. The FWI System also generates four fire behaviour outputs based on the above indices: the Initial Spread Index (ISI), the Build-Up Index (BUI), the Fire Weather Index (FWI), and the Daily Severity Rating (DSR), with higher values indicating elevated fire danger. A fire danger rating system should act as a tool on tracking the day-to-day susceptibility of forests to fire, or the system should enable fire managers to properly assess the levels of preparedness and the suppression resources needed to keep fire losses to a minimum. The system should be capable of measuring weather variations that cause the day to day changes in fire danger. The fire danger information provided through the system can be used to define the fire season (Liu et al., 2015), determine appropriate fire prevention measures, assess the likelihood of fire occurrence, determine fire suppression response and resources deployment, inform public, make decisions to close areas at high risk, issue or cancel burn permits, plan and conduct controlled burns.

The graphic results have been prepared using the SigmaPlot v.10.0 (Ekoungoulou et al., 2018a) software. Analysis of Variance (ANOVA) was used (Ekoungoulou, 2014) to test possible differences between fire occurrence among different months and years. Fire ignition causes and their spatial distribution were showed as topographic maps using the version 9.3 of ArcGIS software.

Results and Discussion

Spatial distribution of three classes of forest fire

Spatial distribution of forest fires in Sanming was showed in *Table 1*, and the fires were categorized into three classes. Class 1 means fire warning, Class 2 means ordinary fire, and Class 3 indicates serious fire. According to this classification scheme, the fires that burn less than 1 hm^2 are classified as Class 1 fire; the fires that burn between 1 hm^2 and 100 hm^2 are Class 2 fires, and Class 3 fires are the ones burn more than 100 hm^2. There were 133 Class 1 fires, 674 Class 2 fires and 11 Class 3 fires occurred in Sanming between 2000 and 2009, respectively, and total fire area and total burnt areas in this period were 11,730.27 hm^2 and 8,721.16 hm^2, respectively. In the southeastern Youxi and Datian counties, Class 3 fires occurs more frequently than in other counties, and burnt areas in the two counties were relatively large compared to other counties (*Fig. 2*). There were 172 and 146 fires, and burnt areas were 1,703.70 and 2,350.50 hm^2, respectively in Youxi and Datian counties from 2000 to 2009. So, Datian counties was considered the highest vulnerable to forest fire in Sanming city during the study period. The results revealed that Classes 1 and 2fires distributed in all countries, but only Class 1 fires occurred in the Sanming district from 2000 - 2009.

Ignition causes

According to the statistical data of forest fire occurrences in the last 10 years in Sanming, a substantial number of forest fires were caused by human. *Fig. 3* indicates that 64.97% of fires were caused by waste-land-burning, followed by 9.41 of careless smoking, 4.48% of fire from outside, 3.47% of children-playing-fire, and lightning of

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0.82%. Clearly, most forest fires in Sanming are caused by human activities, whereas lightning only cause a small number of forest fires. Waste land burning is the major causes of forest fire in Sanming, and such caused fires were unevenly distributed in the study area. A total of 462 fires were caused by waste-land-burning; among these fires, 60 were Class 1 fires; 398 were Class 2 fires, and only four Class 3 fires, respectively. *Fig. 4* indicates that most of waste-land-burning fires were n Youxi (172 cases) and Ninghua (95 cases) counties, and in the two counties human disturbance was mainly cause for forest fires. The spatial and temporal changes of forest fires in the study are studies in the following aspects: daily changes, monthly and seasonal variations, and annual changes.

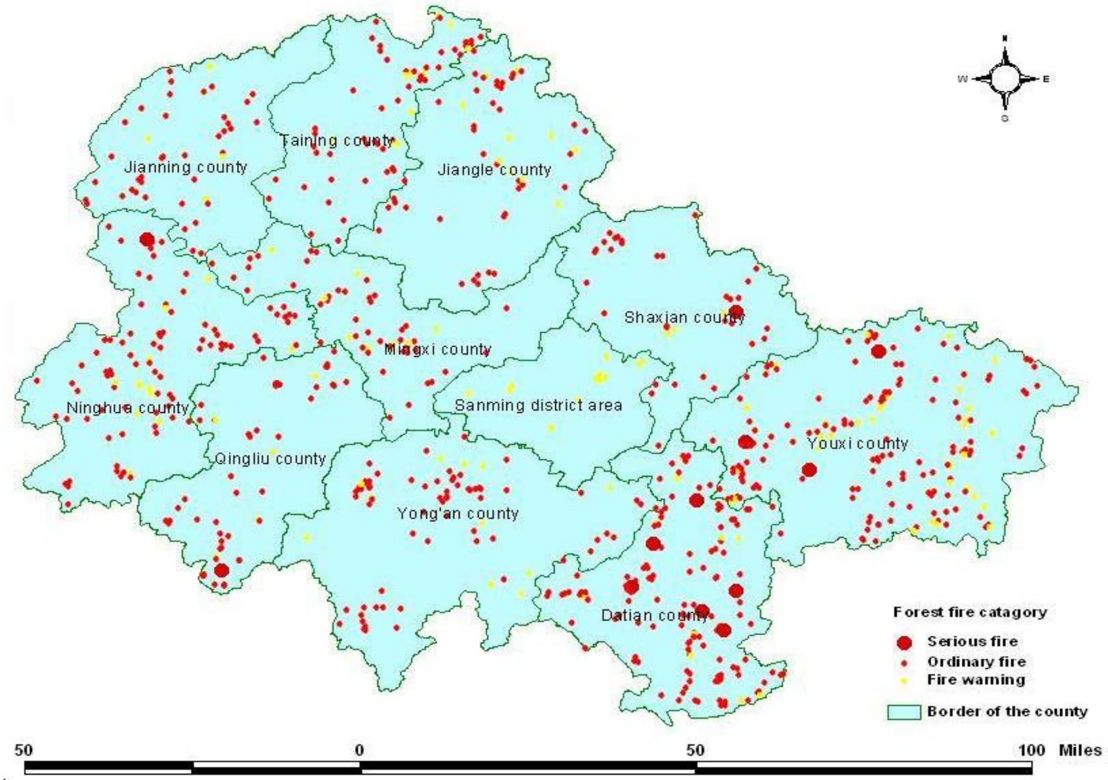

Figure 2. *Spatial distribution of three classes of forest fire the study area*

The daily variation of forest fires

In the *Fig. 5a*, it was found that most of the forest fires occurred in Sanming between 9 a.m. to 5 p.m., and during this time period 92.42 % of the total fires, or 161 fires, occurred at 2 p.m with a burnt forest area 2,271.10 hm^2 (*Fig. 5b*). No fire has ever occurred from 1:00 am to 5:00 am, and only nine fires occurred between 5:00am to 6:00am. This is because there were almost no human activities in such time period daily and weather at such times were relatively cool.

Fig. 5c and *Fig. 5d* showed the temporal distributions of fire frequency and burnt area along the day time from 1:00am to 11:00pm. The fires caused by waste land burning peaked mainly from noon to 3 p.m., with a total of 308 fires burnt 5,213.90 hm^2 areas. The fires with unknown causes occurred from 9 a.m. to 9 p.m. with a total of 108 fires and a burnt area of 1,207.70 hm^2, which were comparatively lower than those of

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the waste land burning fires. Lightning-caused fires mainly occurred from noon to 5 p.m., and the total burnt area was 120.10 hm^2.

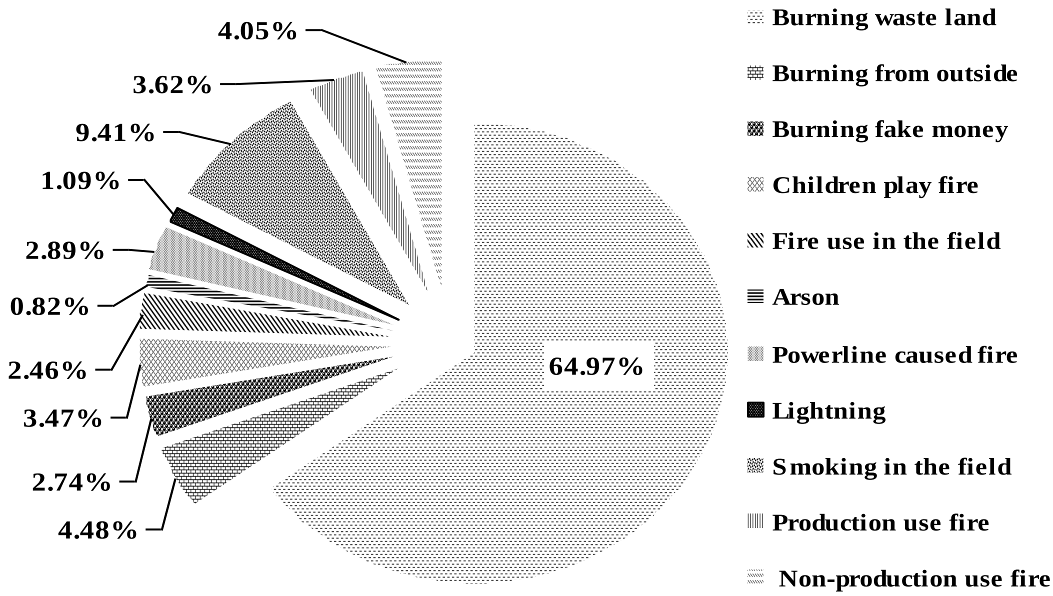

Figure 3. *Causes of forest fires in Sanming during the years 2000 – 2009*

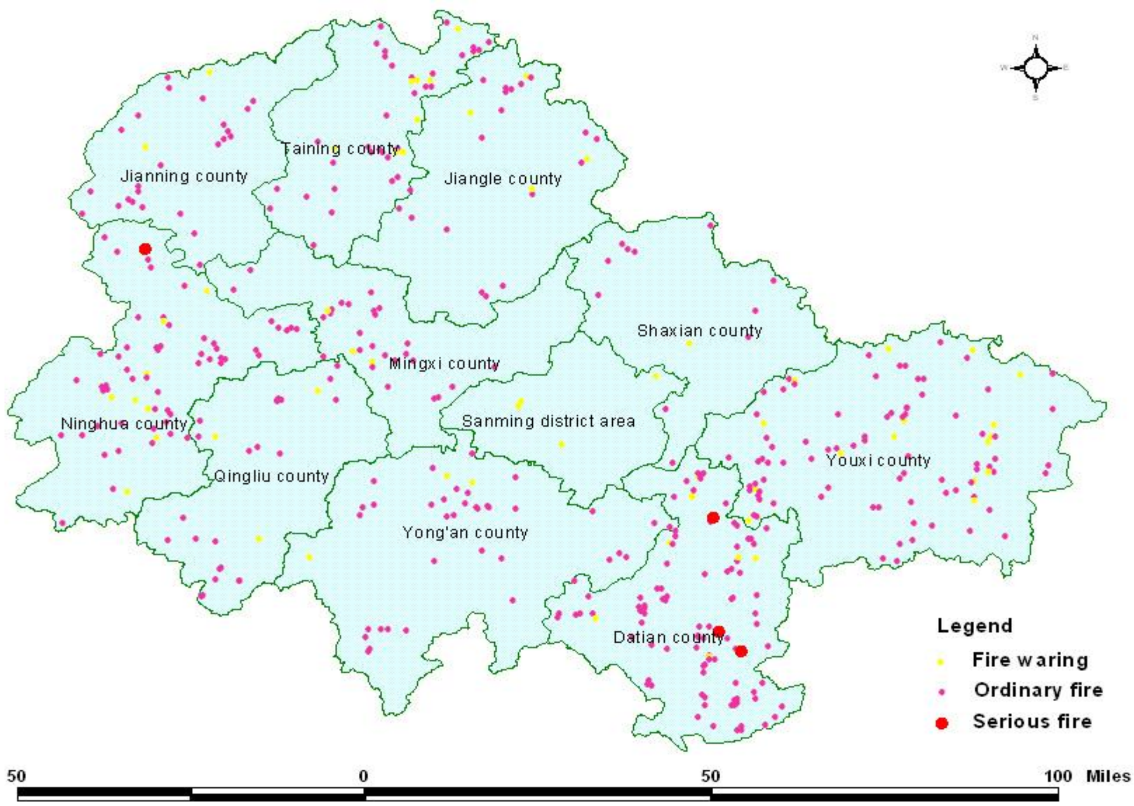

Figure 4. *Forest fire occurrences in Sanming due to burning waste land*

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Table 1. *Forest fire statistics in Sanming between 2000 and 2009*

Study Area	Number of fire	Forest fire classes			Fire area (hm^2)	Burnt area (hm^2)
		Class 1 Fire warning	Class 2 Ordinary fire	Class 3 Serious Fire		
Datian	146	13	127	6	3528.00	2350.50
Youxi	172	34	136	2	2442.10	1703.70
Yong'an	95	12	82	1	1315.50	1139.10
Qingliu	46	11	34	1	1027.60	832.20
Shaxian	58	5	52	1	946.00	779.70
Mingxi	85	13	72	0	774.90	524.32
Jiangle	42	4	38	0	512.80	438.40
Jianning	51	10	41	0	480.10	374.90
Taining	52	9	43	0	384.30	305.80
Ninghua	59	10	49	0	311.27	269.84
Sanming	12	12	0	0	7.70	2.70
Total	**818**	**133**	**674**	**11**	**11730.27**	**8721.16**

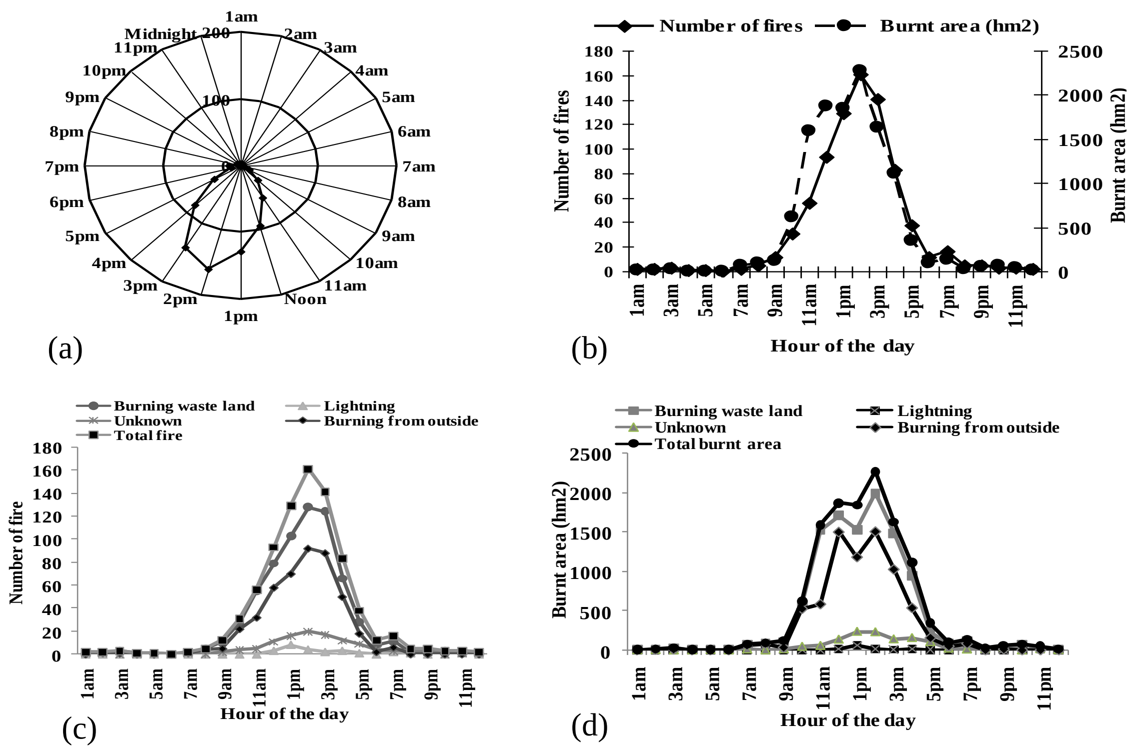

Figure 5. *Forest fire and burnt area distributions in a day time*

Monthly change of forest fire

As *Fig. 6a* indicates, over the 10-year period 2000- 2009, fire frequency was higher in spring (January-March) than in other seasons., because during the period of January-March weather are relatively dry and relative humidity are low (*Fig. 6b*). March is the month with most forest fires occurred and large areas burned, followed by February and

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January. During the period 2000-2009, there were 269 fires occurred in March that burned 4,976.40 hm^2, which accounted for 33% of fire occurrences and 41% of total area burnt, respectively. February and January were ranked as the second and third in terms of fire frequency and areas burned; there were 179 fires in February with an area burned of 3,730.50 hm2, which accounted for 22% of total fire occurrences and 31% of areas burned. The same figures for January were 87 and 1,170 hm^2, which were 11% of total occurrences and 10% of areas burned.

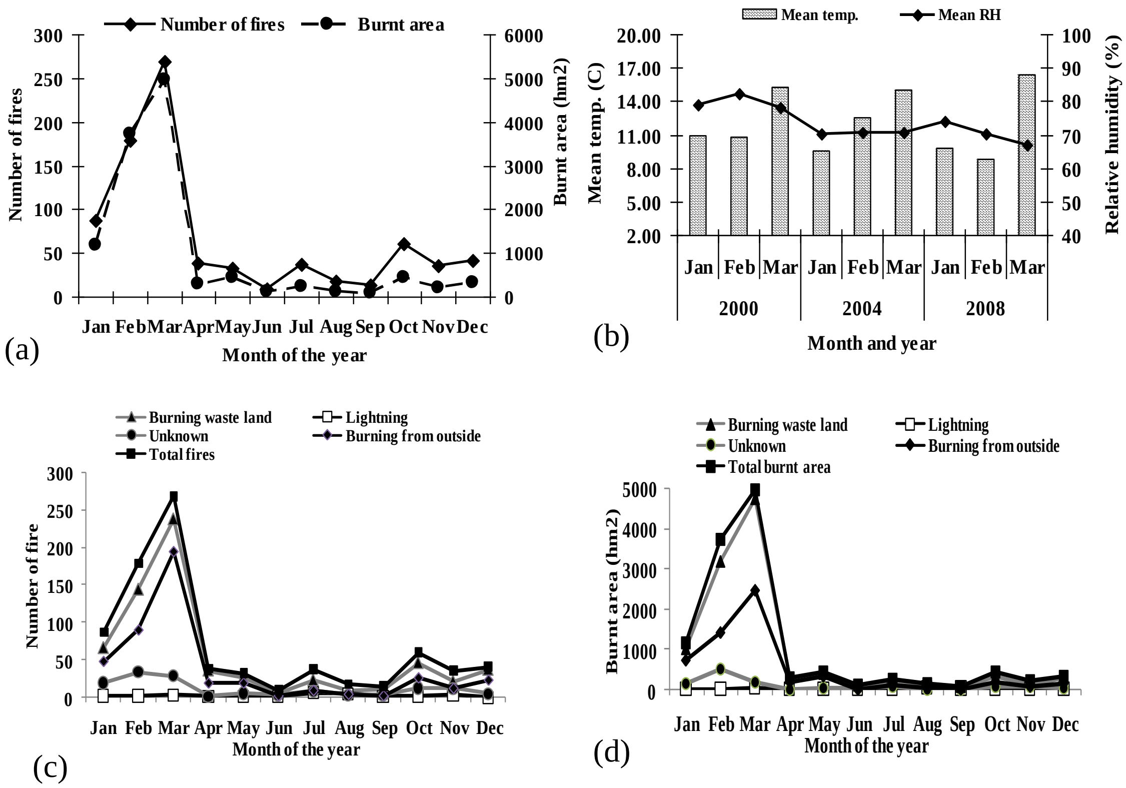

Figure 6. *Forest fire and burnt area distribution in the month of the year*

Fig. 6c and *Fig. 6d* contain the monthly distributions of fire frequency and areas burned by different ignition causes. Waste land burning for crop production and burning from outside sources were major ignition causes that accounted for about 70% of total fire occurrences 84% of all area burnt in three months from January to March. The period of May to December appeared to be the time least prone to forest fires. The fires of unknown causes were most likely to occur in the beginning months of a year and the frequency of such fires was highest in February. Lightning-caused fires were the least serious in the study area.

Forest fire annual distributions

Fire situations varied from year to year in the period 2000-2009, and the statistics showed in *Fig. 7a* and *Fig. 7b* suggested that the years with more than 100 forest fires and an area more than 1,500 hm^2 were 2000, 2004, 2008 and 2009. Other years suffered less forest fires. Waste land burning, burning from outside sources, and unknown causes were the three major ignition causes. The severity of such fires was raising from 2007,

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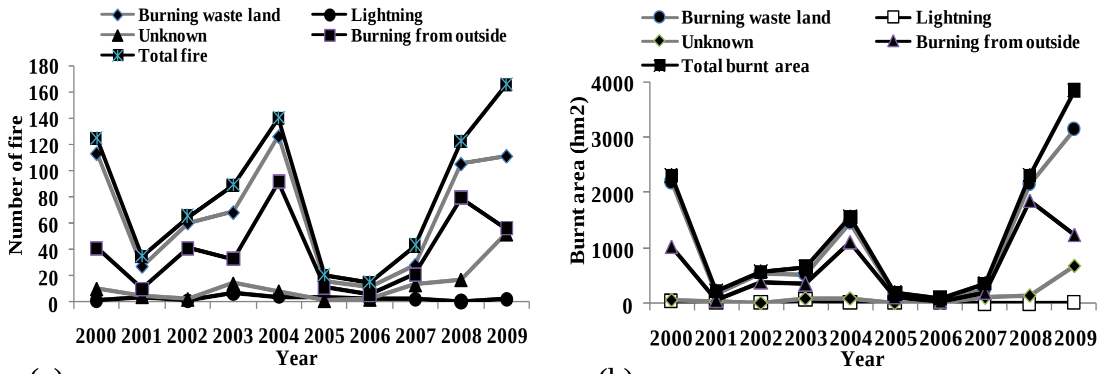
and in 2009 the total forest occurrences and areas burned by such fires were 165 and 3,861.30 hm^2, respectively.



(a) (b)

Figure 7. *Forest fire annual distributions in Sanming*

Influence of forest fire by weather parameters

Forest fires are more likely to occur when it is dry and less likely to occur when it is wet and with low temperature. *Fig. 8a* and *Fig. 8b* depicted decreasing trends of rainfall and relative humidity caused by increasing trends of temperature and wind speed. Such weather change patterns lead to a dry weather condition that favors more forest fire occurrences. All serious fires occurred in the day time between 10:30 and 16:15 hours because of dry and warm weather during this time period of the day. In Sanming, most of serious fire occurred in 2008 and 2009 in the early noon when temperature is maximum (> 29°C), wind speed reaches > 3 m/s, and relative humidity is low with no precipitation (*Table 2*).

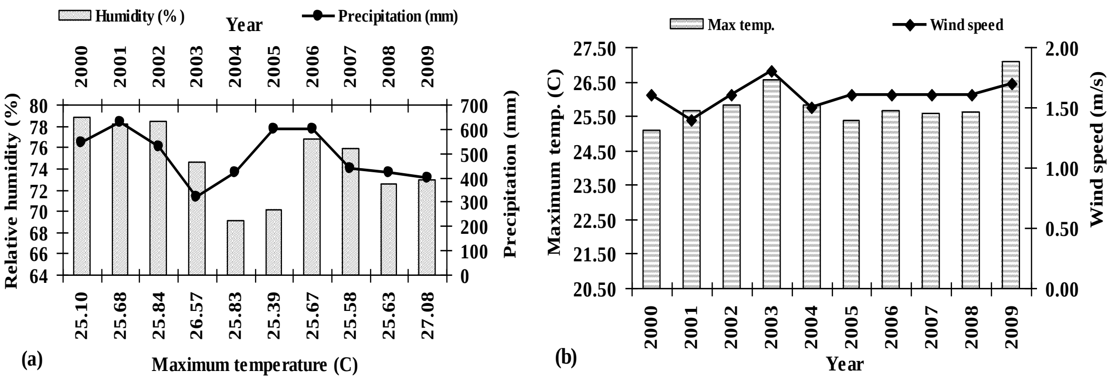


Figure 8. *Weather parameters change trend in Sanming between 2000 - 2009*

Table 3 consisted of the F-test results on annual and monthly forest fire distributions. Have significant relationship with changes of temperature, precipitation, relative humidity and wind speed, and such atmospheric movement prone to highest forest fires in Sanming.

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Table 2. *Serious forest fire occurrences in Sanming during the study period*

Sl. No.	**Date (Year/month/day)**	**Time (24 hours)**	**Area burnt (hm^2)**	**Maximum Temperature ($^{\circ}C$)**	**Relative humidity (%)**	**Precipitation (mm)**	**Wind speed (m/s)**
1	2000-03-28	11:53	179.50	30.6	50	000	1.5
2	2000-03-28	13:30	236.10	30.6	50	000	1.5
3	2008-03-02	12:40	254.00	23.7	55	000	1.4
4	2008-03-03	12:10	265.50	23.6	48	000	1.3
5	2008-03-04	10:30	170.00	22.3	48	000	1.6
6	2008-03-04	12:50	113.90	22.3	48	000	1.6
7	2009-01-18	14:30	185.80	23.7	65	000	0.9
8	2009-02-12	13:40	176.10	29.2	50	000	3.5
9	2009-02-12	16:02	294.60	29.2	50	000	3.5
10	2009-02-12	11:30	287.00	29.2	50	000	3.5
11	2009-02-12	11:20	498.70	29.2	50	000	3.5

Table 3. *Statistical analysis showed relationship between forest fire and weather parameters*

Analysis (95% confidence interval)			
	F	P	Remark
Forest fire annual distributions	1.64	0.078	Significant
Forest fire monthly distributions	1.18	0.002	Significant
Effect of temperature on forest fire occurrences	1.28	0.032	Significant
Effect of relative humidity on forest fire occurrences	1.39	0.067	Significant
Effect of precipitation on forest fire occurrences	1.45	0.042	Significant
Effect of wind speed on forest fire occurrences	2.20	0.012	Significant

Sanming zoning map based on fire proneness

Sanming can be divided into three zones based on fire proneness, i.e., the high risk zone, the reasonable risk zone, and the low risk zone (*Fig. 9*). The southeasttern Youxi and Datian counties are delineated as the high fire risk zone (Class I fire danger area) because of high human disturbance and concentrated distribution of more combustible Masson pine forests. The reasonable risk zone (Class II fire danger area) includes the northwestern Jianning, Mingxi, Ninghua, Qingliu, and South Yong'an counties; the human disturbance in these counties is minimal and the area has been covered by less flammable Chinese fire forest. Taining, Jiangle, Shaxian counties and Sanming district belong to the low risk zone (Class III fire danger area) where only few fires occurred in small. The vegetation cover in the zone is less combustible species of eucalyptus and bamboo. The map provides a useful tool for local forest managers for planning and executing their fire prevention and suppression exercise.

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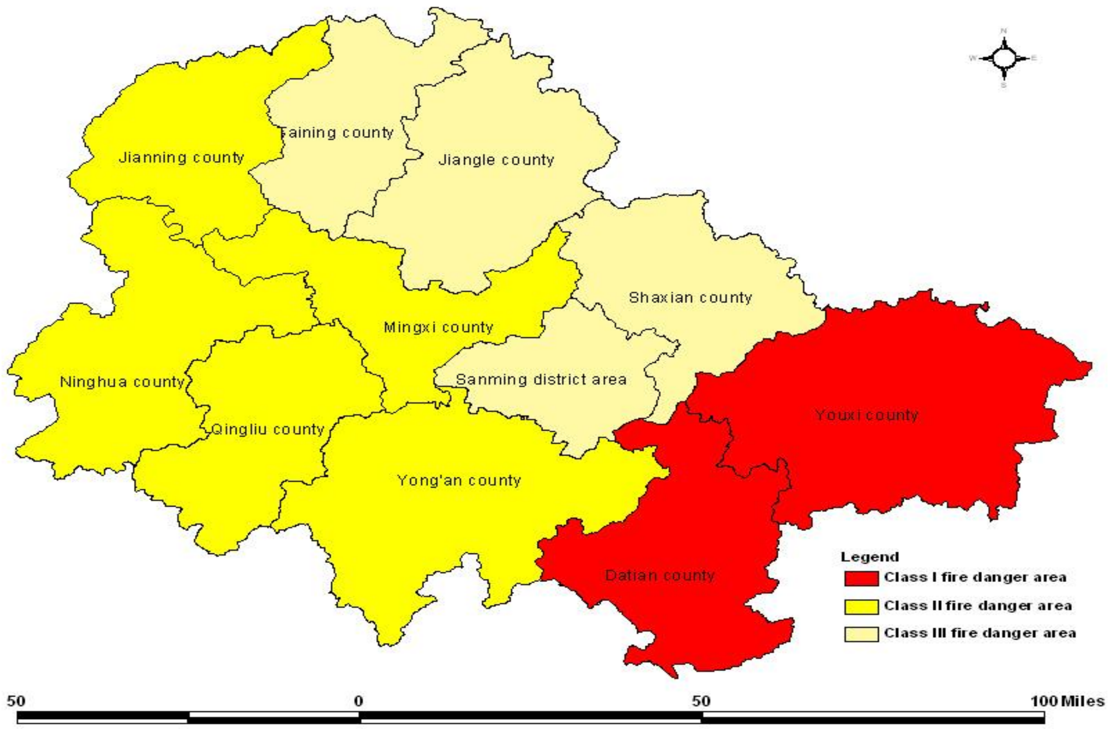

Figure 9. *Sanming zoning map based on forest fire proneness*

In Sanming city, most forest fires are caused by human-being, and lightning and arson fires only make up a small portion of all fires in the period 2000-2009. Our results are similar to the finding by (Zhong et al., 2003) that most forest fires in China are human-caused. Temporal and spatial analyses of forest fires are important for successful forest fire management (Keane et al., 2003). In the current study, we analyzed the temporal and spatial patterns forest fires based on forest fire statistics between 2000 and 2009 in the city. The highest numbers of fires occurred in Sanming around 2 p.m., and there are similar studies in other localities in China that forest fires are more likely to occur at 2:00 p.m in Beijing, Wuyishan Mountain and Hangzhou city (Huang, 2009; Liu et al., 2009). A study conducted Toronto, Canada illustrated that the fires incident density changes over time (in hour), the period between after-lunch time and the beginning of evening time seems to have the densest patterns of forest fire appearance (Asgary et al., 2010). The study also found the important number of occurs of forest fire in the spring and the feeble number of fire damage occurs in the autumn. The time-series processing of monthly forest fire occurrences and zone burned did show a strong seasonal pattern. Spring season was highly incident of fire of forest occurrences in Sanming and feeble fire of forest distributed in other seasons of year. Dry weather, heavy sunshine, low humidity and high wind speed from January to March explains this district difference among seasonal and monthly forest fire characteristics.

Forest fire occurrences goes upward over time especially the ascending trend after the year 2007 and in 2009 the highest number of fire (165 cases) and areas burned (3,861.30 hm^2) was found there. Weather and climate influence forest fire comportment and account for the variability in fire harshness at different time scales. Valdiya (2006) asserted that the accretion in temperature increment the chance of fire appearance

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whereas precipitation and humidity have the different relation with fire. The data of weathers processed regarding this study have also strong relationship with forest fire occurrence. The counties throughout all of Sanming were classified into three group based on fires of forest proneness to examine the spatial assessment of fires of forest. In Sanming, many fires of forest were occurred in spring from January to March and a little forest fires can be registered in others seasons of the year. Dynamic of the wildland fires were clearly and detected in Youxi County and Sanming District, respectively. Southeast areas had larger forest fire appearances compare to other areas because of heavy forest use by human and more combustible species, a well-developed firefighting system with rapid suppression prevented large forest fires about the fire risk zone.

Conclusion

Fujian is a green province in China with forest coverage of 65.95%, and Sanming is one of the green cities in the provinces with forest coverage of 71%. Forest fires are recurrent disturbance events in Sanming because the city is dominated by over-matured, more combustible and flammable species. In this study, we found that the temporal and spatial patterns of forest fires exhibited considerable variations along time and by changing weather characteristics. The new insights into the temporal and spatial dynamics of forest fires in Daming could be applied to help allocate firefighting resources in fire season for immediate fire suppression in the southeastern China. Also, our results can be used to verify and readjust the fire precautionary period. During the 1960s, a wide range of people migrated to Sanming from other parts of Fujian and the increased urbanization and human activities increased opportunities for fire ignition. The results from this study can be used to help closely monitor fire danger conditions in the city. For example, population can be notified that January-March is the period most venerable to fire through some education programs, such that people would be more careful in their life and production activities in the period. Also, our results can be incorporated into legislation such that some practices in forest areas that are conducible to fire could be banned legally. According to this research's results, it's recommended to set and slopes, and to collect weather and forest fire data daily in Fujian area. These findings indicate that either the frequency or the mean length of prolonged weather, alone, cannot fully describe the short-term climate influence of an area.

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Conflict of interests. The authors have declared that no competing interests exist.

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