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An analysis of fatalities from forest fires in China, 1951–2018

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ABSTRACT

The frequent occurrence of fatalities from wildfires is an ongoing problem in China, even though great improvements have been achieved in overall wildfire management in recent years. We analysed the occurrence patterns and correlative environments of fatalities from forest fires in China from 1951 to 2018. Changes in fire policies affected changes in the numbers of fires, forest area burned and number of fatalities before and after 1987, after the large Great Black Dragon Fire that burned in the Daxing'anling Mountains in northeastern China. Most fatalities occurred in the southern, southwestern and eastern forest regions of the country where population centres are concentrated, while most of the burned area was distributed in forests of northeast China with fewer population centres. Fatalities were correlated with higher values of fire weather indices, coniferous forests, coniferous and broad-leaved mixed forests, moderate–average slopes (5.1–15°), and primarily small fires of less than 100 ha in area. These results should be a first step to help improve awareness of inherent dangers during wildfires and to assist fire managers and policy-makers in strengthening safety procedures for both professional firefighters and the public to reduce wildfire fatalities in the future.

Keywords: China, fire environment, fire frequency, fire management, fire size, fire suppression, forest fire fatalities, forest fire.

Introduction

Wildfire is an integral and inevitable ecological disturbance process in forest ecosystems worldwide (Bowman *et al.* 2020). At the same time, wildfires can cause extensive damage to human communities and infrastructure and often cause human fatalities, both of firefighters and civilians (Crompton *et al.* 2010; Turco *et al.* 2019). Recent major fire years in locations around the world have focused attention on linkages between anthropogenic climate change and wildfires, and the high likelihood of increased impacts from climate-affected changes in wildfire frequency, extent and severity on human activities, properties and infrastructure in coming years and decades (Diakakis *et al.* 2016).

Recent large and severe wildfires and wildfire seasons are increasingly exceeding the limits of suppression capabilities and resulting in greater environmental and societal impacts (Moore 2019). With increased fire occurrence and severity levels, fatalities of both firefighters and civilians have become a significant problem in many countries (Molina-Terrén *et al.* 2019). In 2007, a series of extreme fires with extreme behaviour burned 270 000 ha of forest and agricultural land in Greece, which resulted in >3000 homes destroyed and 80 people killed (Xanthopoulos 2008; Viegas *et al.* 2009). Also in Greece in 2018, a series of wildfires killed 99 people, the deadliest fire season in Greek history (AghaKouchak *et al.* 2018). In California in 2017, extreme wind-driven wildfires led to 46 fatalities and thousands of destroyed structures (Nauslar *et al.* 2018). The most destructive and deadliest wildfires in California history occurred in 2018, resulting in 86 fatalities and the loss of 18 804 structures (Cal Fire 2019; Coogan *et al.* 2019). In Australia, thousands of fires between June 2019 and March 2020 burned more than 18.6 million ha with 34 fatalities and the loss of 3500 homes (Munawar *et al.* 2021). Fatalities in all of these instances included a mix of both firefighters and civilians.

During extreme wildfire years, governments and organisations at all levels of society are most concerned with fire suppression, yet suppression activities during wildfires present many hazards to firefighters and can result in firefighter fatalities (Alexander 2010). Most firefighter fatalities occur directly from exposure to fire and gases such as during entrapments and burn-over events (Fayard 2009). Other common causes of firefighter fatalities are aviation activities, vehicle accidents or medical events such as heart attacks (Mangan 1999; Butler *et al.* 2017). De Ronde (2002) summarised reasons for firefighter fatalities in South African forest wildfires, which included the occurrence of extreme spotting conditions, lack of escape routes, wrong or unclear firefighting instructions, lack of adequate training on basic firefighting procedures, and vital safety measures not being followed. In the US, Britton *et al.* (2013) found that peak incident management level, person-days of exposure and a fire's resistance to control were significantly related to the odds of a fire resulting in at least one injury or death. Blanchi *et al.* (2014) found that over 50% of all firefighter fatalities in Australia from 1901 to 2011 occurred on days where the McArthur Forest Fire Danger Index (FFDI) exceeded 100 (the current threshold for declaring a day as potentially 'catastrophic'). Entrapment was the most frequent cause of death of firefighters (75.6%) in Sardinia from 1945 to 2015, and 47% of the entrapments occurred on days with extreme weather conditions (high temperature and/or strong winds) (Cardil *et al.* 2017). In Greece, most fatalities deaths between 1977 and 2013 (208 fatalities during 78 forest fires) occurred under adverse meteorological conditions (Diakakis *et al.* 2016).

A fire produces a complex toxic environment involving flame, heat, oxygen depletion, smoke and noxious gases. Most fatalities from fires are not due to burns, but are a result of inhalation of toxic gases produced during combustion (Stefanidou *et al.* 2008). Page and Butler (2017) presented empirical models to estimate the distance from flames that would result in a low probability of either fatal or non-fatal injuries. The significant variables for the fatal injury model were fire shelter use, slope steepness and flame height. Different types of suppression policies are also an important factor influencing the fatalities from wildfires. For example, Molina-Terrén *et al.* (2019) analysed the forest fire fatalities in southern Europe based on a historical fire database from 1945 to 2016, and suggested that training on safety protocols and procedures were helpful for the firefighter's ability to survive fire threats.

Fatalities in wildfires have always been an important problem in China (Du *et al.* 2019). The largest wildfire on record in China, the 'Great Black Dragon Fire', occurred in the Daxing'anling Mountains in northeastern China in 1987, burning 1.33 million ha of forests. The large fire swept through three towns and resulted in 213 fatalities (including some civilians) with more than 50 000 people displaced (Xu 1987). After the big fire, government agencies at all levels from national to local strengthened forest fire management, and forest fire numbers and extent were reduced significantly. There were only two forest fires on average that burned >1000 ha per year during the period 1988–2018, with a maximum fire size of 0.2 million ha during this period. Total fatalities, including firefighters and local residents who participated in suppression activities, from forest fires from 1988 to 2012 in China were 4418 people, which is still a quite serious problem in fire management (Liu 2015; Yang *et al.* 2015). More recently, 31 and 19 firefighters died during fire suppression actions in the spring fire seasons of 2019 and 2020 in Sichuan province, China, respectively. Previous research has found that fatalities during wildfires in local areas in China were correlated with dangerous fire environments (e.g. heavy fuel loads, steep slopes, or high winds), human error, or untenable firefighting strategies (misjudgements in suppression actions, incorrect locations for firebreak construction and incorrect escape routes) (Han and Yao 2012; Jiang *et al.* 2012). However, there has not yet been any study to summarise general characteristics and causes of fatalities from forest fires across all of China. Here, we compile and analyse overall characteristics of forest fire fatalities in China as compared with both fire statistics and selected environmental variables as a first step toward improving fire management and suppression capabilities and strategies in the future.

Methods

Data sources

Annual fire statistics from 1951 to 2018 were obtained from the Forest Fire Management Office of the National Forestry and Grassland Administration. The statistics we used include annual number of fires, burned area in forests and total number of fatalities (Table 1). Data for 1951–1987 include only annual data for all of China, whereas statistics from 1988 to 2018 are summarised monthly by province. Fire statistics became more detailed after 1987 as fire management improved at all levels of organisation from local to national. Starting in 1999, fire statistics also include other detailed information for individual fires, such as occurrence date, specific location, burned area, number of fatalities and vegetation type. We compared these more detailed fire data from 2010 to 2018 with historical hourly observed weather data of more than 2000 weather stations obtained from the national Meteorological Information Centre. Hourly weather data include temperature, precipitation, relative humidity, and wind speed and direction. In addition, we calculated the annual average burn rate for the period 1951–2018 by using annual burned areas divided by total forested areas. Annual forested area was derived from national forest inventory data collected at 5-year intervals (Zhang 1988; National Forestry and Grassland Administration 2014, 2019).

Fire weather indices for each fire with fatalities during 2010–2018

We used the R package 'cffdrs' to calculate daily fire weather index (FWI) system indices (Wang *et al.* 2017) based on

Table 1. The data used for fire analysis.

Name	Period	Source	Processing method
Annual fire statistics by province	1951–2018	Forest Fire Management Office of the National Forestry and Grassland Administration	ANOVA, Pearson's correlation coefficients test
National forest inventory data	1951–2018	Forest Fire Management Office of the National Forestry and Grassland Administration	Statistical analysis
Fatality statistics by province	1988–2018	Forest Fire Management Office of the National Forestry and Grassland Administration	ANOVA, Pearson's correlation coefficients test
Fatalities from every wildfire	1999–2018	Forest Fire Management Office of the National Forestry and Grassland Administration	Statistical analysis
Historical hourly observed weather data (2412 stations)	2010–2018	Meteorological Information Center	FWI calculation

noon temperature, relative humidity, wind speed and precipitation. Indices we calculated include fine fuel moisture code (FFMC), duff moisture code (DMC), drought code (DC), initial spread index (ISI), buildup index (BUI) and FWI (Van Wagner 1987). FFMC, DMC and DC represent moisture levels of different fuels, while ISI, BUI and FWI reflect potential fire behaviour. Daily spatial interpolation of these indices was carried out using ANUSPLIN 4.36 software. Corresponding fire weather information related to fatalities during individual fires was extracted from these spatial maps. We compared fire weather conditions when fatalities occurred with the corresponding 50 and 95th percentiles of the indices for individual fires during 2010–2018.

Analyses

We divided the period of record for this study into earlier and later stages, before and after 1987, based on overall trends in fire policy (Tian *et al.* 2020). We used one-way analysis of variance (ANOVA) to analyse differences between number of fires, burned area in forests and number of fatalities between these two periods ($\alpha = 0.05$). We used Pearson's correlation coefficients to test for annual and monthly correlations among number of fires, burned area in forests and number of fatalities based on nationwide data from 1951 to 2018 and 1988 to 2018. We also looked at differences in numbers of fatalities during large and small fires (>100.1 ha or ≤100 ha in area, respectively) by decade based on data from 1951 to 2018.

Data available from 1988 to 2018 also allowed us to examine numbers of fatalities by forest types and other spatially derived environmental characteristics. Forest types included coniferous forest, coniferous and broad-leaved mixed forest, coniferous and shrub forest, coniferous and bamboo mixed forest, broad-leaved forest, bamboo forest and shrub. Forested areas in China were divided into six forest regions: northern, northeastern, eastern, southern, southwestern and northwestern (Ma *et al.* 1997). ANOVA was performed to analyse the differences between fires, burned area in forests and fatalities among the regions ($\alpha = 0.05$). For individual fire data available from 1999 to 2018, fires were mapped based on their spatial distributions and classified into four classes according to the number of fatalities reported for the fire: I, 1–3 fatalities; II, 4–10; III, 11–30; and IV, >30. We also grouped fires into 10 size classes based on their burned area to examine relationships between numbers of fatalities and fire size: A, <1 ha; B, 1.1–4.0 ha; C, 4.1–100 ha; D, 100.1–200 ha; E, 200.1–500 ha; F, 500.1–1000 ha; G, 1000.1–2000 ha; H, 2000.1–10 000 ha; I, 10 000.1–20 000 ha; and J, >20 000 ha. Finally, ArcGIS software was used to extract topographic information for each fire based on mean slope angles, and the information was organised into six classes: i, 0–2°; ii, 2.1–5°; iii, 5.1–15°; iv, 15.1–25°; v, 25.1–35°; and vi, >35° (Liu and Tang 1987). The environmental factors (including forest types, fire weather, and slope) that correlated with fatalities during the individual fires were analysed using R studio.

Results

Relationships between fatalities, fires and forested area

Between 1951 and 2018, there was a strong positive correlation between annual number of fatalities and total number of fires across all of China ($r = 0.68$; Fig. 1*a*). During the earlier period from 1951 to 1987, wildfires frequently occurred with larger burned areas, which also resulted in many fatalities (Fig. 1*a*). In this earlier period, the annual average number of fires, burned forest area and number of fatalities were 16 308, 941 893 ha and 110, respectively. The number of fires, extent of burned area and number of fatalities decreased significantly after the establishment of professional firefighting agencies and improved fire management after the Great Black Dragon Fire in Daxing'anling in 1987 (Fig. 1*a*, *b*), even as forested area in China started to increase dramatically (Fig. 1*b*). During the later period of fire records from 1988 to 2018, average annual fires and burned area in forests decreased significantly by 58.3 and

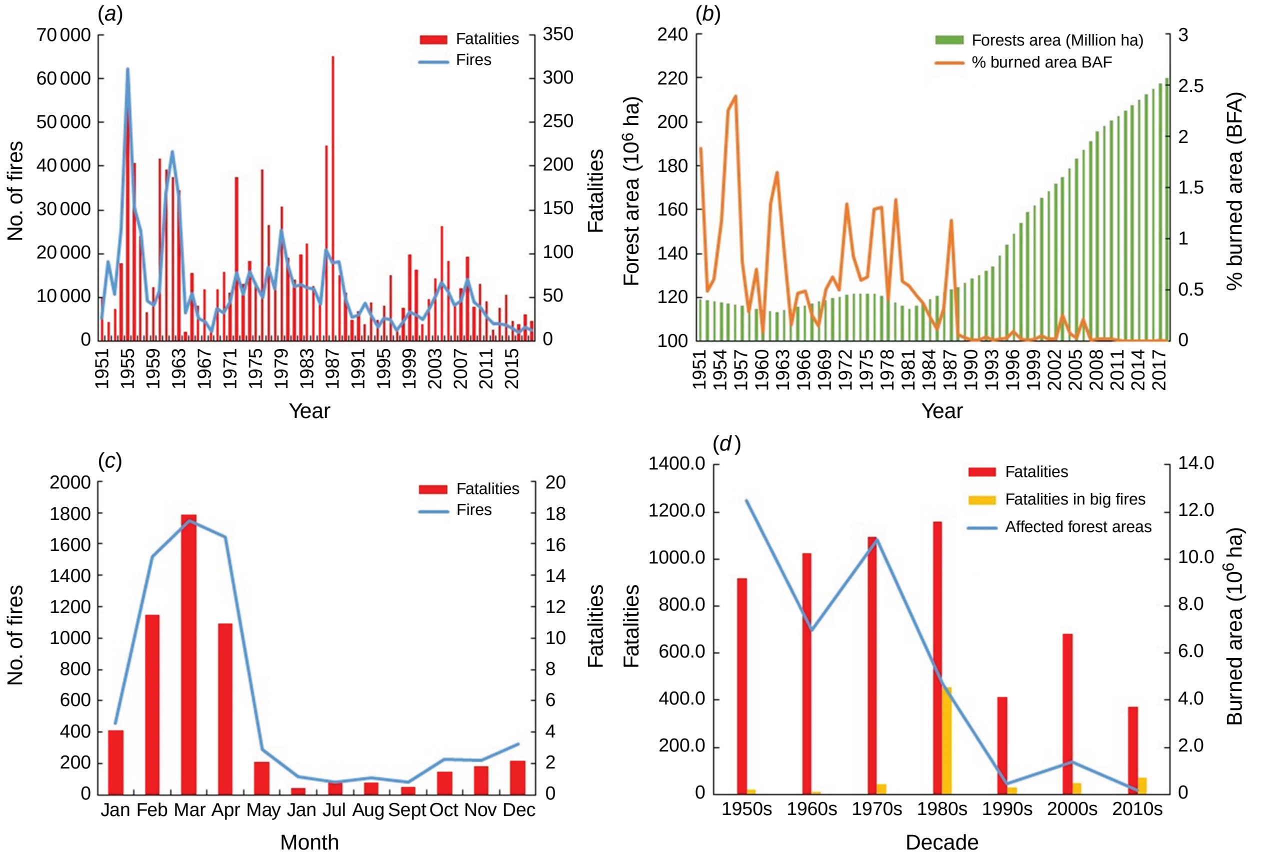

Fig. 1. Relationships between number of fires, burned forest area (BFA) and number of fatalities across all of China. (*a*) Annual total numbers of fires and fatalities (1951–2018); (*b*) annual burned forest area (ha) relative to total forested area (1951–2018); (*c*) average numbers of fires and fatalities by month (1988–2018); and (*d*) total number of fatalities and number in large fires (>100 ha), and burned forest area by decade (1951–2018).

92.6% in comparison with those in the earlier period, and average annual fatalities dropped by over half, to 50. The average annual burned rate also dropped to 0.04% (range from 0.003 to 0.26%) in the later period from 0.8% during 1951–1987 (Fig. 1*b*).

The average monthly number of fatalities showed a strongly positive correlation with the number of fires from 1988 to 2018 ($r = 0.97$; Fig. 1*c*), but not with burned area in forests ($r = 0.06$). Fire seasons are not coincident for the six forest regions owing to their varying climate regimes and vegetation types. However, spring (March to May) accounts for part of the fire seasons for most regions where fires occurred frequently (Tian *et al.* 2020; Fig. 1*c*). The maximum number of fires (1752) and fatalities (18) across all of China occurred in March, while the maximum burned area in forests (38 260 ha) occurred later in May.

Decadal variability in the number of fatalities indicated that the most fatalities occurred in the 1980s, when there were 1161 fatalities in total, including 213 fatalities during the Great Black Dragon fire in Daxing'anling in 1987 (Fig. 1*d*). The proportion of fatalities during large fires (>100 ha in area) was highest in the 1980s among the seven decades, accounting for 39.4% of all fatalities (457 fatalities in five large fires). The minimum proportion of fatalities (1.2%) during big fires occurred in the 1960s. Fatalities from large fires have increased over the past three decades, peaking at 19.3% in the 2010s (Fig. 1*d*).

Spatial distribution of forest fire fatalities

The annual number of fires, burned forest area and number of fatalities by forest regions and provinces showed significant differences in fire records available from 1988 to 2018. The southern forest region had the highest number of average annual fires and fatalities, which accounted for 45 and 40.7% of the total of each, respectively (Fig. 2*a*). Notably, 18.9 and 14.3% of total fatalities occurred in Hunan and Guizhou provinces in the southern forest region, respectively, but their corresponding burned areas only accounted for 6.7 and 2.5% of the total for all of China (Fig. 2*b*). Fatalities in the eastern and southwestern forest regions included 23.5 and 21.3% of the totals, respectively. The northeast forest region had the lowest number of fatalities but the greatest burned area in the country, with burned area mainly

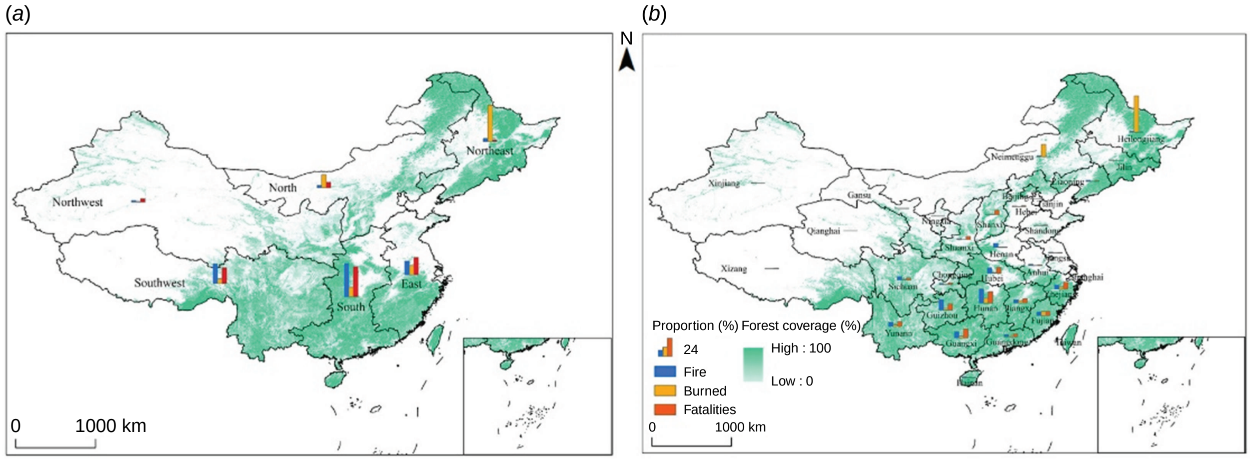

Fig. 2. The number of forest fires, number of fatalities, and forest area burned by forest regions (*a*), and by province (*b*) from 1988 to 2018.

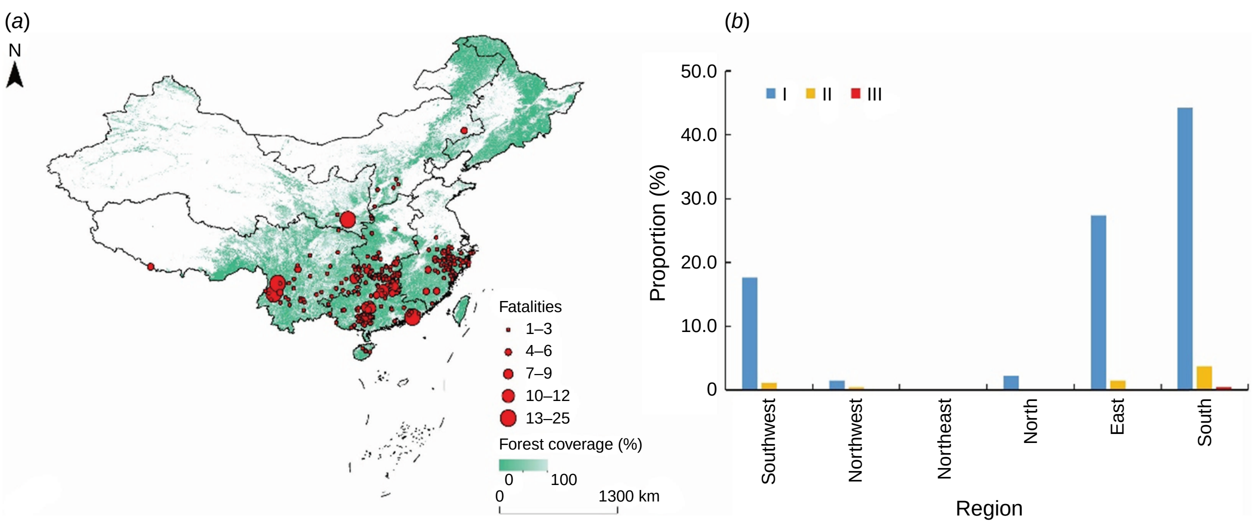

Fig. 3. The distribution of fires by fatality classes during the period 1988–2018. (*a*) Locations of fires by fatality class in China; (*b*) statistics of fires by fatality class by region, where I, 1–3 fatalities; II, 4–10; and III, 11–30.

distributed in Heilongjiang province, which accounted for 48.8% of total burned area in China but only 1.5% of total fatalities. In addition, 16.8% of the total burned area occurred in the northern forest region (mainly in the Inner Mongolia autonomous region), but the number of fires and fatalities in this region were only 1.5 and 0.3% of the total for all of China, respectively. Finally, the northwestern region has few forests and correspondingly had the fewest average annual fires (2.2%) and lowest total burned areas (0.8%). Both average annual fires and burned areas were less than 1% for Shaanxi province in the northwestern region, but this area had a total of 5.9% of the fatalities of the entire country.

During 1999 to 2018, fatalities were mainly distributed in the south, southwestern and eastern forest regions, which accounted for 48.3, 28.8 and 18.7% of all fatalities, respectively (Fig. 3*a*). There were no fatalities in the northeastern forest region during this period. Fires with I (1–3 fatalities), II (4–10) and III (11–30) classes of fatalities during the period were 92.9, 6.7, and 0.4%, respectively (Fig. 3*b*). There were no fires with Class IV (>30) fatalities. Fires with Class III fatalities only occurred in the southern forest region, whereas fires with Class I and II fatalities were distributed in southern, eastern, southwestern and northwestern forest regions.

Fire characteristics and fatalities

All fatalities (406 total) from 1999 to 2018 occurred during fires that burned <1000 ha (Fig. 4*a*). There were 53 528 fires during this period and 0.5% of these (267 fires) caused

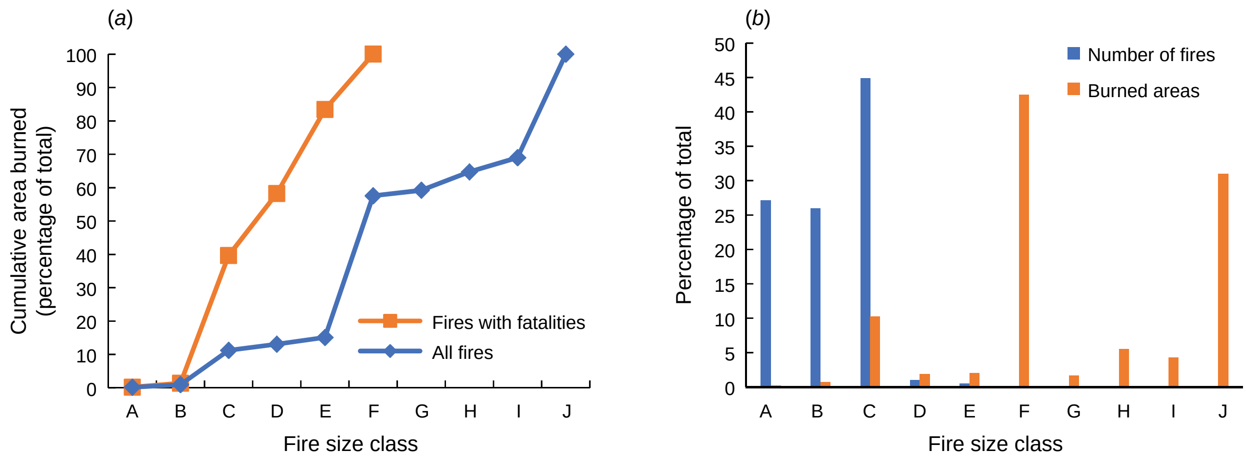

Fig. 4. Distributions of the number of fires and burned areas by fire size class – A, <1 ha; B, 1.1–4.0 ha; C, 4.1–100 ha; D, 100.1–200 ha; E, 200.1–500 ha; F, 500.1–1000 ha; G, 1000.1–2000 ha; H, 2000.1–10 000 ha; I, 10 000.1–20 000 ha; and J, >20 000 ha – for the period 1999–2018. (*a*) Cumulative burned area for fires with fatalities and all fires by fire size class; (*b*) percentage of total number of fires and area burned by fire size class.

Table 2. Number of fatality fire events by fire size (FS) class, burned forest area (ha; BFA) and number of fatalities recorded across China from 1999 to 2018 by fire size.

FS class	Fire size (ha)	Number of fatality fire events	BFA	Fatalities	Average fatalities per fire
A	<1	42	18.2	42	1
B	1–4	49	132.3	64	1.3
C	4.1–100	156	3625.0	253	1.6
D	100.1–200	12	1622.1	33	2.7
E	200.1–500	6	2569.9	12	2
F	500.1–1000	2	1533.3	4	2

No fatalities were recorded in any fires over 1000 ha in size.

fatalities. Fires with size ≤100 ha accounted for 98% of all fatalities, even though their burned areas covered only 19% of total burned areas during this period (Table 2). Fires that burned 100.1–200 ha had the maximum number of fatalities per fire.

Environments of fatality occurrences

Coniferous forest and coniferous and broad-leaved mixed forest were the main forest types where fires with fatalities occurred. A total of 58.1% of all total fatalities from 1999 to 2018 occurred in coniferous forest fires (Fig. 5). Broad-leaved forests and coniferous and broad-leaved mixed forest fires accounted for 15.5 and 14.8% of the total fatalities, respectively. Bamboo forest and coniferous and bamboo mixed forest only accounted for 1.2% of the total fatalities.

Fires with fatalities mainly occurred on fairly shallow terrain with slope classes of iii and ii, which accounted for 43.1 and 22.8% of the total fatality events, respectively. The fatalities occurring in sites with slope iii and ii accounted for 45.1 and 22.4%, respectively. Fatalities from fires with slope Classes iv and i accounted for the same percentage, 14.5%. Only 2.5% of the total fatalities occurred on terrain with slope Class v (25.1–35°) and none in slope Class vi (>35°).

There were 37 fires with fatalities from 2010 to 2018 for which we have detailed weather information. Most of these fatalities (54%) occurred under fire weather conditions with >50th percentile FFMC, and 35% of fatalities occurred when conditions were >95th percentile FFMC. Fire weather indices indicated that most fatalities occurred in weather conditions with high or very high fire danger (Fig. 6). Ninety percent of the fatalities occurred on days with ISI exceeding the median of all fire seasons, and 97% of the fatality cases occurred on days with FWI percentile >50, which indicated fast fire spread conditions. In addition, 35% of the fatality cases occurred under extreme fire weather conditions where the FWI was >95th percentile. Only one fatality occurred when FWI was <50th FWI percentile.

Conifer forests with slopes >5° and high fire weather indices accounted for 69% of all fatalities from 2010 to 2018. The maximum number of fatalities in a single fire was 23, which occurred in a coniferous forest with an

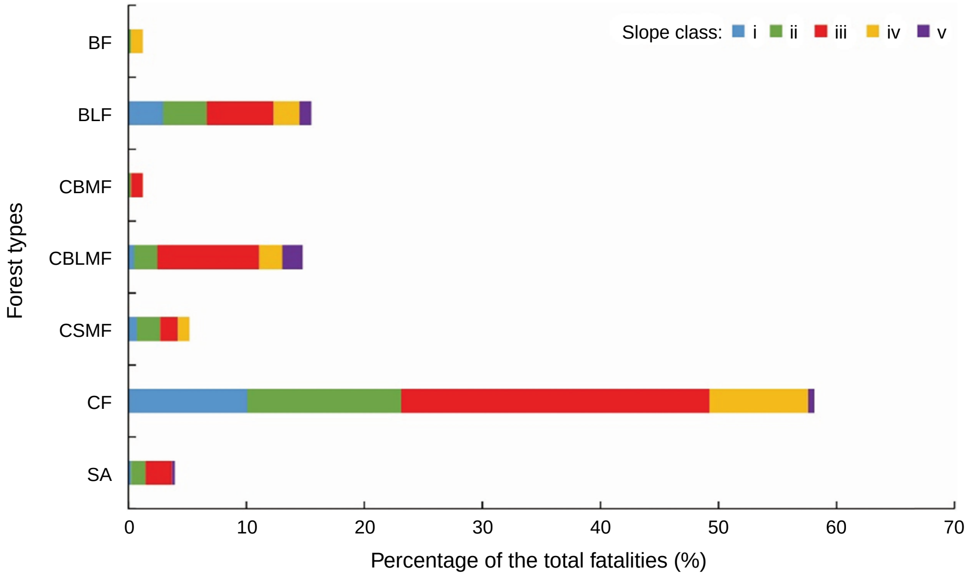

Fig. 5. Percentage of fatalities during the period 1999–2018 in various vegetation types and terrain. Slope classes: i, 0–2°; ii, 2.1–5°; iii, 5.1–15°; iv, 15.1–25°; v, 25.1–35°; and vi, >35°. Vegetation types: BF, bamboo forest; BLF, broad-leaved forest; CBMF, coniferous and bamboo mixed forest; CBLMF, coniferous and broad-leaved mixed forest; CSMF, coniferous and shrub forest; CF, coniferous forest; SA, shrub.

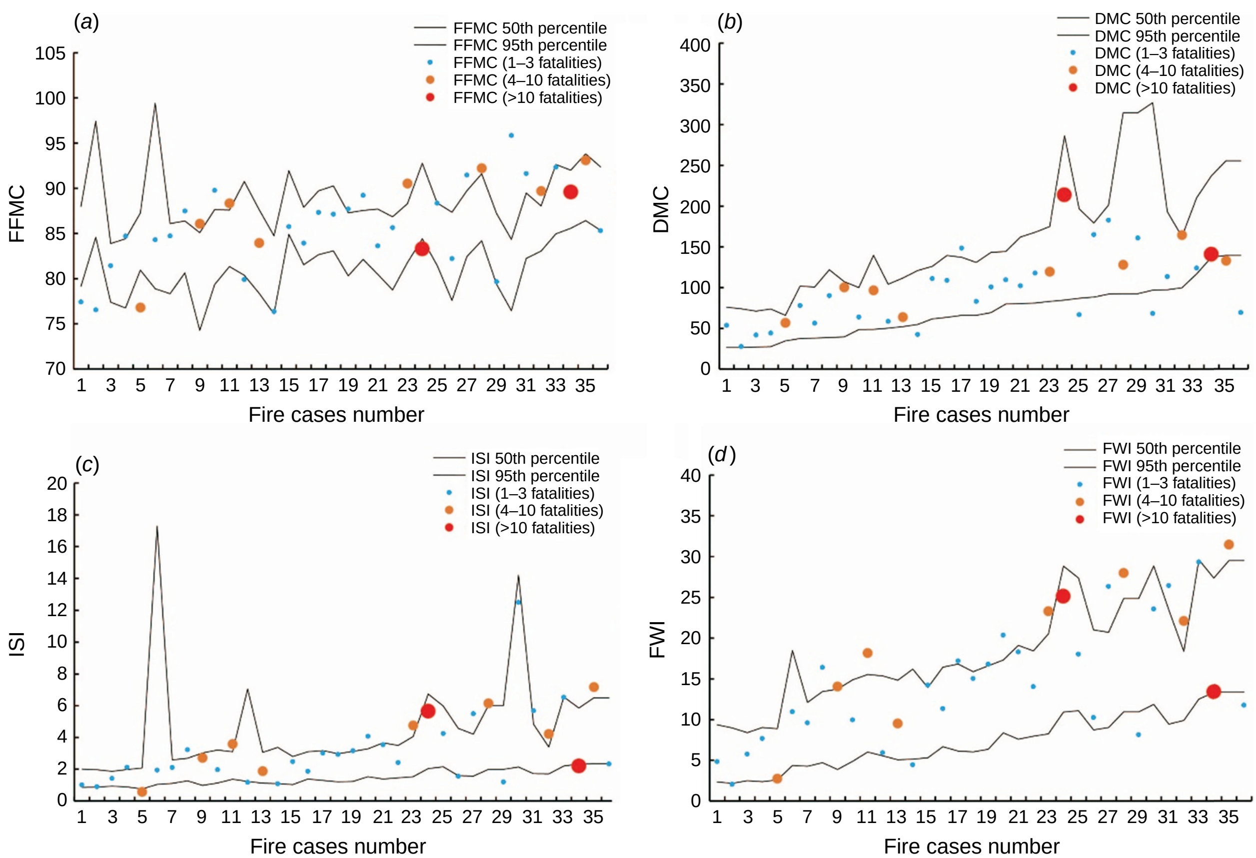

Fig. 6. Fire weather indices associated with fatalities during the period 2010–2018: (*a*) FFMC; (*b*) DMC; (*c*) ISI; and (*d*) FWI.

average of 17.1° slope and high FWI (>50th percentile). Fires in broad-leaved forests also resulted in more fatalities if the fire weather indices were high and/or the slope was steep. For example, a fire that burned only 7 ha caused five fatalities in a broad-leaved forest with an 18.4° slope and a very high FWI (>95th percentile). Even when FWI was <50th percentile, a fire caused four fatalities under conditions of broad-leaved forest and 11.7° slope. Overall, fatalities mainly occurred under conditions when unexpected fire behaviours occurred during suppression actions.

Discussion

Characteristics of fire fatalities in China

Forest management policies in China since 1951 can be divided into three stages, which are mirrored to some extent changes in fire management as well. There was a period of intense forest harvest from the early 1950s to the late 1970s, followed by a period of reconciling harvest with forest cultivation from the early 1980s to the 1990s, and most recently a period focused on sustainable forest management from the late 20th century to the present (Zhang 2008). During the first period, fire suppression was mainly dependent on local residents who typically lacked any sort of training or professional equipment, and fatalities occurred frequently. After the Great Black Dragon Fire in 1987, professional fire agencies were established at all levels in the country, with increased efforts and funding directed to improving wildfire suppression abilities (Tian *et al.* 2020; Fig. 1). Permanent and seasonal fire brigades became the main force in firefighting, although unfortunately these professionals also have formed the bulk of fatalities over the last three decades.

Factors that affect the occurrence and characteristics of fatality events during wildfires have been a focus of a great deal of forest fire management research (e.g. Molina-Terrén *et al.* 2019). Through analysis of fatality events from 1951 to 2018, we found that fatalities in China were frequently related to the fire environment, such as fuel type, terrain and weather (Blanchi *et al.* 2014; Diakakis *et al.* 2016; Molina-Terrén *et al.* 2019). Conditions conducive to fuel combustion such as coniferous forest and mixed forest, >25° slope, and high fire weather indices would have contributed to more serious and changeable fire behaviour, thus causing firefighter and civilian injuries or death as has been found in other areas of the world (Cardil *et al.* 2017; Nauslar *et al.* 2018). For example, a fire in December 2010 in Daofu in southwest China resulted in 23 fatalities when fire behaviour increased suddenly owing to strong wind gusts blowing into heavy fuel loads in the bottom of a valley coupled with the chimney effect of the valley topography. Another nine fatalities occurred in Jianchuan, Yunnan Province, in March 2011 because of wind gusts blowing into heavy fuels.

Although there are linkages between fire environment and fatalities, there was no obvious relationship between fire size and fatalities in China. Active fire policy has effectively reduced the annual burned area and fire numbers since 1987, but fatality events are still a serious problem, especially in south China. Most fatalities in recent decades have occurred in small-size fires, with even the most severe fatality event (31 fatalities) in recent years not in a large fire under the extreme fire weather conditions; it occurred in suppressing a fire with total burned areas 20 ha in Muli, Liangshan, Sichuan Province on 30 March 2019. This phenomenon was significantly different from reports from other countries or regions (Xanthopoulos 2008; Viegas *et al.* 2009; AghaKouchak *et al.* 2018; Nauslar *et al.* 2018; Cal Fire 2019; Coogan *et al.* 2019). This is likely due to the collective forest tenure reform that began in the 2000s, especially in the heavily populated southern region. Fire likelihood in more populated areas is strongly impacted by human ignition sources (Zong *et al.* 2021) with the result that most wildfires are generally of small size and high frequency. Notably, the historical fire record used in the present paper showed that all victims of fires were firefighters and local residents who participated in suppression activities after 1988. This phenomenon was also different in other regions (Haynes *et al.* 2010; Molina-Terrén *et al.* 2019). Individual landowners or local residents still feel the need to try to suppress these fires themselves, with the result that they have experienced most of the fatalities. This is in contrast to larger and more complex fires that have had a lower injury and fatality incidence rate owing to professional firefighter cadres working these larger events (Britton *et al.* 2013).

Suggestions for fire management in the future

Improving public awareness of wildfire and fire effects on both ecosystems and human infrastructure is an important strategy for mitigating future impacts from wildland fires (De Ronde 2002; Alexander 2010). Firefighters also need to continually increase professional training to improve their understanding and judgment of fire behaviour. Creating consistent training opportunities and educational materials concerning fire behaviour, fire ecology and suppression techniques for local and seasonal firefighters is of critical importance for promoting professional firefighting resources in China at all levels from local to national. At the same time, government and fire agencies must emphasise to civilians to not try to put out rapidly spreading wildfires themselves but to instead notify and wait for professional fire brigades. Fires in wildland–urban interface areas have increased in past decades and a significant number of fatalities occurred in these areas (Diakakis 2016). An in-depth revision of fire management policies and practices across China is needed, with emphasis on prevention planning in urban areas, better training of firefighters and an increase in firefighting resources (Molina-Terrén *et al.* 2019). There is a need to develop consistent training on fire safety procedures to minimise accidents and reduce fatalities, specifically for volunteer fire brigades around the country (Viegas and Simeoni 2011). Furthermore, more effective early warning systems could help to avoid or reduce the high number of fatalities (De Ronde 2002). Firefighters must learn to adjust suppression strategies according to fire risk, fire environment and fire behaviours, and they must especially learn when to avoid direct suppression efforts in fast-moving and high-intensity wildfires.

The potential for larger and more intense forest wildfires across China is predicted to increase significantly in many regions in the future (Tian *et al.* 2017; Hayes 2021). Forested areas have been increasing over the past four decades owing to the changes in forest management and aggressive fire policies (Fig. 1*b*), with the result that more forests with heavy fuel loads can burn during fire season. Efforts at afforestation have also resulted in increased fuel amounts and canopy closure across many areas (Tian *et al.* 2005). These forest management practices create factors that contribute to higher-intensity fires that burn across larger areas. There is a large need for fuel treatment projects, including the use of mechanical thinning, ecological restoration and prescribed fires, in many areas that have been identified as having high fire risk.

At present wildfire management is in a period of transition in China. The Ministry of Emergency Management of the People's Republic of China was established in November 2018, and included the transfer of wildfire management from the State Administration of Forests and Grasslands. Local wildfire agencies are still in a stage of reform to better align with national directions. Greater professionalism and policy reforms in China's fire management structure from local to national levels should be expected in coming years. Certainly, an assessment of safety protocols for both firefighters and civilians to reduce the incidence of fatalities during future events must be a central component of these reforms. One direction is to establish an incident command system to improve the level of professional control and direction, especially during highly technical fires but also during smaller events. There is also a need to improve training for firefighters to increase professional judgment capabilities concerning fire behaviour during individual fires. A component of this could be achieved through a series of published technical guidelines focusing on fire danger, fire behaviour and fire suppression strategies that will provide greater flexibility and guidance during individual incidents. At the national level, there is the need to redefine a series of fire regime zones, using information such as local to regional characteristics of fuel, weather and fire behaviours, which will assist in strengthening regional fire management actions and protocols. Overall, this is a period of transition in Chinese wildfire management that will continue to improve firefighter and civilian safety and decrease fatalities going forward.

Limitations

Owing to fire data limitation, we only described forest types and slopes related to fatality occurrence from 1999 to 2018. The spatial interpolation maps of daily fire weather indices associated with fatalities only include the period 2010–2018. Nevertheless, the results reveal the general features and causes of fatalities in past decades, which is helpful to improve fire suppression and fire management strategies in China.

Conclusion

The paper systematically analysed temporal and spatial distributions of forest fires and fatalities for every eco-geographical zone based on fire records of the period 1951–2018. The number of fires, burned areas and fatalities have significantly decreased across China, especially after 1987 owing to increased funds, staff and professionalism in fire management. There were fewer burned areas and high fire frequency in southern, southwestern and eastern China, but more fatalities owing to high fire frequency and complex fire behaviour at local sites. Most fatalities occurred in fires with size <100 ha.

Forest type, slope and fire weather showed influences on fatal events through affecting fire behaviours. Most fatalities occurred in conditions with coniferous forests or conifer and broadleaved mixed forests, moderate slopes (5.1–15°), and high fire weather indices. Fatal accidents mainly occurred owing to unexpected fire behaviours during fire suppression. Fire management policies and strategies need to change to avoid fatalities in suppression, especially for the forests the south and southwest China.

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