

Research

Predicting dynamics of wildfire regimes in Yunnan, China

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Abstract

In recent years, the rise in global warming has significantly increased forest fires, affecting the environment and economy. Predicting forest fire dynamics under climate change is now a crucial research field. To address this need, this study focuses on the impact of climate change on forest fires, with a particular focus on the fire dynamics in Yunnan Province. This study utilizes the RegCM regional climate model and the Canadian Fire Weather Index (FWI) to simulate and analyze forest fire dynamics in Yunnan Province from 2019 to 2033 under three climate scenarios: RCP2.6, RCP4.5, and RCP8.5. Findings indicate climate change will increase temperatures, alter humidity and wind speed, and reduce precipitation in Yunnan, extending the fire danger period, especially under RCP8.5 scenarios. The FWI values rise across Yunnan, particularly in the west under RCP2.6 and RCP8.5. The study concludes that future carbon emissions correlate with these changes, leading to more frequent, longer, and severe forest fires. This research is vital for managing and preventing forest fires in Yunnan, a region prone to such disasters.

Article Highlights

1. The study utilizes the Regional Climate Model (RegCM) and the Canadian Fire Weather Index (FWI) to simulate and analyze forest fire dynamics in Yunnan Province under various climate change scenarios.
2. Findings indicate that climate change will lead to increased temperatures, altered humidity and wind speed patterns, and reduced precipitation in Yunnan, thus extending the fire danger period, especially under certain climate scenarios.
3. The research underscores the future correlation between carbon emissions and forest fire frequency, severity, and duration, emphasizing the need for effective forest fire management strategies in the region.

Keywords Wildfire regime dynamics · RCM · Regional climate model (RegCM) · Fire Weather Index (FWI)

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1 Introduction

Forests are an important part of in terrestrial ecosystems [1], largely due to the cyclical process of forest material. Wildfires, as an integral element of these ecosystems, contribute significantly to their regulation [2]. However, wildfires are also natural disasters, and their occurrence and behavior are directly or indirectly influenced by climate change [3–5]. The increasing frequency and intensity of wildfires, exacerbated by global warming, have led to substantial, often irreparable, damage to life, property, and forest ecosystems [6, 7]. Over recent decades, the world has witnessed several catastrophic fires: in 1987, a massive wildfire ravaged the Greater Khingan Mountains in China, consuming an area of 17,000 km² and resulting in direct economic losses of 500 million yuan, alongside an indirect loss of 6.913 billion yuan. August 23 and 24, 2007, saw Greece grappling with 170 wildfires, affecting over half of the country's land area. In July 2019, Australia faced a severe wildfire that scorched over 800 ha, leading to the tragic loss of 3 billion animals. The year 2020 witnessed wildfires rekindling in Siberia post the melting of ice and snow during summer, burning more than 2000 km² of land.

Climate change has notably altered wildfire activities, leading to various challenges, including a prolonged fire danger period [8]. This shift has necessitated a transition in wildfire prevention strategies, evolving from a seasonal approach to a more comprehensive, year-round effort. The geographical scope of wildfire-prone areas has expanded [9], enabling fires to spread beyond localized forest zones to broader regions. Moreover, the escalation in the severity of fire weather conditions has contributed to more frequent wildfires and reduced the intervals between successive fires [10]. The increasing incidence of natural fires [11], often triggered by phenomena such as lightning strikes, has prompted a strategic pivot in wildfire prevention, now encompassing both human-caused and natural fires. These emerging challenges in wildfire management are being addressed through advanced wildfire forecasting systems and fire danger rating systems [12–14]. These tools facilitate long-term, regional predictions of wildfire regime dynamics and fire danger assessments, serving as critical components in global wildfire mitigation strategies. Research in China and internationally indicates an anticipated increase in the area and occurrence of wildfires due to climate change. For instance, Flannigan's [15] research on North American wildfires revealed a significant impact of climate change on seasonal severity, subsequently increasing wildfire frequency. Stocks [16] integrated the Canadian Fire Weather Index (FWI) with climate models to project future shifts in Canadian fire danger, indicating an escalation in its severity. Furthermore, Zhao's [17] research highlighted that climate change would likely push the forest vegetation belt northward in eastern China, affecting the spatial distribution of wildfires. Wang's [18] comparative study of wildfires in China's Heilongjiang Province and three global regions showed that climate change is shifting the central focus of fire sites across various longitudes and latitudes. Although prior studies have explored the general link between climate change and forest fires, there remain key scientific questions that are not fully addressed. Particularly, there is a lack of in-depth analysis of the specific impacts of climate change on forest fire dynamics in specific regions such as Yunnan Province. While previous work provides a general connection between climate change and variations in forest fire frequency and intensity, detailed studies on how to quantify these changes and their specific impacts on forest fire management practices in particular areas are lacking. Moreover, previous research often didn't fully leverage advanced climate models and comprehensive fire risk assessment tools like RegCM and FWI in assessing fire risks. Therefore, this study aims to fill these knowledge gaps by combining regional climate models and fire risk assessment tools to provide more detailed predictions and analysis of the changes in forest fire risks in Yunnan Province under various climate scenarios.

Yunnan Province has one of the highest rates of wildfire in China, with the highest number of wildfires in the country [19]. The present study thus uses Yunnan Province as an example and uses the RegCM regional climate model simulation most suitable for the region to simulate daily meteorological data for the area from 2019 to 2033 and the Canadian FWI to calculate fire danger and predict and analyze future wildfire regime dynamics in different climate scenarios (RCP2.6, RCP4.5, RCP8.5). The results of the study should provide a reference for wildfire management in the region.

2 Data and method

2.1 Overview of study area

Yunnan Province is in southwest China (21° 8'–29° 15' N, 97° 31'–106° 11' E) and is crisscrossed by mountains and rivers, producing a variety of landforms. The terrain is high in the northwest and low in the southeast, the altitude

ranges from 80 to 6726 m, and the altitude decreases from north to south. Yunnan Province has a three-dimensional subtropical and tropical monsoon climate characterized by small annual temperature differences, large daily temperature differences, and distinct dry and wet seasons. The temperature varies with altitude. Yunnan Province is the richest region in China in terms of forest vegetation types [20], with a forest cover of 40.77%. The territory from south to north includes tropical forests dominated by rainforests, monsoonal rainforests, monsoonal evergreen broadleaf forests, semi-humid evergreen broadleaf forests, warm thermal coniferous forests, warm coniferous forests, and subtropical forests. With increasing altitude, one finds warm coniferous forests, cold coniferous forests, scrub meadow, and alpine tundra [21]. Figure 1 shows a schematic diagram of the location and vegetation distribution of Yunnan.

2.2 Model configuration

2.2.1 Baseline meteorological data

The baseline meteorological data were selected from the China National Meteorological Information Centre (<http://data.cma.cn>) and include 2018 meteorological data on temperature, precipitation, humidity, and wind speed from 25 meteorological stations in Yunnan Province. To convert these point data into gridded data, a process was undertaken using ArcGIS. Firstly, ArcGIS was employed to calculate the annual average temperature, precipitation, minimum humidity, and average wind speed. These calculated averages were then spatially interpolated across the region of Yunnan Province to create a continuous surface. This interpolation process involved assigning values to each grid cell based on the nearest point data and their respective values, ensuring that each 1 km × 1 km grid cell in the region had an associated value for each meteorological parameter. This gridded data set, with a spatial resolution of 1 km, effectively represents the current climate and allows for a more detailed and spatially comprehensive analysis of the meteorological conditions across the entire province.

Fig. 1 Distribution of the location and vegetation in Yunnan

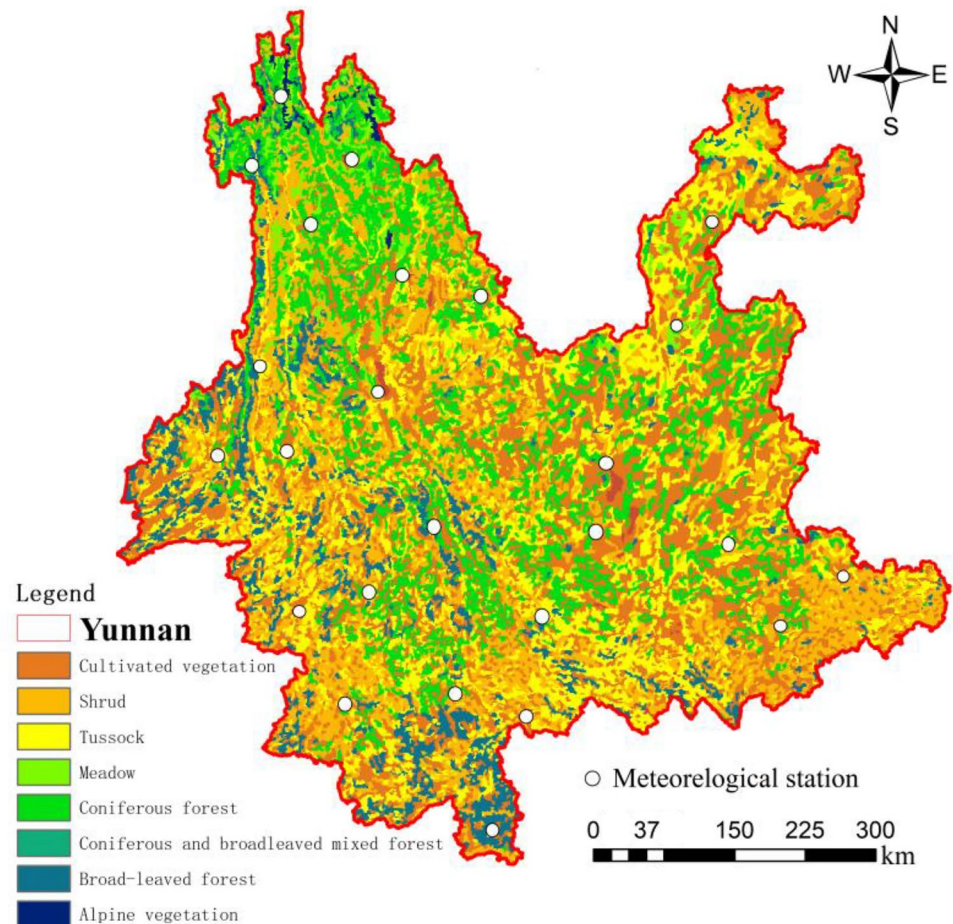
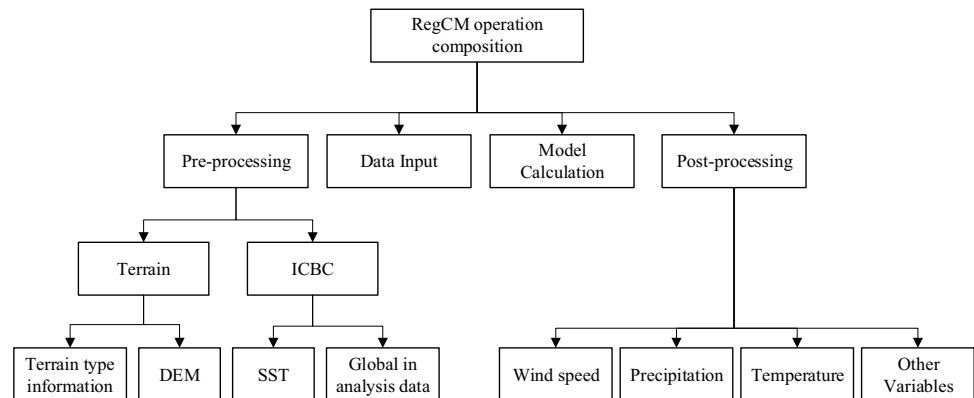


Table 1 The dynamic and physical configuration of RegCM4.6

	RegCM
Cumulus convection scheme	MIT
Land surface setting	BATS
Planetary boundary layer scheme	Modified Holtslag
Microphysical parameterization	SUBEX
Radiation scheme	Data

Fig. 2 Flow chart of RegCM operations



2.2.2 Future meteorological data

The future meteorological data are projected for 2019–2033 using the RegCM(version 4.6) regional climate model [22–25] developed by the International Centre for Theoretical Physics, Italy. RegCM requires several parameters to be configured for adaptation to the simulation area. The center of the simulation area is set at the center of the administrative division of Yunnan Province (25° 30' N, 101° 36' E), with a horizontal resolution of 30 km and a buffer zone set in 10 grids. In terms of dynamic framework and physical parameterization, the horizontal resolution is set to 30 km, and the vertical direction has 19 layers [26]. Table 1 lists the physical parameterization settings. The driving dataset consists of three future climate scenario datasets provided by the MPI-ESM-MR [27] global climate model in CMIP5. Using the data provided by RCP2.6, RCP4.5 and RCP8.5 as the initial and lateral boundary conditions for the model calculations, and the SST data from these three scenarios as the sea surface temperature, the climate of Yunnan was simulated for 2019–2033 under the three climate change scenarios. The simulation period is 15 consecutive years from January 1, 2019, to December 31, 2033 (of which 2018 is the start-up period). Figure 2 shows a flowchart describing RegCM operation.

2.3 Fire danger calculations

The forest fire danger rating system is a tool used to assess the degree of fire danger, typically considering factors such as temperature, humidity, wind speed, and precipitation, all of which are influenced by climate change. In future climate change scenarios, more frequent droughts, higher temperatures, and less precipitation are expected, leading to drier, more flammable conditions in forest areas, thus increasing the fire danger rating. Moreover, climate change may also cause the fire season to become longer and the fire hazard period to extend, making forest fire danger management an even more pressing issue. Therefore, the importance of the forest fire danger rating system will become more pronounced under future climate change scenarios, making it a key tool for the prevention and management of forest fires.

The Canadian Fire Weather Index (FWI) system, a key part of the Canadian Forest Fire Danger Rating System (CFFDRS) [28], comprises six components: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Build Up Index (BUI), and Fire Weather Index (FWI). These components are categorized into combustible moisture codes (FFMC, DMC, DC) and fire behavior indexes (ISI, BUI, FWI), used together to classify fire danger into five levels (see Table 2). Each component relies on specific meteorological data for calculation. For instance, FFMC uses precipitation, temperature, relative humidity, and wind speed, while DMC and DC require temperature and humidity, and BUI and ISI are based on combinations of these indexes. The FWI, the system's final index, combines BUI and ISI.

Table 2 FWI indicators for different fire danger levels

Fire danger level	Low	Medium	High	Higher	Extreme
FFMC	0–21	21–27	27–40	40–60	> 60
DMC	0–63	63–84	84–88	88–91	> 91
DC	0–80	80–190	190–300	300–425	> 425
ISI	0–2	2–5	5–10	10–15	> 15
BUI	0–20	20–30	30–40	40–60	> 60
FWI	0–5	5–10	10–20	20–30	> 30

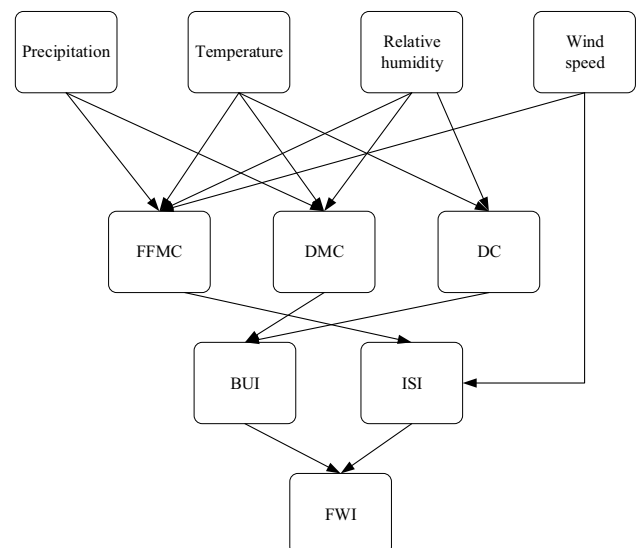
Figure 3 shows the structure of the FWI System, widely recognized as a leading global fire weather forecasting tool [29], the FWI System has been effectively applied in various regions, including Yunnan, China [30]. It integrates meteorological conditions, geographical factors, and combustible moisture content to predict fire danger levels at different locations. In this study, FWI calculations are based on average daily data from the RegCM simulation, following methodologies by Williams [31] and initial FWI data from Tian's [32] research on Yunnan's forest fire danger.

3 Results

3.1 Interannual variation in meteorological factors

The interannual variability of four key meteorological factors—maximum temperature (Tmax), total daily precipitation (Pre), minimum relative humidity (RHmin), and average daily wind speed (Wavg)—under three climate scenarios (RCP2.6, RCP4.5, RCP8.5). According to the data presented in Fig. 4, it was observed that the patterns of change in maximum temperature, minimum relative humidity, and average wind speed were somewhat consistent across the three scenarios. However, total precipitation exhibited distinct patterns, with RCP2.6 and RCP4.5 showing similar trends, while RCP8.5 presented a different behavior. In detail, for maximum temperature, both RCP2.6 and RCP4.5 scenarios indicated a gradual upward trend, with a marginal difference between them. In contrast, the RCP8.5 scenario initially showed an increase, followed by a decrease. The most notable increase was under RCP8.5, with a rise of 0.56 °C, while RCP4.5 witnessed the least increase, at 0.53 °C. As for minimum relative humidity, RCP4.5 and RCP8.5 scenarios demonstrated an initial increase before a decline, whereas RCP2.6 consistently rose. The largest change occurred in the RCP4.5 scenario, with a decrease of 0.41%, while RCP2.6 saw the least change, increasing by 0.24%. Regarding average daily wind speed, both RCP2.6 and RCP4.5 experienced a declining trend over the years, while RCP8.5 initially saw an increase, followed by a decrease. The changes in wind speed for RCP2.6 and RCP4.5 were minor and similar, decreasing by 1.21% and 1.19%, respectively. RCP8.5, however, showed the least variation, with an overall increase of 1.14%. In terms of total precipitation, RCP2.6 and

Fig. 3 The structure of the FWI System



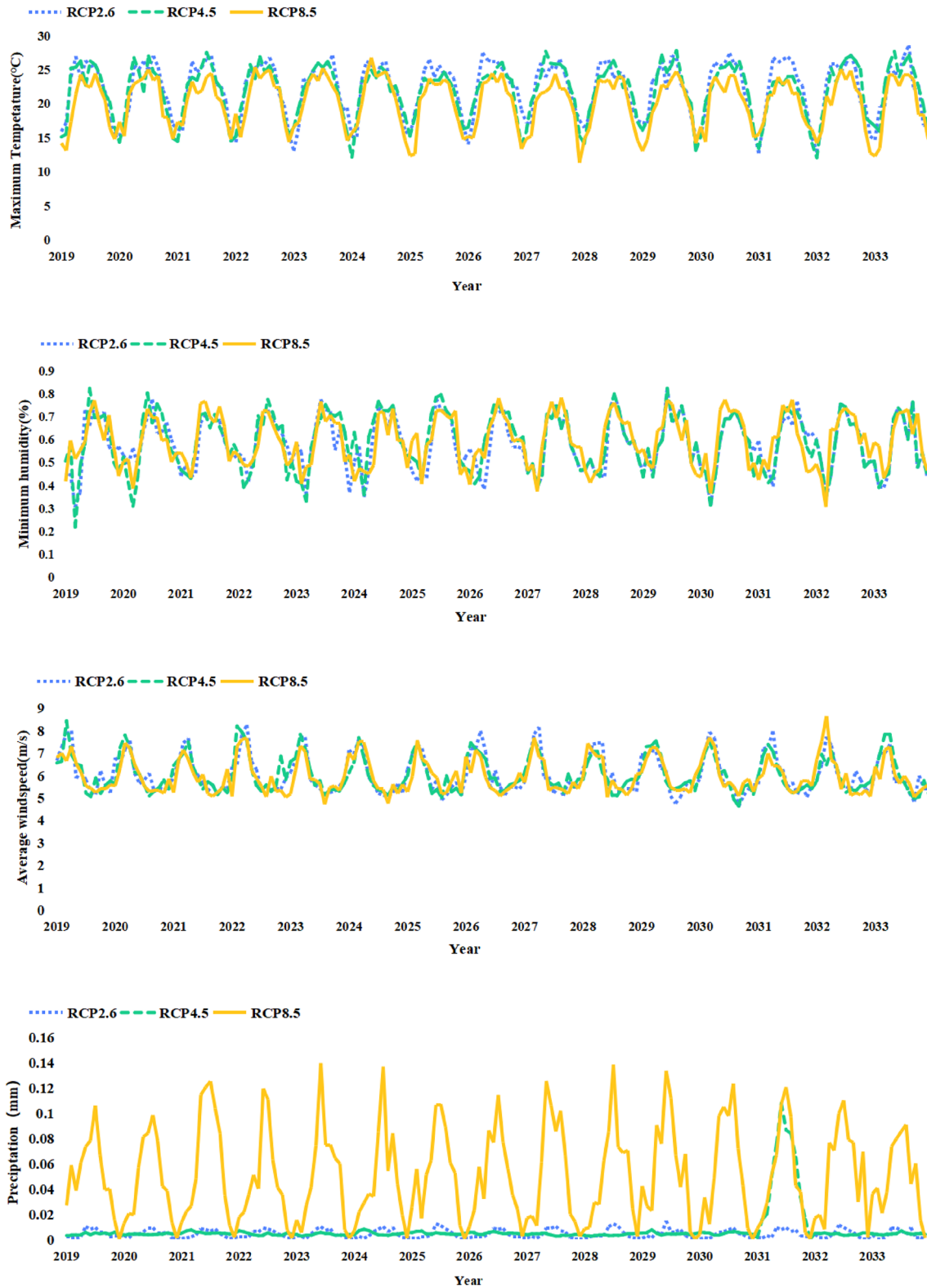


Fig. 4 Interannual variability of meteorological factors in RCP2.6, RCP4.5, RCP8.5 scenarios

RCP4.5 scenarios did not show obvious overall changes. RCP2.6 displayed a consistent annual increase, whereas RCP4.5 initially increased, then decreased. RCP8.5, on the other hand, was notably different from the other scenarios, showing an overall annual decrease of 1.6%. The most variability was observed in the RCP4.5 scenario, with a dramatic increase of 87% in precipitation in 2031 compared to previous years.

3.2 Fire danger period

3.2.1 Overall changes in the fire danger period

Utilizing the criteria of standard fire danger periods ($\text{FWI} > 10$) and high fire danger periods ($\text{FWI} > 20$), this study examines the period from 2019 to 2033, divided into three distinct analysis intervals: 2021s (mean of 2019–2023), 2026s (mean of 2024–2028), and 2031s (mean of 2029–2033). This approach facilitates a comparison between these intervals and the historical benchmark of 2016s (mean of 2014–2018), allowing for an assessment of the changing patterns of fire danger amidst different climate change scenarios.

To analyze the exact beginning and end of the fire danger period and high fire danger period, each month is divided into three periods: (a) early, (b) middle, and (c) late, and each period is analyzed separately. The results are shown in Table 3 and compared in Fig. 5. The latter shows that, in the RCP2.6 scenario, the onset of fire danger gradually delays over the years, reaching an average delay of 3.84 days by 2031s compared to 2016s. Conversely, under RCP4.5, the onset progressively advances, with 2031s starting 4.6 days earlier than 2016s. This scenario also shows a consistent clustering of start dates around a specific time. In RCP8.5, the trend is similar to RCP4.5, with an advancement of 3.23 days by 2031s. Regarding the conclusion of the fire danger period, RCP2.6 indicates a slight delay over time, averaging 0.96 days later by 2031s compared to 2016s. In RCP4.5, the end date advances, averaging 5.54 days earlier by 2031s. RCP8.5 follows a delay trend, with the end date in 2031s being 7.73 days later than in 2016s. Collectively, the duration of fire danger across scenarios typically spans from December to the following June. Notably, under the RCP8.5 scenario, the increase in the FWI index is the greatest, with the fire danger days extending to 192 by 2031s. In contrast, RCP4.5 shows the least change, maintaining around 180 days in both 2016s and 2031s.

The high fire danger period, characterized by elevated wildfire frequency, also exhibits a delayed onset across all scenarios over the years. By 2031s, the first day of high fire danger in RCP2.6, RCP4.5, and RCP8.5 is delayed by 4.34, 1.66, and 7.32 days, respectively, compared to 2016s. The conclusion of this period similarly delays by 1.26, 3.54, and 13.92 days in the respective scenarios for 2031s. The high fire danger period usually extends from March to June, with RCP8.5 experiencing the most substantial change, where the number of high fire danger days increases to 94 days.

3.2.2 Local changes in the fire danger period

We divided Yunnan's 25 meteorological stations, based on their geographical coordinates, into five distinct regions: east, south, west, north, and central. Analysis of the interannual variability in these regions reveals distinct patterns under different Representative Concentration Pathway (RCP) scenarios.

In the eastern region, as depicted in Fig. 6a, the trend under RCP4.5 and RCP8.5 scenarios is aligned, showing a contrast to the divergent trend observed under RCP2.6. Throughout the study period, the Fire Weather Index (FWI) remains below 10 across all scenarios, suggesting a lower fire risk in this area.

Moving to the southern region (Fig. 6b), a similar pattern to the eastern region emerges. Under RCP4.5 and RCP8.5, the mid-year FWI values stay below 10, but notably, they exceed 15 in January and February, indicating potential fire danger during these months; in the western region, as shown in Fig. 6c, under RCP4.5 and RCP8.5, the FWI falls below 10 from September to November annually. However, from December to April, the FWI surges above 20, signaling a heightened fire risk during this period; in the northern region, represented in Fig. 6d, exhibits similar variability trends

Table 3 Comparison of results between fire danger periods and high fire danger periods

	RCP2.6		RCP4.5		RCP4.5		RCP8.5		RCP8.5		RCP8.5	
	2016s	Days	2031s	Days	2016s	Days	2031s	Days	2016s	Days	2031s	Days
Fire danger period	12a–5c	181	12b–5c	184	12a–5c	181	12a–5b	180	12a–5c	181	11c–6a	192
High fire danger period	3a–5c	88	3b–5c	85	3a–5c	88	3b–5b	90	3a–5c	88	3c–6a	94

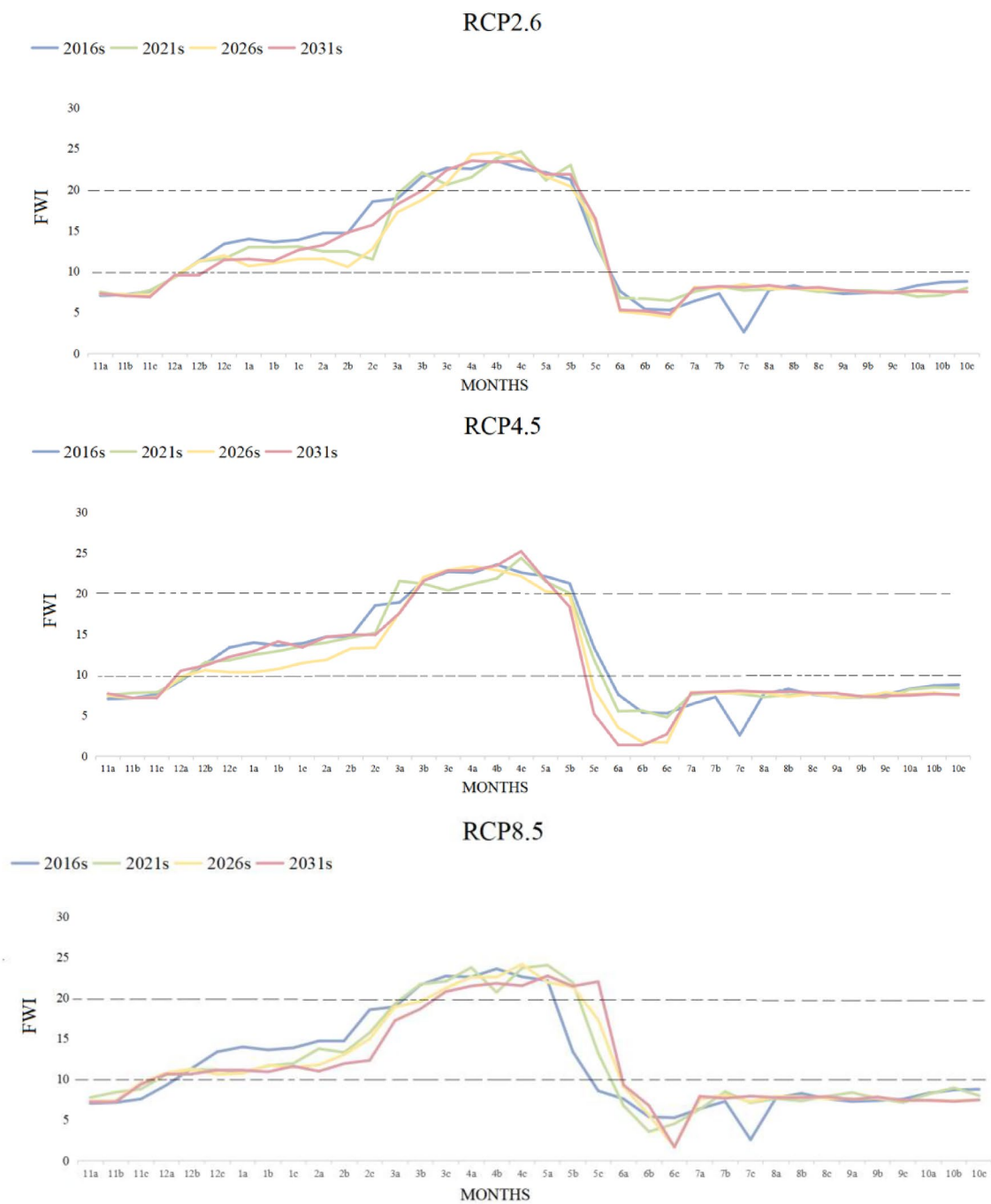


Fig. 5 Distribution of fire danger periods in different climate scenarios

under RCP4.5 and RCP8.5, which differ from RCP2.6. For most years under RCP4.5 and RCP8.5, except for 2020–2022, the FWI is lower in November and December but rises above 15 from January to May, with peaks over 20 from March to May, indicative of high fire danger. Under RCP2.6, the FWI is generally below 10 towards the year-end but exceeds 15 from May to November, with values over 20 from June to August, also suggesting a high fire risk; lastly, the central region (Fig. 6e) displays variability trends under all three scenarios akin to the eastern region. The FWI values consistently stay below 10, implying a minimal fire danger during the study period in this area.

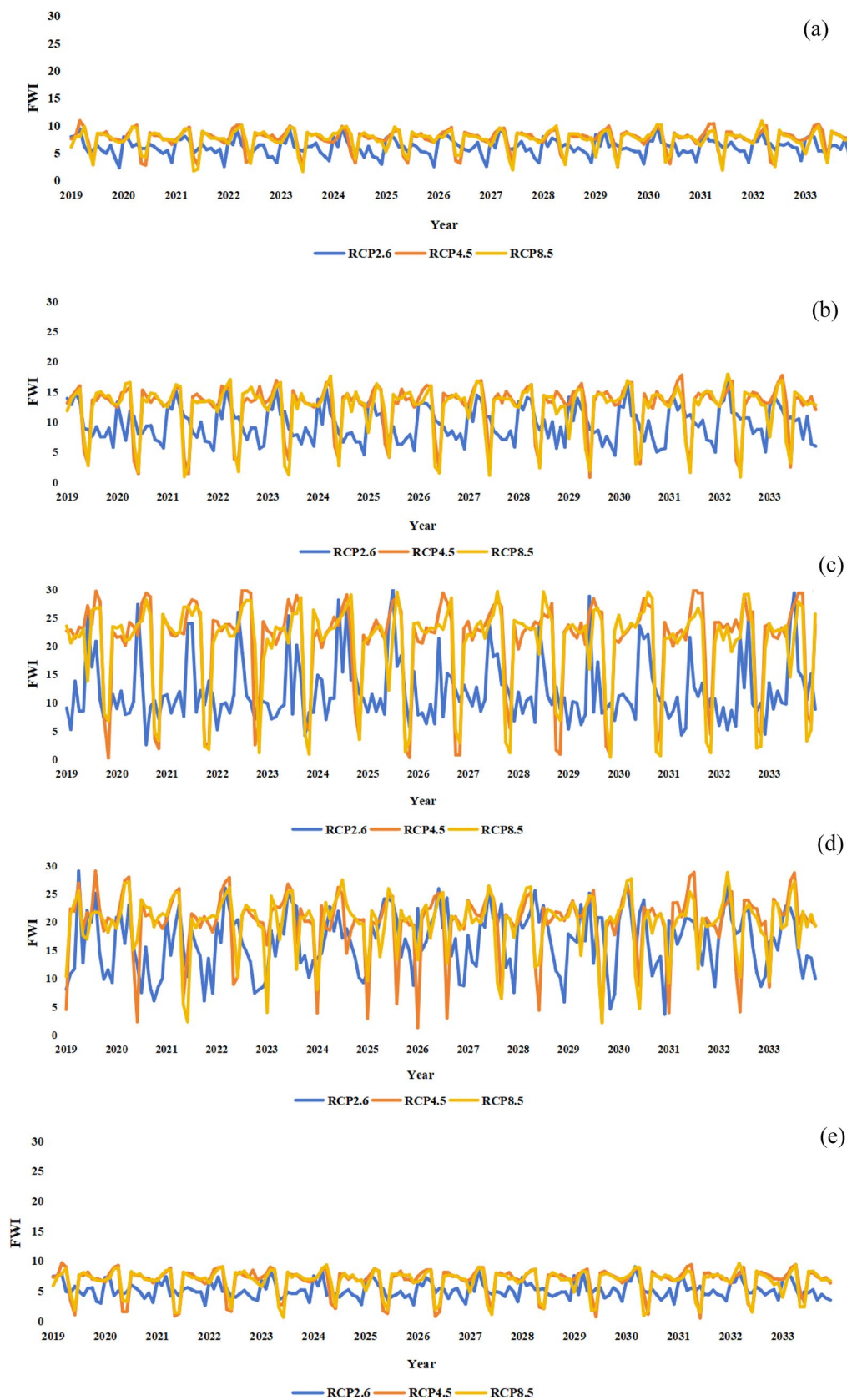


Fig. 6 Variations in local fire danger across different regions. **a** Eastern region; **b** Southern region; **c** Western region; **d** Northern region; **e** Central region

3.3 Fire danger zone

This study explores the spatial distribution of fire danger areas across various climate scenarios (RCP2.6, RCP4.5, and RCP8.5) during four distinct periods: 2016s (2014–2018), 2021s (2019–2023), 2026s (2024–2028), and 2031s (2029–2033). Under the RCP2.6 scenario, as illustrated in Fig. 7, most regions consistently exhibit FWI values between 3 and 15 across all periods, with a notable increasing FWI trend from northeast to southwest. However, a decrease to 2.2 in FWI is observed in southeastern Yunnan by 2031s, contrasting with northwestern Yunnan, where FWI initially exceeds 17.5 but later diminishes by 3.8 in the 2031s. Most forested areas in Yunnan experience a FWI increase, particularly in the west, while the northeast sees the least rise. Figure 8, showcasing the RCP4.5 scenario, reveals a pattern similar to RCP2.6, with an overall upward FWI trend, except for some fluctuations in the northwest and southeast, peaking at a deviation of 4.7. A notable FWI decrease by 1.3 is observed in southwest Yunnan during the 2026s, despite the prevailing upward trend. The RCP8.5 scenario, depicted in Fig. 9, aligns with the trends of the other scenarios, generally marked by an increase in FWI, except in parts of the northeast and southeast. The most substantial rise is in northwestern Yunnan, where FWI consistently exceeds 17.5 and shows an increase up to 5.3 between 2031 and 2016s. Throughout Yunnan, all scenarios indicate an increasing FWI, signaling a heightened fire danger, especially in the western region, where FWI ranges between 4 and 8. The increase is less marked in northeastern Yunnan.

Furthermore, the spatial grid difference method was utilized to analyze fire danger area distribution across each period and scenario, as shown in Fig. 10. As per Table 4, under RCP2.6, there is a gradual expansion of the Fire Danger Level 2 Elevated Zone in central Yunnan and the Elevated Fire Danger Level 1 Zone in southern and eastern Yunnan. In RCP4.5,

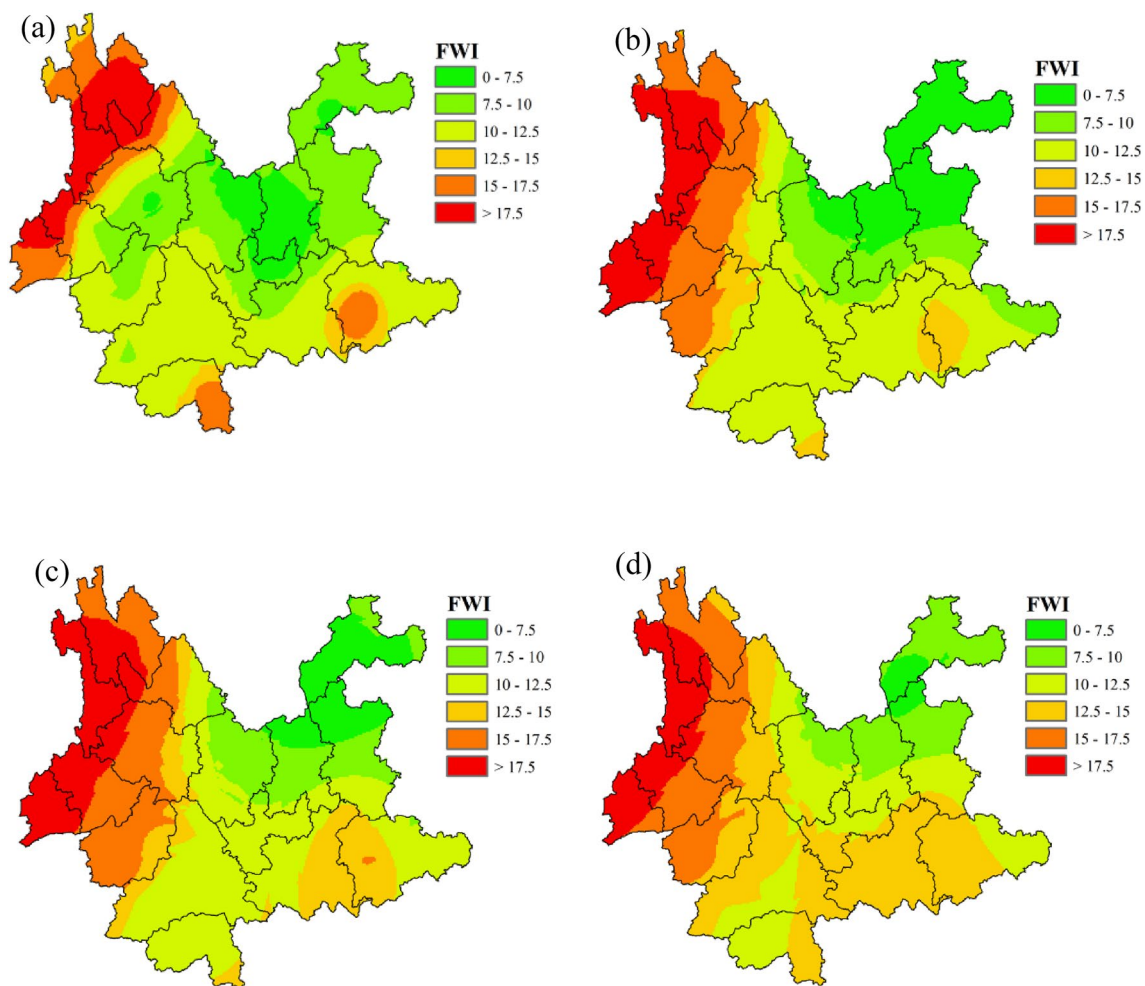


Fig. 7 The spatial distribution of FWI values in the RCP2.6 scenarios for the four periods. **a** 2016s; **b** 2021s; **c** 2026s; **d** 2031s

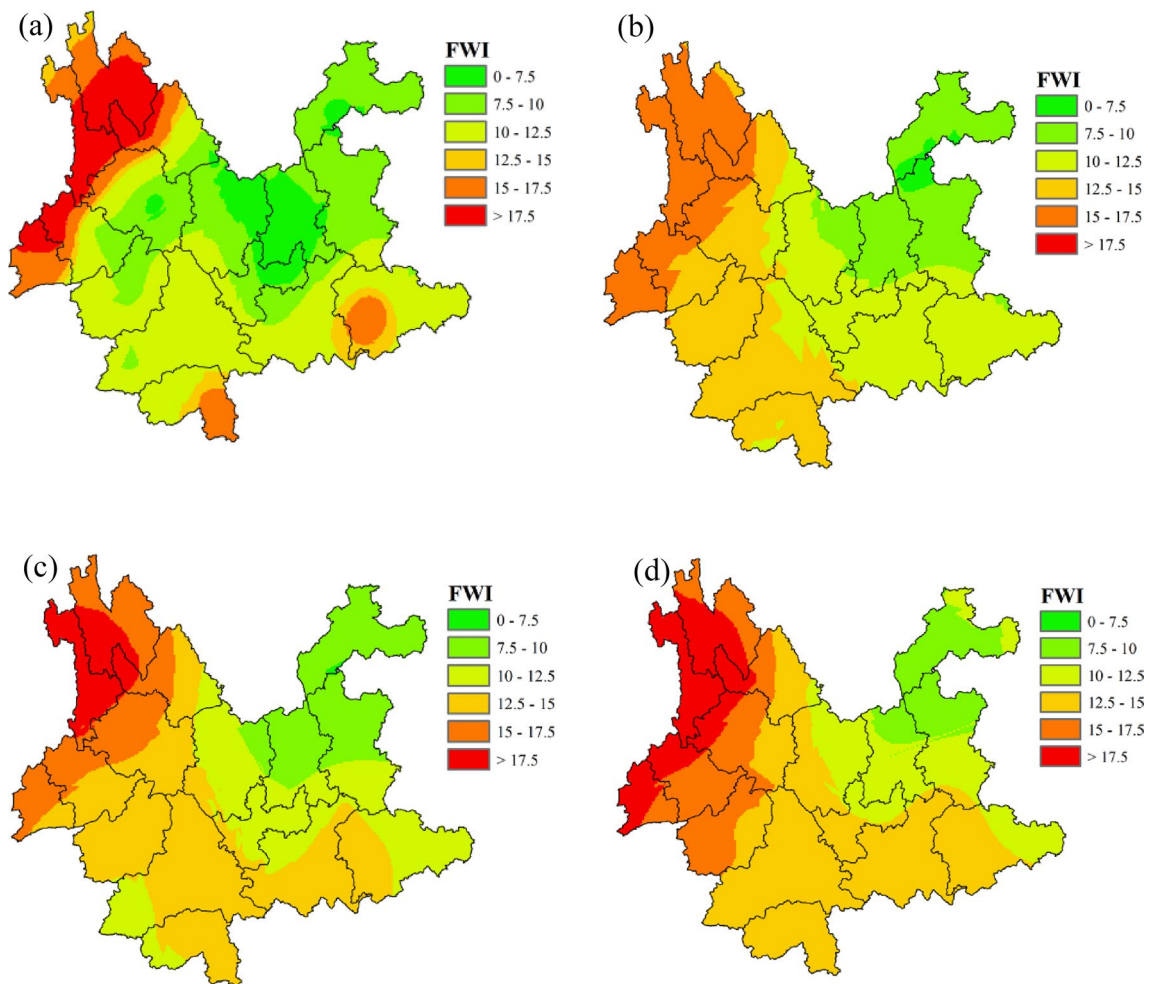


Fig. 8 The spatial distribution of FWI values in the RCP4.5 scenarios for the four periods. **a** 2016s; **b** 2021s; **c** 2026s; **d** 2031s

these zones exhibit a sporadic spread across southwest, central, and southeast Yunnan. Under RCP8.5, a expansion of the Level 2 Elevated Zone is noted in western Yunnan, highlighting an escalating danger in this area.

4 Discussion

In this study, we conducted a detailed analysis of future fire dangers in Yunnan Province, focusing on the potential impacts of climate change on fire hazards. Utilizing the RegCM regional climate model, we simulated the meteorological conditions in Yunnan Province from 2019 to 2033 and applied the Canadian Fire Weather Index (FWI) to assess the impact of different climate change scenarios on fire dangers. These scenarios include RCP2.6, RCP4.5, and RCP8.5. The Intergovernmental Panel on Climate Change (IPCC) in its fifth assessment report proposed greenhouse gas concentration scenarios for future climate assessment, forming four categories from low to high concentration pathways (RCP): RCP2.6, RCP4.5, RCP6.0, and RCP8.5, with the numerical values behind RCP representing the level of radiative forcing of CO₂ concentrations by 2100 [33]. Due to the small differences between RCP4.5 and RCP6.0, RCP2.6 is usually chosen as the lowest pathway, RCP4.5 as the intermediate, and RCP8.5 as the highest. RCP2.6 is the most optimistic scenario, assuming that humanity adopts more proactive measures to address climate change, leading to a decline in future greenhouse gas emissions, with a temperature increase not exceeding 2 °C by the end of this century. RCP4.5 indicates that human carbon emissions will start to decrease after 2080, but the outcome will still exceed reasonable values, with a temperature rise reaching 2.7 °C. RCP8.5 suggests that by 2050, CO₂ emissions will double, and by 2100, the concentration of CO₂ in the air will be 3–4 times higher than before the industrial revolution, with a temperature rise exceeding 4 °C [34].

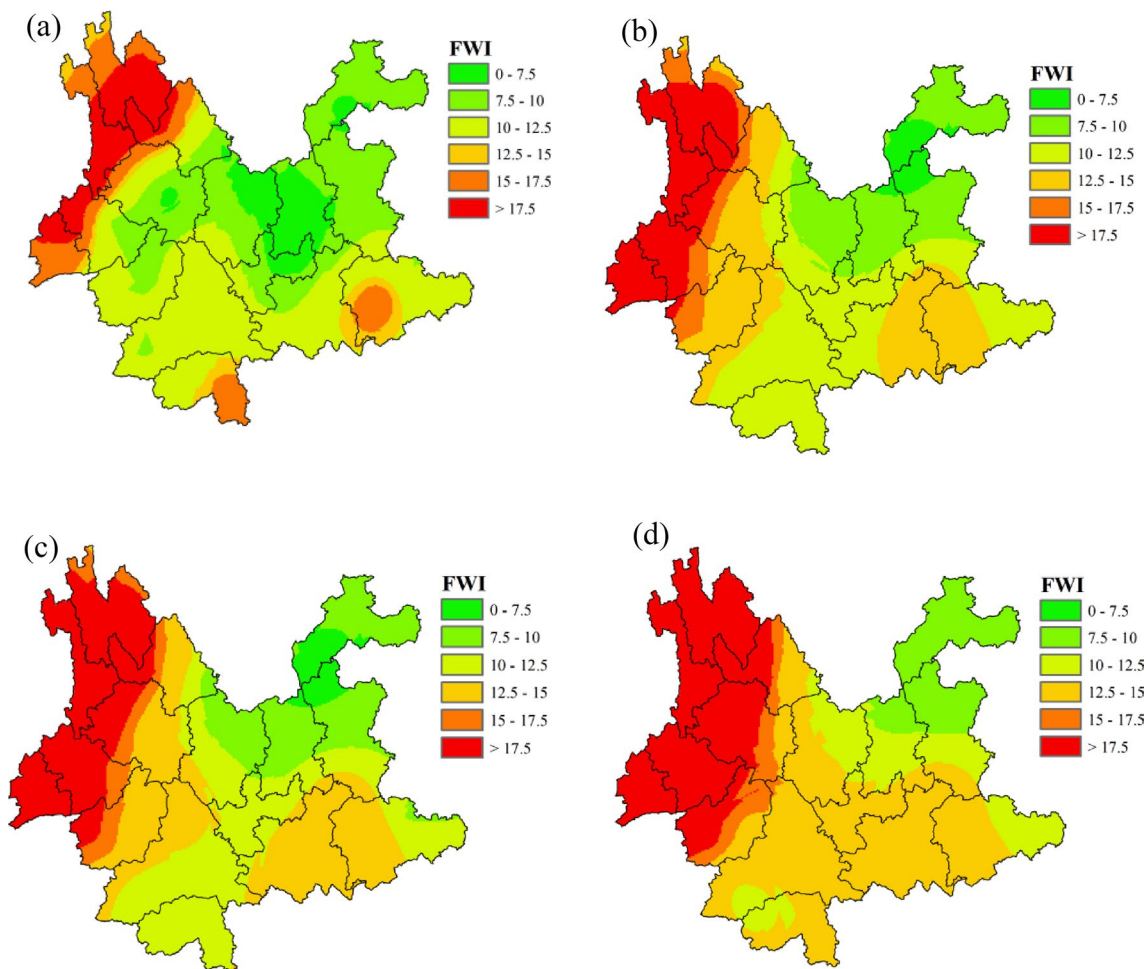


Fig. 9 The spatial distribution of FWI values in the RCP8.5 scenarios for the four periods. **a** 2016s; **b** 2021s; **c** 2026s; **d** 2031s

Based on the comprehensive analysis of forest fire dynamics in Yunnan Province, China, under various climate change scenarios, this study has highlighted insights into the evolving nature of fire risks in the region. Under the RCP2.6 scenario, the study observed a general increase in the Fire Weather Index (FWI), with the greatest rise in FWI seen in western Yunnan, indicating an increase in fire danger. However, some areas like southeastern Yunnan displayed a slight decrease in FWI by 2031s compared to 2016s, revealing the variability within the region. The RCP4.5 scenario showed a similar upward trend in FWI across Yunnan, though with noticeable fluctuations in northwest and southeast Yunnan. These variations suggest a more sporadic spread of fire danger zones, particularly in these areas.

Contrastingly, under the RCP8.5 scenario, the study found the most substantial changes, with northwestern Yunnan's FWI exceeding 17.5, pointing to a rise in fire danger. This scenario predicts a notable increase in fire danger days, especially in the western region, highlighting the need for enhanced fire risk management in the coming years. Moreover, the study revealed that under all scenarios, the high fire danger period typically extends from March to June, with RCP8.5 exhibiting the largest increase in the FWI index. The spatial grid difference method used in the analysis effectively illustrated the distribution and expansion of fire danger zones across Yunnan, emphasizing the need for adaptive fire management strategies. This research provides valuable insights for policymakers and forest managers in Yunnan, aiding in developing targeted and effective forest fire prevention and management strategies amid changing climatic conditions.

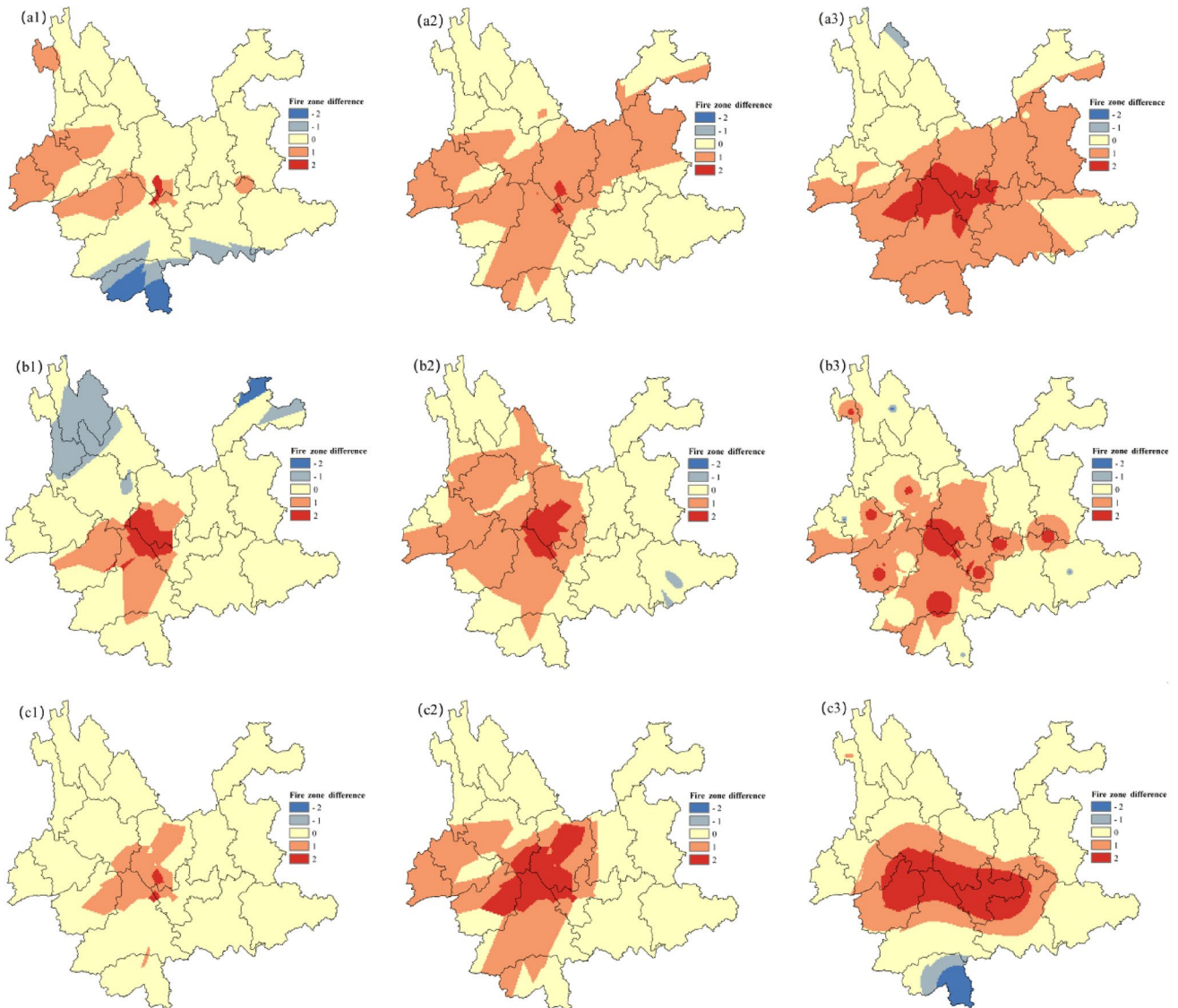


Fig. 10 Variation of the difference in fire danger zones between the different scenarios for each period and 2016s. **a** RCP2.6; **b** RCP4.5; **c** RCP8.5; **1** 2021s; **2** 2026s; **3** 2033s

Table 4 The code of fire zone difference

Difference	Code
-2	The reduced fire danger level 2 zone
-1	The reduced fire danger level 1 zone
0	The no change fire danger zone
1	The elevated fire danger level 1 zone
2	The elevated fire danger level 1 zone

5 Conclusion

This study focuses on Yunnan Province, thoroughly analyzing how climate change exacerbates the risks and challenges of wildfires. The intensification of global warming has led to an increase in the frequency and intensity of extreme wildfires, a trend that is evident not only in Yunnan Province but also globally, as seen in severe fires in areas

such as China's Daxing'anling, Greece, Australia, and Siberia. This indicates that climate change is altering the fire environment and impacting fire behavior. In the study of Yunnan Province, the RegCM regional climate model and the Canadian FWI system were used to predict and analyze future fire risks. Although these models are effective, they have certain predictive errors. Although the RegCM model has high predictive accuracy in Yunnan's forest areas [35], there may still be differences between its predictions and actual situations since the model samples are not from that region. To reduce these discrepancies, it is necessary to construct a more precise regional climate model using actual climate and terrain data from Yunnan's forest areas. The FWI, as a mainstream fire risk calculation model, has been proven to be applicable to Yunnan [36–38], but its calculation results may also have biases.

The study shows that future forest fire risks in Yunnan Province are positively correlated with the increase in carbon emissions. Therefore, effectively reducing forest fire losses requires controlling future greenhouse gas emissions [39], a task not only for forest fire management departments but also requiring the participation and effort of the entire society. Forest fire management departments should focus on the annual temperature increase in the region and, based on the conclusions of this study, pay attention to the changes in fire risk periods and areas, especially the areas where fire risk level two jumps, to improve emergency response capabilities for sudden major fires. Considering the long construction period required for fire prevention infrastructure such as fire monitoring, fire roads, wells, and communication facilities, it is necessary for forest fire management departments to plan ahead in infrastructure construction and emergency preparation. This study provides valuable experience for forest fire prevention and management worldwide, emphasizing the importance of collaboration between policymakers, scientists, and local managers to develop effective strategies to address the threats posed by future wildfires.

Author contributions Conceptualization: XDeng, FZ; funding acquisition, FZ; writing—reviewing and editing, XDeng, FZ, JL, FZ and HD; field investigation, experiment, and data analysis, XDeng, XDai; All authors have read and agreed to the published version of the manuscript.

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Data availability Data sets generated during the current study are available from the author on reasonable request. The meteorological data are available from China National Meteorological Information Centre but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. To request data for this study, please contact the author, X.Deng.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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