Landslides
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Spatiotemporal patterns of non-seismic fatal landslides in China from 2010 to 2022

Abstract Landslides represent a major global natural disaster, often leading to severe consequences, including substantial loss of life and property. However, research on the spatiotemporal distribution characteristics of fatal landslide events across different climate regions and their association with precipitation remains limited. In this study, we compiled a database of non-seismic fatal landslides in China from 2010 to 2022 to examine their spatiotemporal distribution and relationship with precipitation. From 2010 to 2022, China experienced a total of 710 fatal landslide events, causing 5158 fatalities. The data revealed a declining trend in both the number of fatal landslides and associated fatalities, with the number of fatal landslides demonstrating a recurring cycle of 3–4 years marked by continuous decreases within each cycle. The initial year of a new cycle witnessed a significant increase in the number of fatal landslides, suggesting a periodic occurrence, which is related to El Niño. The central subtropical humid region recorded the highest number of fatal landslide events, attributed to its highest annual precipitation. The trend in fatal landslides closely corresponded with variations in precipitation, increasing in spring and summer and decreasing in autumn and winter. The cumulative frequency distributions of fatal landslides and fatalities followed a power-law distribution, with a sharp decline observed when exceeding a certain value, indicating a deflection effect. Despite the low population density, the plateau climate region has the highest risk of life loss among all climate regions. Understanding the spatial distribution of non-seismic fatal landslides can significantly aid in formulating more effective disaster prevention and mitigation policies.

Keywords Landslide · Fatal landslide · Spatiotemporal distribution · Landslide risk

Introduction

Landslides are a widespread geological hazard causing significant annual loss of life and property globally (Salvati et al. 2010; Petley 2012; Qiu et al. 2018; Cui et al. 2019). At least 17% of natural disaster fatalities are due to landslides (Kjekstad and Highland 2009; Lacasse et al. 2009). The "Sendai Framework for Disaster Risk Reduction 2015–2030" emphasizes the importance of understanding disaster risk, advancing landslide data collection, and analyzing data to support policymakers and inform the public (UNISDR 2015).

China is a high-risk country for landslides, with 15% of global rainfall-induced landslide events occurring there (Froude and Petley 2018). It also has one of the highest fatality rates from landslides (Petley 2012; Lin et al. 2017). The increasing impact of landslides on human lives is exacerbated by economic growth, urbanization, land use change, population growth, and extreme precipitation events. Awareness raising of fatal landslides is needed to reduce associated losses (Li et al. 2017, 2024; Zhu et al. 2021, 2023; Zhou et al. 2022).

Fatal landslides, those resulting in loss of life, require a comprehensive database for understanding spatiotemporal patterns and mitigating damage. This is especially important in mountainous regions where hazard assessments and dissemination of knowledge about fatal hazards are crucial. Research on fatal landslides focuses on their spatiotemporal distribution and connections to climate change or social indicators (Kirschbaum et al. 2015; Haque et al. 2016; Görüm and Fidan 2021; de Azevedo Couto et al. 2023), as well as post-event assessments of life loss and causes (Myung and Jang 2011; Salvati et al. 2018; Shabbir et al. 2022; Shinohara and Kume 2022). Further, Studies by Badoux et al. (2016), Strouth and McDougall (2021), and Cabral et al. (2022) have compared life losses and proposed measures to reduce fatal landslide impacts (Pollock and Wartman 2020; Ye et al. 2024).

Landslide databases, derived from media reports, historical archives, government databases, field surveying, and research papers, are either event-based or historical. Event-based databases focus on specific triggers, such as precipitation or storms, while historical databases document landslides over certain periods and geographical areas. For instance, some databases for studying landslides in Germany and thaw slumps on the Tibetan Plateau (Damm and Klose 2015; Yang et al. 2023; Liu et al. 2024). In China, research on fatal landslides includes Zhang and Huang's (2018) analysis of non-seismic fatal landslides from 2004 to 2016, showing an upward trend in events but decreased economic losses. Lin and Wang (2018) compiled the FLEIC database of fatal landslides from 1950 to 2016, revealing frequency variations. Zhang et al. (2023) constructed a database of fatal landslides from 1940 to 2020, linking GDP/urbanization rates to anthropogenic landslides.

Despite studies on the temporal and frequency distribution of fatal landslides (Guzzetti et al. 2005; Petley 2012; Zhang and Huang 2018), research on their spatiotemporal patterns in China is limited. Only a few studies have applied power-law functions to the frequency distribution of landslides in Shaanxi Province (Qiu et al. 2020). Research on spatial distribution has mainly focused on administrative and geomorphological divisions, not climate regions (Lin and Wang 2018; Zhang and Huang 2018; Zhang et al. 2023). Therefore, this study aims to: (1) compile a database of fatal landslide events, (2) analyze their spatiotemporal distribution and relationship with precipitation, and (3) compare risks of life loss across different climate regions to enhance scientific understanding and raise awareness of risk for fatal landslides in China.

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Materials and methods

Data collection

The main factors triggering fatal landslides include precipitation and earthquakes. This study specifically focused on non-seismic fatal landslides, primarily those induced by precipitation. Following the updated Varnes classification of landslide types as revised by Hungr (Varnes 1978; Cruden and Varnes 1996; Hungr et al. 2013), this research collected data on landslide events causing loss of life, such as landslides, collapses, rockfalls, and debris flows.

Given the limited data availability before 2010, this study specifically focuses on fatal landslide events occurring between 2010 and 2022. The data sources include disaster and government reports, the international disaster databases EM-DAT (https://public.emdat.be/) (Guha-Sapir et al. 2018), the NASA Cooperative Open Online Landslide Repository (COOLR) (https://gpm.nasa.gov/landslides/index.html) (Kirschbaum et al. 2009, 2015), the Global Fatal Landslide Database (Froude and Petley 2018), the Landslide Blog of Petley (https://eos.org/landslide-blog), as well as reports from media and published research papers.

Since EM-DAT records only severe events (with more than 10 fatalities or affecting over 100 people), and recent databases may contain location errors, corrections were applied using information from local media reports. Cross-checks and data updates for fatal landslides were conducted using multiple information sources. In cases of discrepancies, the reliability of the sources was assessed based on the following hierarchy: government websites > news media and databases > personally published information, with information from government websites used as the standard for cross-checking. For events not recorded by government websites, the most severe case reported was used (Guzzetti 2000), typically identified by the highest number of fatalities, as fatalities from fatal landslide events are often underestimated (Froude and Petley 2018). In situations where fatal landslides occur concurrently with significant geological or meteorological disasters, the resulting loss of life is often attributed to the larger events such as earthquakes, floods, or meteorological disasters, rather than to the landslides themselves (Kirschbaum et al. 2009; Perkins 2012), Consequently, casualty figures are typically reported collectively (Guzzetti et al. 2005), complicating the task of isolating data on fatalities directly resulting from landslides. The lack of comprehensive follow-up reports has led this study to use the initially reported numbers of fatalities as the final count (Garcia-Delgado et al. 2022). Although this method of data collection may still lead to an underestimation of the actual loss of life attributable to fatal landslides, what was collected is sufficient for our study.

The catalogue contains the following information for each record: unique identifiers ID, date and time of fatal landslide events, location (depending on the level of detail recorded in information sources), triggering factors, fatalities, missing persons, and information sources. To describe the uncertainty in the exact location of fatal landslides, we adopted the method of Kirschbaum et al. (2009), assigning a radius of confidence to fatal landslides whose locations were not accurately recorded to explain the uncertainty in the event's occurrence location (Table 1). The categories in Table 1 represent the accuracy of the fatal landslide location, with Category 1 being the most accurate. The triggering factors were categorized as either 'precipitation' or 'unknown,' with 'unknown' indicating cases where the information source did not provide sufficient detail. Since most landslides are caused by multiple factors, the triggering factor here refers to the factor determined by the information source.

Following this approach, this study compiled the Fatal Landslide Database for China from 2010 to 2022, including 710 fatal landslide events (Fig. 1), resulting in 5158 fatalities. The most severe event was a debris flow that occurred on August 7, 2010, in Zhouqu County, Gansu Province, causing 1765 fatalities (Guha-Sapir et al. 2018). Due to the fact that 36 fatal landslide events could only be determined at the provincial level, they were therefore excluded from the spatial analysis. Considering the multi-year average mean temperature, precipitation and moisture conditions, China is divided into seven climate regions (Zhao 1983; Yao et al. 2018).

Power law relationship

This study employed a power-law function to fit the cumulative frequency of fatal landslide events and the fatalities. The calculation formula is as follows (Guzzetti et al. 2001; Qiu et al. 2019, 2020):

$$CF = aN^b$$

where: CF represents the cumulative frequency, N denotes the number of landslides or fatalities, and a and b are constants.

Results

Temporal characteristics of fatal landslides

Annual temporal distribution of fatal landslides

The number of fatal landslide events and associated fatalities in China showed a downward trend during the period from 2010 to 2022, with the highest number of fatal landslide events (126) in 2013, while in 2010, the highest number of fatalities was observed, with 57 fatal landslide events resulting in 2613 fatalities. The annual averages for the number of fatal landslide events and fatalities were 55 and 396, respectively (Fig. 2).

Table 1 Radius of confidence in fatal landslides location

Landslide location classification	Radius of confidence	Reporting of landslide location
1	< 5km	Exact or near exact location of fatal landslides
2	5-50km	Landslide location known within the extent of county or village
3	> 50km	Landslide location known within the extent of province or city

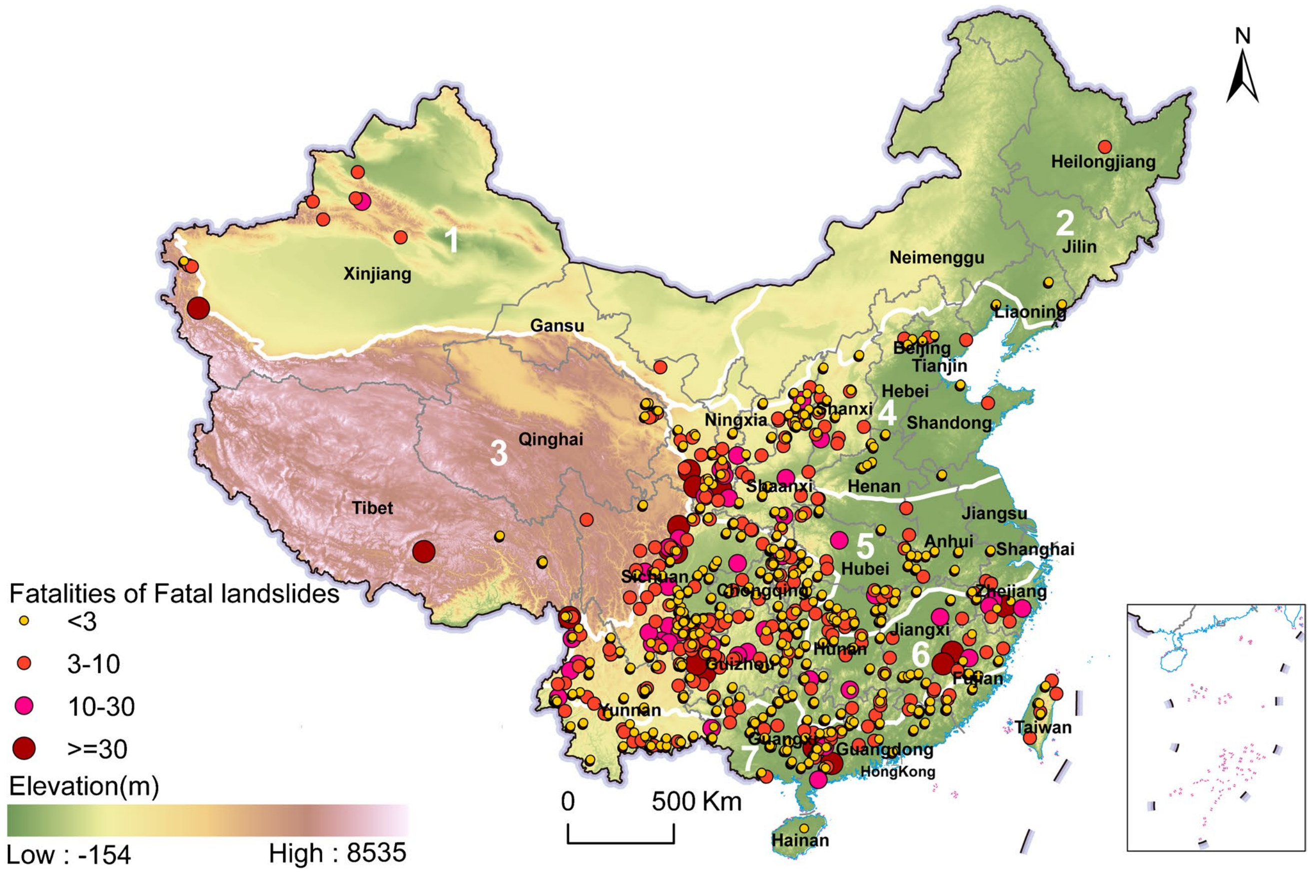

Fig. 1 The spatial distribution of fatal landslides in China from 2010 to 2022.The white lines and numbers represent the seven climate regions of China. 1: Temperate arid region; 2: Temperate semi-humid semi-arid region; 3: Plateau climate region; 4: Warm temperate semi-humid region; 5: North subtropical humid region; 6: Central subtropical humid region; 7: Marginal tropical humid region

The cumulative curve of fatal landslide events in China during 2010–2022 reveals three declining cycles (Fig. 2a): 2013–2015, 2016–2019, and 2020–2022. Within each cycle, the number of fatal landslide events consistently decreased, yet each cycle's initial year marked a sharp increase.

In the first cycle (2013–2015), there was an overall count of 213 fatal landslide events, with the number of fatal landslide events showing a continuous decrease throughout the cycle. In 2015, compared to 2013 and 2014, fatal landslide events decreased by 72.22% and 32.69%, respectively. However, in 2016 (the start of a new cycle), the number of fatal landslide events sharply increased, growing by 108.57% compared to 2015. In the second cycle (2016–2019), 173 fatal landslide events occurred, representing an 18.78% decrease from the first cycle. The third cycle (2020–2022) witnessed a further reduction in the number of fatal landslide events by 37.09% and 22.54% compared to the previous two cycles. The downward trend in fatalities was even more significant, with a 68.66% reduction in fatalities from 2020 to 2022 compared to 2016–2019.

To further explore the periodicity of landslide events, we analyzed the relationship between the number of landslide events and the El Niño Southern Oscillation (ENSO), a factor that causes multi-year changes in rainfall patterns. El Niño is measured by the Ocean Niño Index (ONI). We obtained the ONI values for 2010–2022 and compared them with the number of landslide events (Fig. 2).

From 2010 to 2022, strong El Niño events occurred in 2014–2016 (ONI greater than or equal to + 1.5°C), and weak El Niño events occurred in 2018–2019 and 2019–2020 (ONI between + 0.5°C and + 1.0°C). Our analysis showed that the number of landslide events increased significantly in 2016 and 2020, and the increase in 2020 was lower than in 2016 (Fig. 2).

Monthly temporal distribution of fatal landslides

From 2010 to 2022, fatal landslides in China mainly occurred from May to September. A total of 587 fatal landslide events occurred during this period, constituting 82.68% of the overall occurrences in China during the same timeframe. These events resulted in 4510 fatalities, representing 87.44% of the total fatalities caused by fatal landslides in China during the same period. Among these, July experienced the peak of fatal landslide occurrences, with 199 events (28.03%), while the month of August experienced the most severe loss of life, with an alarming total of 2,323 fatalities, accounting for 45.04% of the annual total (Fig. 3). As shown in Table 2, the monthly distribution of fatal landslides is significantly positively correlated with monthly precipitation in China.

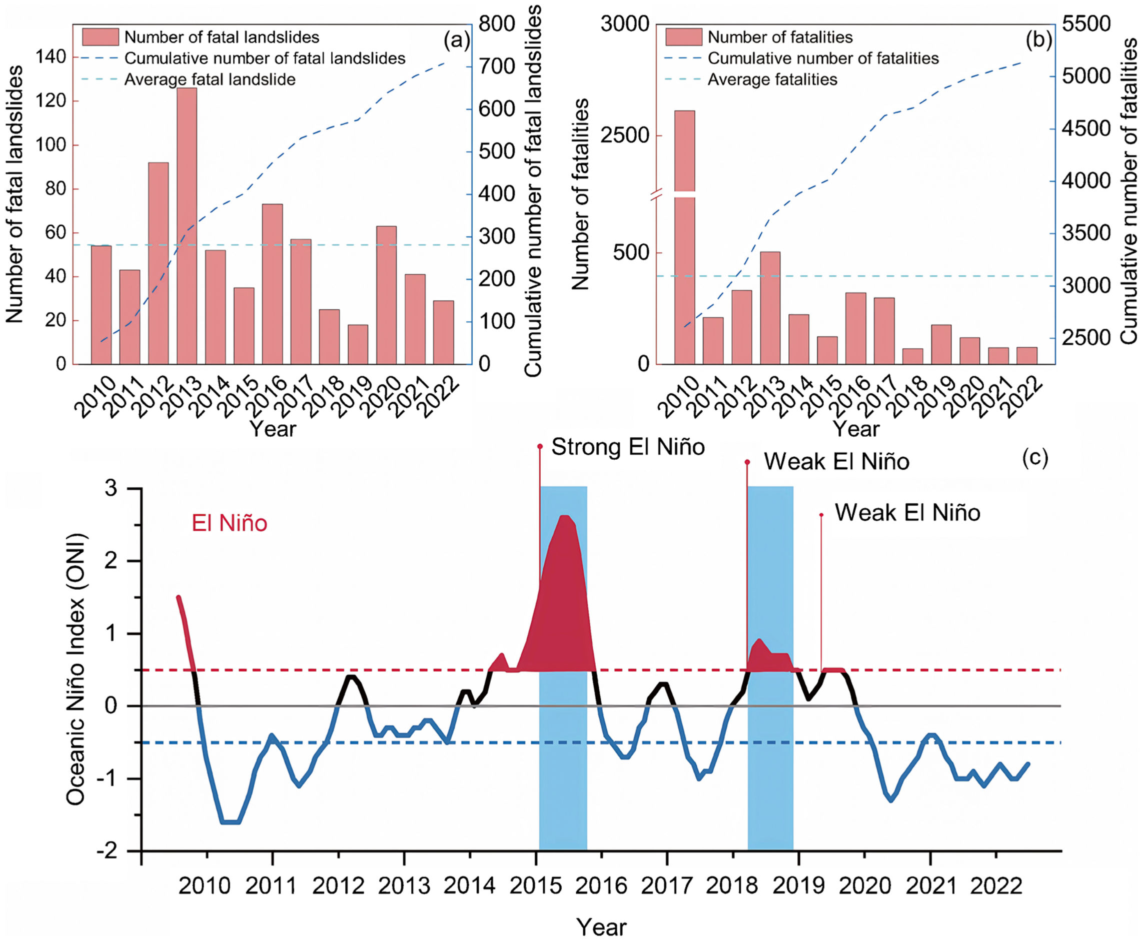

Fig. 2 Temporal variations in number of **a** fatal landslides and **b** fatalities each year, and cumulative curve from 2010 to 2022 **c** Trend of the Oceanic Niño Index (ONI)

Spatial characteristics of fatal landslides

Provincial scale of fatal landslides

Between 2010 and 2022, fatal landslide events occurred in at least one instance across 28 provinces in China. Yunnan province witnessed the highest number of fatal landslide events (109), constituting 15% of all fatal landslide events. The terrain here is complex and mountainous, and residents' awareness of preventing geological disasters is relatively weak, making it a prone area to fatal landslides. It was followed by Sichuan, Guangxi, Hunan, Shaanxi, and Guizhou, with 87, 69, 62, 53, and 51 events, respectively. Fatal landslides in Gansu during this period resulted in 2013 fatalities, accounting for 39% of the total fatalities in fatal landslide events in China during the same period. This total includes the devastating Zhouqu debris flow incident in 2010, which claimed 1765 lives. Excluding this event, Gansu's fatalities are 240. It was followed by Sichuan, Yunnan, Guizhou, and Shaanxi, with 580, 511, 401, and 234 fatalities, respectively (Fig. 4).

Climate region scale of fatal landslides

In different climate regions of China from 2010 to 2022, the central subtropical humid region experienced the highest number of fatal landslide events, reaching 312, constituting 46.29%. This led to 1447 fatalities, with an average of 24 events and 112 fatalities annually. Except for 2010, 2011, and 2017, the central subtropical humid region consistently reported the highest fatalities. The second-highest occurrences were observed in the marginal tropical humid region, with 126 fatal landslide events causing 403 fatalities, averaging 10 events and 31 fatalities annually. The warm temperate semi-humid region and north subtropical humid region witnessed 96 and 90 fatal landslide events, resulting in 414 and 2103 fatalities, respectively. The plateau climate region, temperate arid region, and temperate semi-humid and semi-arid region reported fewer fatal landslide events, with 38, 7, and 7 events and fatalities of 371, 58, and 13, respectively (Fig. 5a and b).

The annual variations in fatal landslide events were similar across different climate regions in China from 2010 to 2022, showing a fluctuating downward trend. Notably, the central subtropical

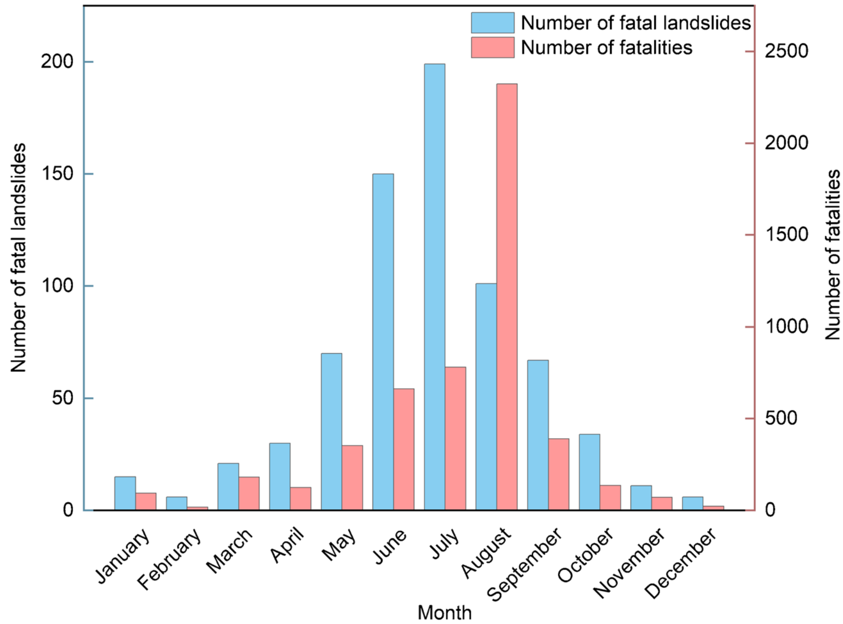

Fig. 3 Monthly variations of number of fatal landslides and fatalities from 2010 to 2022

Table 2 Pearson correlation coefficient between average monthly precipitation and frequency of monthly fatal landslide

Region	Correlation coefficient	*P* value
Temperate arid region	0.83	< 0.05
Temperate semi-humid semi-arid region	0.46	
Warm temperate semi-humid region	0.80	< 0.05
North subtropical humid region	0.78	< 0.05
Central subtropical humid region	0.88	< 0.05
Marginal tropical humid region	0.96	< 0.05
Plateau climate region	0.88	< 0.05
China	0.94	< 0.05

humid region exhibited the most significant downward trend, with the number of fatal landslide events decreasing by 27.55% and 5.63% in 2020–2022 compared to 2016–2019 and 2013–2015, respectively (Fig. 5c).

Fatal landslide events and fatalities in China from 2010 to 2022 showed obvious spatial aggregation characteristics (Fig. 6) and different aggregation centers. Fatal landslide events were mainly concentrated in the marginal tropical humid region, the northern Shaanxi and southern Gansu in the warm temperate semi-humid region, Chongqing in the mid-subtropical humid region, and the junction of Sichuan, Yunnan, and Guizhou (Fig. 6a). The majority of fatalities occurred in central Sichuan, particularly at the intersection of the plateau climate region and the mid-subtropical humid region, as well as at the junction where Sichuan, Yunnan, and Guizhou meet within the mid-subtropical humid region (Fig. 6b).

Frequency distribution of fatal landslide events and fatalities

This study employed a power-law function to fit the cumulative frequency of fatal landslide events and associated fatalities in China from 2010 to 2022, expressed on a log–log scale (Cruden and Fell 1997; Qiu et al. 2024). The fatal landslide events were divided into two classes by the fitted lines: small-scale with low destructiveness and large-scale with high destructiveness. The steepness of the fitted line reflects the frequency of these two classes of events, where the steeper line indicates lower frequency and the flatter line indicates higher frequency. As the number of fatal landslide events and associated fatalities increased from 2010 to 2022, the cumulative frequency continued to decline. As the number increases, their frequency distribution showed a continuous downward trend. When the annual number of fatal landslide events exceeds 63, and the fatalities surpass 66 individuals, the frequency distribution exhibits a deflection effect. (Fig. 7a and b). This indicated that large-scale fatal landslides with high destructiveness occurred less frequently.

To assess the risk of life loss associated with fatal landslides, a comparison was made among five climate regions (plateau climate region, warm temperate semi-humid region, north subtropical humid region, central subtropical humid region, and marginal tropical humid region) with fatal landslide events exceeding 30 times from 2010 to 2020. The results indicated that the plateau climate region posed the highest risk of life loss, followed by the warm temperate semi-humid region, north subtropical humid region, and central subtropical humid region. The marginal tropical humid region exhibited the

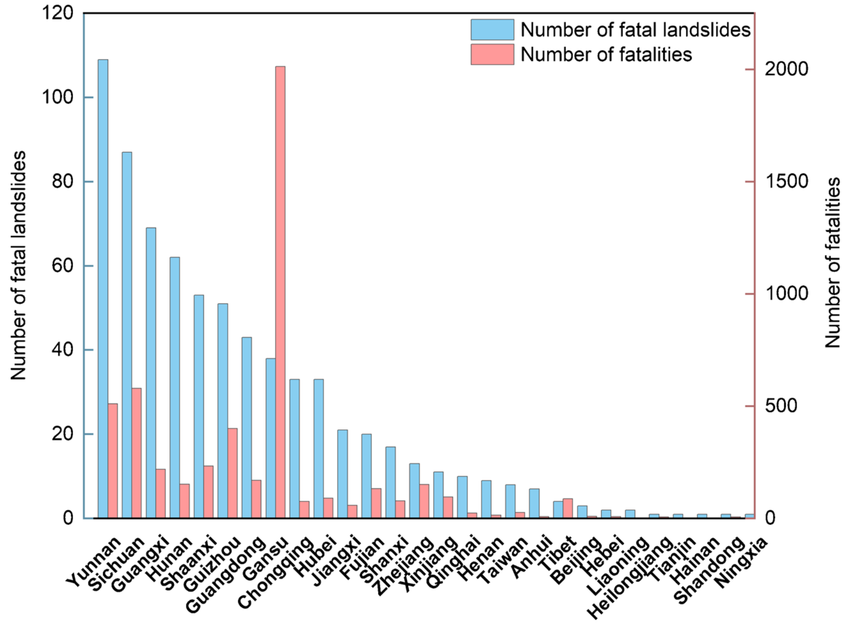

Fig. 4 The number of fatal landslides and fatalities in each province from 2010 to 2022

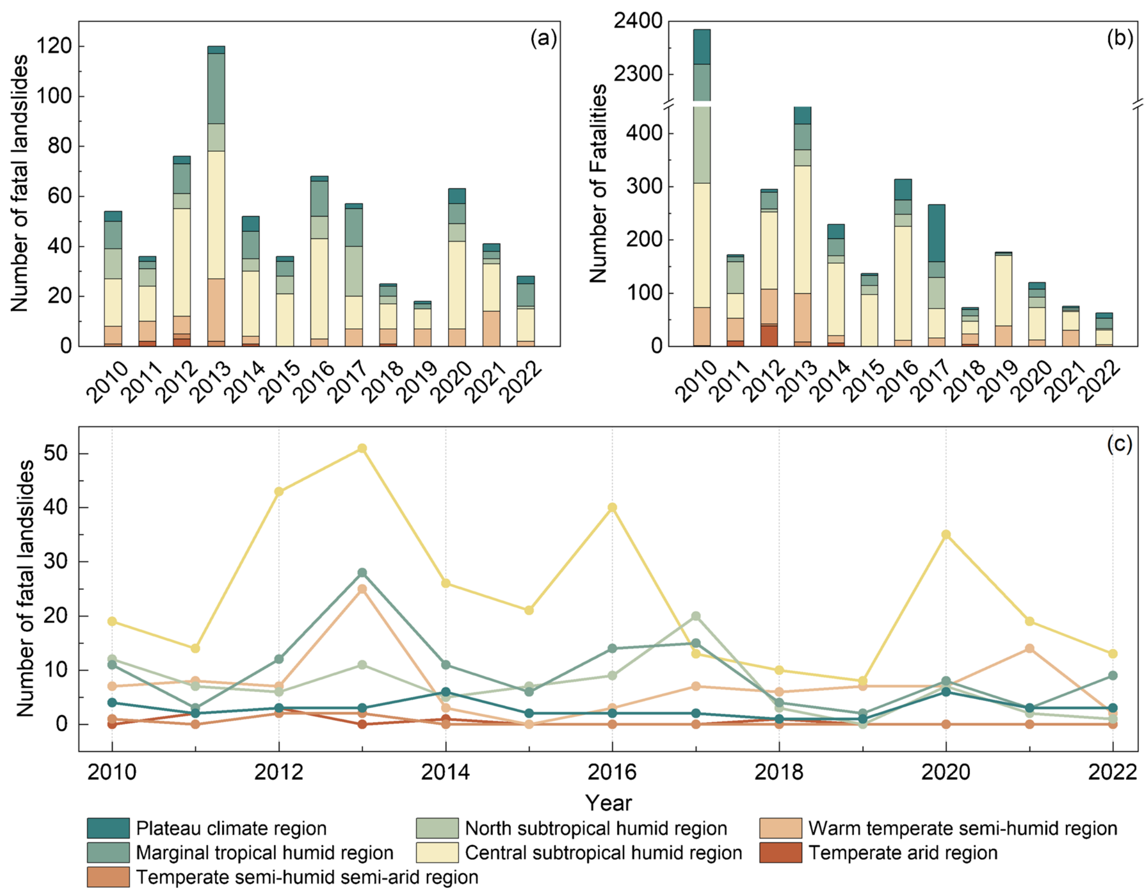

Fig. 5 Distribution of the number of **a** fatal landslides and **b** fatalities in seven climate regions of China. **c** Variation of the number of fatal landslides in seven climate regions from 2010 to 2022

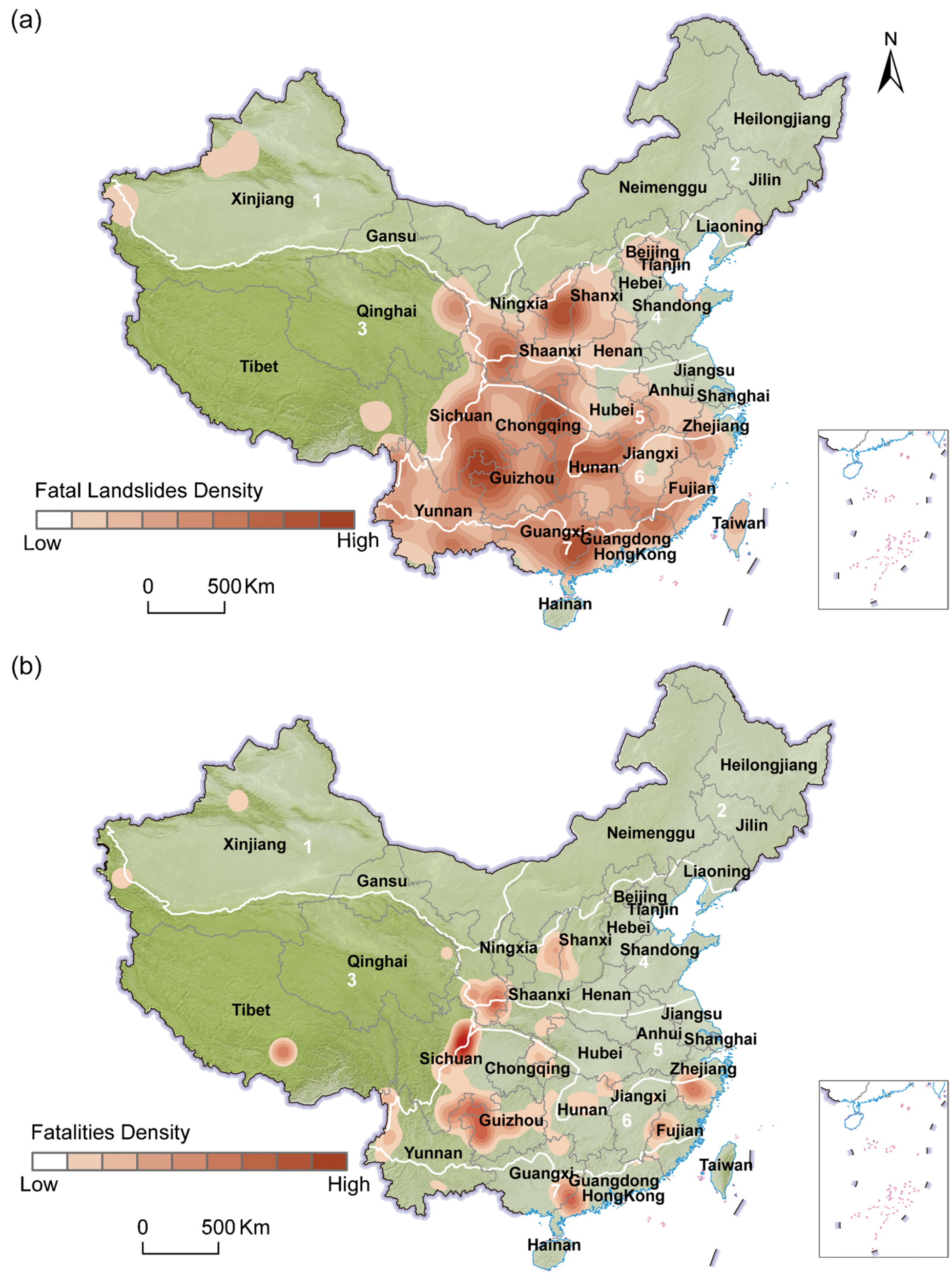

Fig. 6 Kernel density of **a** fatal landslides and **b** fatalities from 2010 to 2022

lowest risk of life loss (Fig. 8a). To better understand the risk of life loss in different climate regions, we compared fatal landslide fatalities with population density (county-based) across climate regions. The results show that although the total number of fatal landslide events in the plateau climate region is fewer, its landslide fatality rate is significantly higher than that in other climate regions (Fig. 8b). This result suggests that landslide events in plateau climate region pose a higher risk of life loss to exposed populations. Furthermore, considering the landslide type, Slide caused the most loss of life (Fig. 8c).

Relationship between fatal landslides and precipitation

The occurrence of fatal landslide events among different climate regions in China from 2010 to 2022 closely aligns with variations in the multi-year average monthly precipitation. Notably, fatal landslides tend to concentrate during the months characterized by increased precipitation, commonly known as the rainy season, within each climate region (Fig. 9). Fundamentally, as precipitation levels rise, there is a corresponding rise in the frequency of

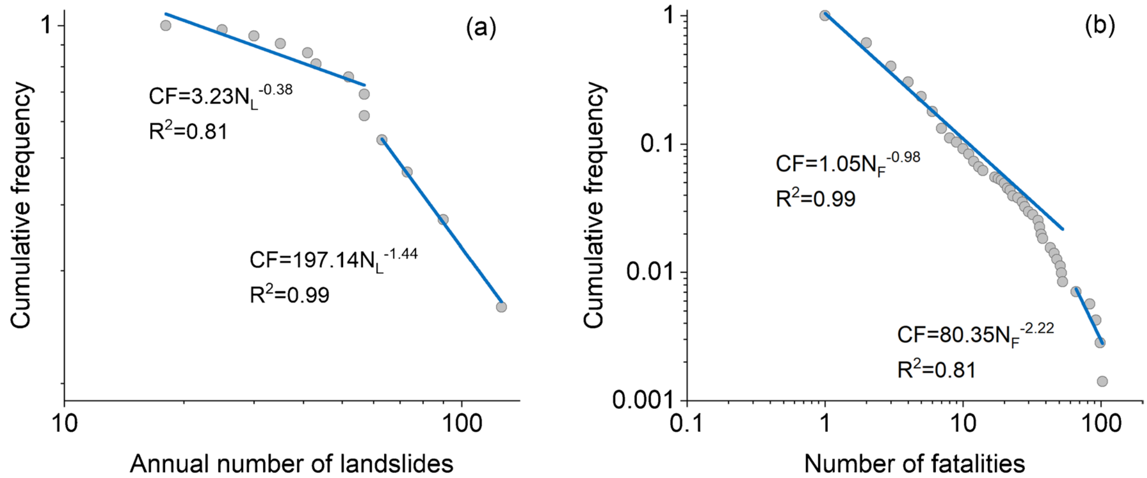

Fig. 7 Cumulative frequency of **a** annual number of fatal landslides and **b** number of fatalities from 2010 to 2022. N_L and N_F represent the number of fatal landslides and number of fatalities respectively

fatal landslide events, showing an ascending trend during spring and summer and a subsequent descent in autumn and winter.

Specifically, the marginal tropical humid region exhibits a complex temporal pattern, marked by a progression of increase–decrease-increase in fatal landslide events from January to December. This pattern shows two peaks of fatal landslide events in June and August, with a slight dip in July (Fig. 9g). This variation correlates with the distinct rainy seasons within the marginal tropical humid region. The initial rainy season spans from April to June, driven primarily by the interplay of cold and warm air masses and monsoons. Subsequently, from July to September, precipitation is predominantly influenced by tropical weather systems, such as typhoons.

For the humid subtropical region (Fig. 9b), the frequency of fatal landslide events escalates from January to June and experiences a subsequent decline from July to December. Conversely, the warm temperate semi-humid region (Fig. 9a), plateau climate region (Fig. 9c), north subtropical humid region (Fig. 9d), and temperate arid region (Fig. 9e) all show an upward trajectory from January to July, and a decrease from August to December.

Additionally, the frequency of fatal landslide events in China throughout 2010–2022 exhibits a significant positive correlation with precipitation, as indicated by a correlation coefficient of 0.94. The positive correlation exists in all climate regions, except for the temperate semi-humid semi-arid region, where a significant positive correlation with precipitation is not observed. The marginal tropical humid region has the highest correlation coefficient, which is 0.96. Additionally, both the plateau climate region and the humid subtropical region demonstrate correlation coefficients of 0.88 (Table 2).

Discussion

Through data collection and integration, this study has compiled a fatal landslide database encompassing the period from 2010 to 2022, which provides the most recent data available (Lin and Wang 2018; Zhang and Huang 2018; Zhang et al. 2023), and reveals a clear downward trend in fatal landslide events during this period. This may be attributed to the response of disaster prevention policies, the increase of investment in disaster prevention, and the strengthening of public awareness of disaster prevention. Additionally, the trend exhibits three distinct 3–4-year decline cycles, aligning with the findings of Qiu on Shaanxi Province (Qiu et al. 2020). However, it differs from the findings of Haque et al. (2016), who believed that fatal landslides in Europe from 1995 to 2014 lacked periodicity.

Our time series analysis indicates that the 3–4-year periodicity in landslide events is closely linked to the El Niño Southern Oscillation (ENSO). During strong El Niño events (2014–2016), its impact led to abnormal increases in precipitation in China, triggering numerous landslides. Even during weak El Niño events (2018–2019 and 2019–2020), the lagged effect on precipitation contributed to landslide occurrences. These findings are consistent with other studies showing El Niño's significant impact on rainfall in East Asia and the increased risk of landslides (Zhou et al. 2020; Emberson et al. 2021; Zhong et al. 2023).

The distribution of fatal landslide events in China from 2010 to 2022 is closely related to climate conditions. The warm temperate semi-humid region, north subtropical humid region, central subtropical humid region, and marginal tropical humid region show an occurrence of fatal landslides exceeding 90 events. For instance, one of the epicenters of fatal landslides is the Loess Plateau in the northern Shaanxi Province in the warm temperate semi-humid region. This region, characterized by soil that is prone to erosion, sparse vegetation, and a landscape dominated by gullies covering over 50% of the total area, experiences numerous fatal landslide events, particularly following intense precipitation events (Derbyshire 2001). In contrast, regions with less precipitation, such as the temperate arid region, temperate semi-humid semi-arid region, and plateau climate region, have lower fatal landslide occurrences and fatalities due to sparse populations and limited rainfall (Wang et al. 2021). In addition, the quality of news reports also affects our collection of information on fatal landslides.

Although we could not obtain susceptibility zoning maps in raster format, we conducted a meaningful qualitative analysis using

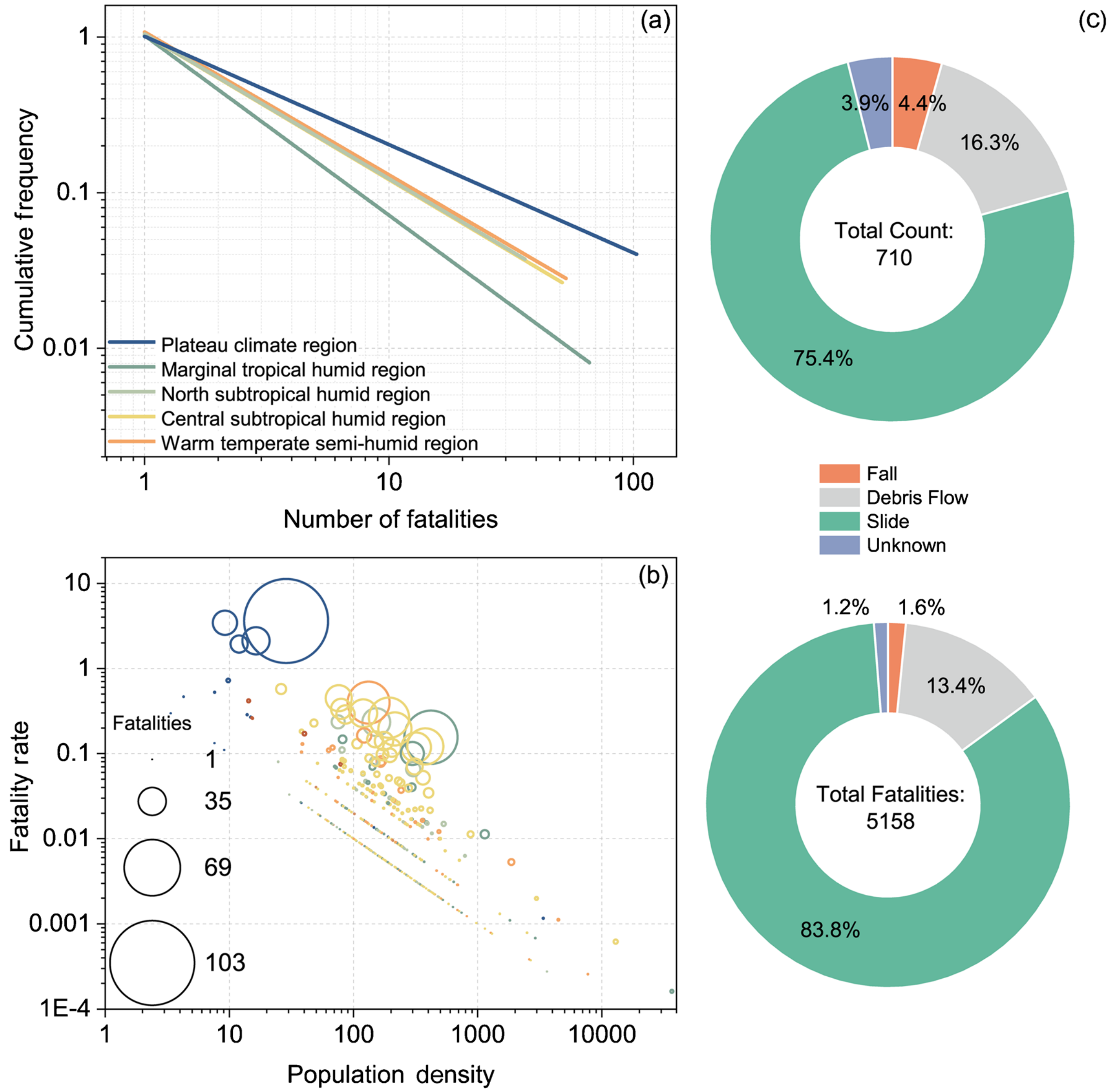

Fig. 8 **a** Comparison of cumulative frequency of the number of fatalities in five climate regions from 2010 to 2022. **b** Fatality rate at different population densities (Each circle represents a county, classified by climate region. The total number of fatalities in each climate region is shown by bubble size). **c** Different types of fatal landslides and their proportion of fatalities

diagrams and descriptions from the literature. For instance, northern Shaanxi has a high fatal landslide density but low susceptibility scores, while southeastern Tibet shows the opposite. These differences may reflect the limitations of landslide susceptibility zoning maps in considering the risk of life loss, and provide an important reference for us to further study landslide risks and improve landslide susceptibility zoning methods.

Existing research has shown the complex connections between fatal landslides and precipitation (Guzzetti et al. 2008). This study proposed that, excluding the mid-temperate semi-humid semi-arid region, the monthly number of fatal landslides in each climate region demonstrates a significant positive correlation with multi-year average monthly precipitation. In the central subtropical humid region, which accounts for 46.29% of the total fatal landslides, the correlation coefficient between fatal landslide frequency and precipitation is 0.88. China, overall, exhibits a significantly positive correlation between the frequency of fatal landslides and precipitation, with a correlation coefficient of 0.94, similar to prior research results (Zhang and Huang 2018; Zhang et al. 2023). In this study, we mainly considered the influence of physical factors such as precipitation on fatal landslides. However, the occurrence of fatal landslides does not only depend on physical factors, but is also affected by a variety of non-physical variables such as population density and residential patterns, infrastructure and emergency response capabilities, land use and management, and socioeconomic status (Kjekstad and Highland 2009; Hao et al. 2018; Garcia-Delgado et al. 2022; Pacheco Quevedo et al. 2023).

Globally, fatal landslides result in severe loss of life annually (Haque et al. 2019; Gómez et al. 2023). Despite the relatively modest

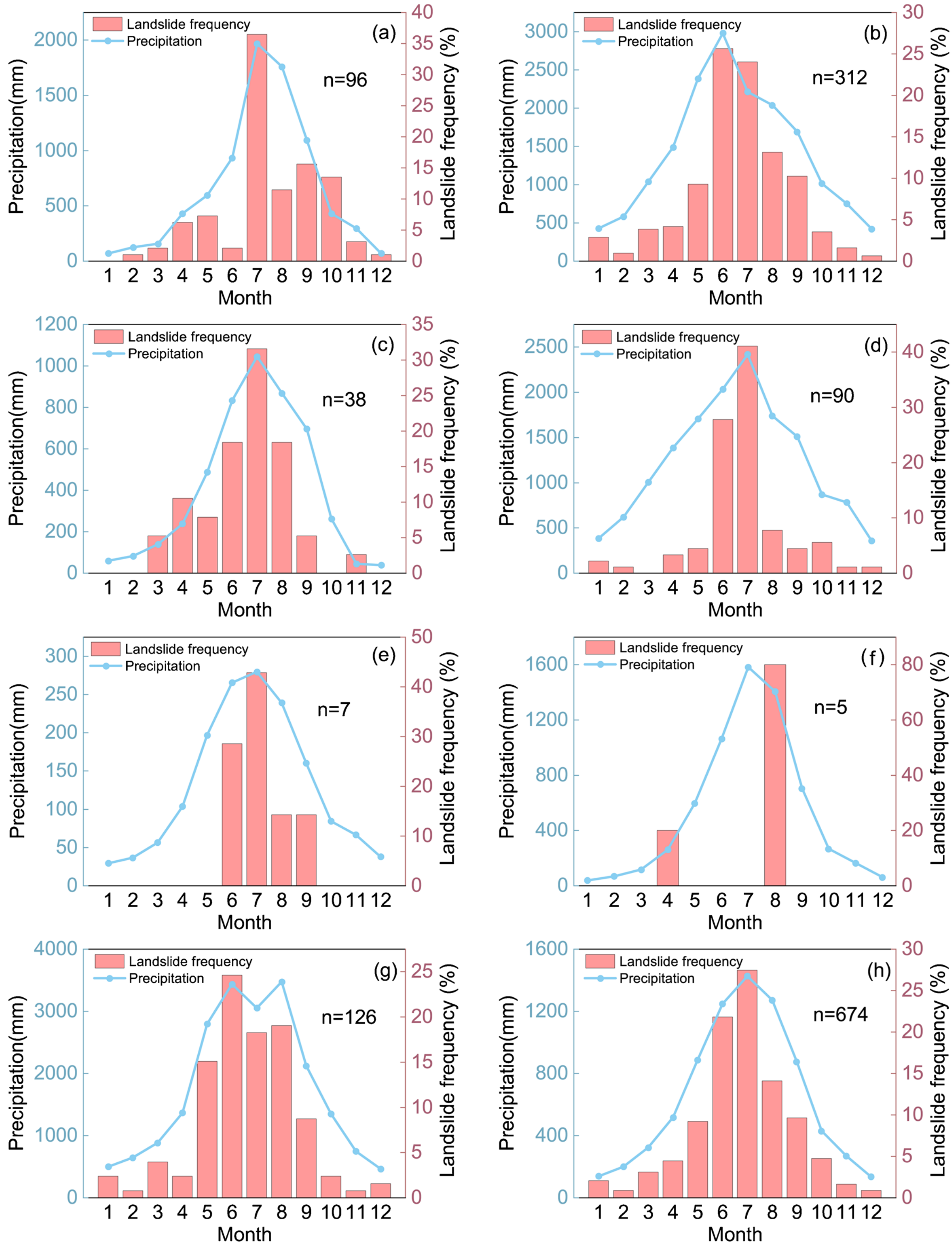

Fig. 9 Monthly variations of frequency of fatal landslides considering average monthly precipitation from 2010 to 2022 **a** Warm temperate semi-humid region; **b** Central subtropical humid region; **c** Plateau climate region; **d** North subtropical humid region; **e** Temperate arid region; **f** Temperate semi-humid semi-arid region; **g** Marginal tropical humid region; **h** China. (*n* represents the number of fatal landslides in the region)

occurrence of fatal landslides in the plateau climate region from 2010 to 2022 (38 instances), this region exhibits the highest risk of life loss among all climate regions. Through comparative analysis of population density and landslide fatality in each climate region, we found that the landslide fatality rate in the plateau climate region was significantly higher than that in other climate regions. Although the total number of fatal landslide events in the region is less, the number of fatalities caused by each fatal landslide event is higher. Moreover, fewer fatal landslides collected may be attributed to reporting capability in the region, resulting in an insufficient sampling of events with fewer reported fatalities in this database. The higher fatality rate may be due to the complex terrain in the plateau area, where landslides are often more severe (Haeberli and Whiteman 2015), resulting in a higher fatality rate. In addition, the inconvenient transportation and difficulty of rescue in the region have led to an increase in the number of fatalities after landslides (Xu et al. 2013; Hao et al. 2018). Likewise, the regional imbalance in fatal landslide occurrences and fatalities can be attributed to reporting limitations, population size, and residential patterns not intersecting with landslide-prone areas (Emberson et al. 2020; Franceschini et al. 2022).

The highly destructive nature of some fatal landslide events can complicate the analysis of their consequences. Regions that have encountered only one or two such destructive events may appear more extreme in their impact (Kirschbaum et al. 2009). This study excludes the extreme debris flow event in Zhouqu County in 2010 when analyzing the cumulative frequency and fatalities of fatal landslide events. This exclusion aligns with the approach of Pereira et al. (2015), who, when analyzing hydrogeomorphic disaster events using a power-law function, excluded extreme events from 1967. The study proposed that the frequency distribution of fatal landslide events and their fatalities from 2010 to 2022 in China follows a power law decay. When the occurrence and fatality numbers reach a certain value (the number of fatal landslide events > 63, fatalities > 66), the cumulative frequency experiences a sharp decline, namely, the deflection effect, aligning with established research conclusions (Guzzetti 2000; Petley 2012). Consequently, this study recommends that organizations and individuals strengthen the monitoring of fatal landslide events characterized by low probability but high potential impact, thereby mitigating their direct and indirect impacts on society.

Conclusions

This study reveals significant trends and patterns in fatal landslide events in China from 2010 to 2022, contributing to a deeper understanding of their spatiotemporal distribution and their relationship with precipitation. The number of fatal landslide events and fatalities showed an overall downward trend with three distinct declining cycles, interrupted by sharp increases at the start of each new cycle. Moreover, the peak period for fatal landslides was from May to September, correlating strongly with higher precipitation levels during these months. The frequency of fatal landslides was closely tied to monthly precipitation trends, increasing in spring and summer, and decreasing in autumn and winter. The study found a significant correlation between fatal landslides and the El Niño Southern Oscillation (ENSO), with increased landslide events following strong El Niño years. Furthermore, the plateau climate region had the highest risk of life loss, by integrating population density, we identified that regions with lower population densities but high landslide activity pose a higher fatality risk. Fatal landslides and their associated fatalities followed a power-law distribution, with a significant drop in frequency for events surpassing 63 landslides or 66 fatalities annually. The findings of this study have important implications for disaster management and policy-making and can aid in developing more effective early warning systems and mitigation measures. Future research will focus on extending the temporal scale of the database to capture more long-term trends. By addressing these key areas, we can improve our preparedness and response to fatal landslides, ultimately reducing their devastating impact on regions across China.

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Data Availability

Data will be available on request.

Declarations

Conflict of interest The authors declare no competing interests.

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