Temporal and Spatial Distribution Characteristics of Flood Disasters with Different Intensities in Arid-Semiarid Region in Northern Xinjiang, China

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Abstract. Floods have devastating environmental and socioeconomic consequences. Flood disaster management is critical for the long-term management of water resources and agriculture in arid areas. Using the data on the number of deaths, destroyed homes, collapsed sheds, livestock deaths, and the crops affected area caused` by 1394 regional floods in Northern Xinjiang (As a typical arid-semiarid region of NorthWest China) from 1981 to 2019, the ratio-weight method and the dimensionless linear summation method was used to calculate the actual disaster damage exponent of flood disaster events. The damage exponent is further used to categorize the severity of disaster events into four grades: normal, moderate, severe, and extremely severe. The analysis results indicated that Bortala Mongolian Autonomous Prefecture experienced the highest frequency of catastrophic occurrences, while Ili River Valley experienced the highest intensity. The flood happened most often in Wenquan County. And Yining County suffered the worst calamity. The occurrence frequency and intensity of disasters from Grades 1 to 3 exhibited a unimodal distribution, with the majority and most vital occurrences in July, whereas the occurrence frequency and intensity of Grade 4 disasters followed a bimodal distribution, with the most occurrences in July and the strongest in April. The annual frequency of heavy rain and flood disasters in Northern Xinjiang increased by 7.7 times every 10 years, indicating a significant linear increase trend. The yearly occurrences of Grades 1 and 2 also increased linearly, by 5.2 and 2.0 times per decade, respectively. There was no linear tendency to increase or decrease flood disasters in Grades 3 and 4. The analysis and division of actual disaster damage are conducive to flood risk management, efficient prevention, and reducing disaster losses.

Keywords: Northern Xinjiang, flood, disaster exponent, disaster intensity, temporal and spatial distribution

1. Introduction

Climate change, solar activity, and the El Nio-Southern Oscillation all impact precipitation extremes and flooding events [1]. Extreme precipitation events have grown dramatically in size and frequency on both a global and regional scale [2], but it is seasonal, regional, and influenced by human activities. During the Paleocene-Eocene Thermal Maximum, extreme precipitation became more severe in tropical and subtropical Africa and parts of South America, while average annual precipitation and extreme rates increased at high latitudes. The authors concluded that rainfall in tropical East Africa became more episodic and extreme, possibly more seasonally distributed. And extreme precipitation rate is particularly sensitive over much of tropical Africa, especially during the rainy season. Extreme precipitation is exacerbated by increasing soil erosion, particularly in North Africa and the Tethys Ocean. Because of its extreme continentality, the continental United States, like Northwest China, experiences the smallest increase in global specific humidity in the western United States, which is arid but has extreme precipitation [3,4]. The number of heavy precipitation events in the United States increased by 20% in some densely populated areas [5].

The most developed region in China, with a dense population and large agricultural area, often experiences flash floods and river floods caused by extreme rainfall events. The frequency of floods in China significantly shows an increasing trend. In the recent 30 years, 8 flooding events have occurred on average every year (EM-DAT, http://www.emdat.be/) [6]. Changes in the frequency of extreme precipitation events are therefore highly relevant, especially where the resilience of existing infrastructure is already exceeded. Flood disasters have destructive solid power, often causing severe disasters such as death and injury of humans and animals, collapse

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of houses, destruction of farmland, and collapse of bridges [7].

According to official data released by China government, from 2000 to 2019, the average number of people affected by floods in the country reached 114 million yearly, and the average annual death and missing persons were 1,195. The disaster area is 9.88 million hectares, and the direct economic loss accounts for 0.48% of GDP [8]. According to data from the China Ministry of Water Resources, 148 million people were affected by the flooding in 2020, and the direct economic losses from these floods were 178.96 billion Yuan, with these numbers being respectively 12.7% and 15.5% higher than the average values of the previous five years [9]. Heavy rainfall events frequently occur in Xinjiang, causing severe disasters [10,11]

Statistics show that, from 1961 to 2019, 3,220 flood disasters devastated 86 counties (cities) in Xinjiang virtually annually, resulting in a total of 1,365 fatalities, more than 51.7×10^4 destroyed homes, 16.0×10^4 collapsed sheds, 156.3×10^4 dead livestock, and covering a damaged farmland area of 376.9×10^4 hm^2 [12].

Some scholars have conducted preliminary research on flood disasters in Xinjiang. Zhang Q. et al. showed that higher probabilities of flood disasters are found in Northern Xinjiang than in Southern Xinjiang [13]. Sun G. et al. used district data from 1901 to 2010 to investigate the spatial distribution characteristics of extreme hydrological occurrences in Xinjiang, China. The frequency distribution was symmetric along the Tianshan Mountains, with an even distribution in Junggar Basin and Tarim Basin. Compared to the southeast, the northwest had a higher frequency of flood disasters. The incidence was highest in the west Tianshan Mountains and gradually declined south-eastward [14]. Based on the daily precipitation data of 44 national meteorological stations in Southern Xinjiang from 2010 to 2019, Yanying, W. et al. evaluated flood disasters and economic data, as well as the spatial and temporal changes in flooding situations in Southern Xinjiang [15]. According to Wang H. et al., the high precipitation is located mainly in Northern Xinjiang, the western part of the Tianshan Mountain Area. High precipitation values (300-530 mm) range from 15.1 to 505.8 mm annually. Recently the importance of changes in temporal patterns of heavy precipitation events on agriculturally dominated areas flooding has been highlighted [17,18]. Northern Xinjiang has a relatively humid climate, abundant water sources, relatively fertile land, a relatively dense population, and highly concentrated areas of productivity.

This article aims to provide a different perspective to measure the hazard of flood disasters and reveal the temporal and spatial distribution of actual disaster damage caused by flood disasters. The characteristics are conducive to formulating corresponding defense measures and are significant to protecting people's lives and disaster prevention and mitigation.

This research goal considers:

(1) To calculate the actual disaster damage exponent by statistical methods, based on the data of the number of deaths, destroyed homes, collapsed sheds, dead livestock, and the crops affected area caused by flood disasters in Northern Xinjiang from 1981 to 2019;

(2) To classify the intensity of the disaster events.;

(3) To analyze the temporal and spatial variation characteristics of storm and flood disasters with different intensities in Northern Xinjiang;

(4) And to explain the reasons for the interannual variation of disasters, using the number of days above heavy rain and rainstorms.

2. Experimental

2.1 Overview of the Study Area

Northern Xinjiang refers to the area north of the Tianshan Mountains in Xinjiang(79°57' - 91°32'E, 43°23' - 49°10'N), which is mainly mountainous, basin and Gobi, reaching the north slope of the Tianshan Mountains and the Yili Valley in the south, the Altai Mountains in the north, and the Junggar Basin in the middle, with a total area of about 5.95×10^5 km^2 (Figure 1). Flood disasters can be triggered by intense thunderstorms, tropical cyclones, large low-pressure systems, monsoons, ice plugs, or snowmelt [19]. In Northern Xinjiang, due to the interception and uplift of water vapor by tall mountains, the precipitation mainly occurs in the mountains, and when the precipitation reaches, it will lead to a flood of a certain magnitude [20]. In addition, the underlying gobi saline and alkaline land are in the majority, causing severe desertification and a fragile ecological environment, which can easily lead to flood disasters [21]. As a typical arid and semi-arid area in northwest China, Northern Xinjiang has a temperate continental climate, with considerable precipitation variation and uneven spatial distribution. The average annual precipitation of nearly 60a is 195mm, and 300-1000mm in mountainous and surrounding areas [22]. Floods in Xinjiang mainly originate from mountain areas and are induced by ice-snow melt and precipitation. Due to the increase in heavy rain in summer, floods have occurred more frequently since the late 1980s.

Generally, Northern Xinjiang is more prone to drought than Southern Xinjiang, with more floods due to increased summer torrential rain [23]. Since the 1980s, the global climate has shown a trend of warming and wetting. The increase of declining water in the warming background is conducive to alleviating the drought in Northern Xinjiang, but it also brings more challenges to disaster risk control.

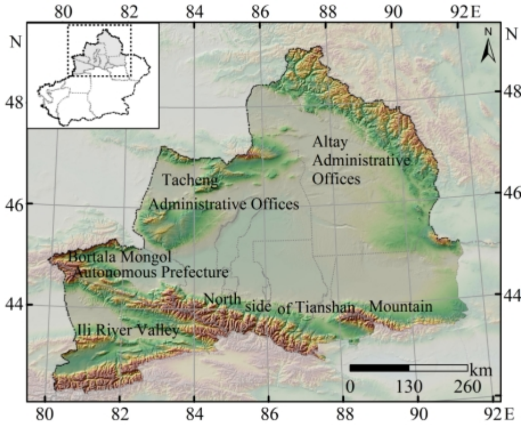

Fig. 1. Topography and administrative map of Northern Xinjiang.

2.2 Data

Data were based on the Xinjiang Uygur autonomous region department of flood disasters information from 1981 to 2019. Thirty-eight counties (city), 1394 disaster records in Northern Xinjiang contain occurrence time (month), area (county/city), deaths (persons), destroyed homes (houses), collapsed shed (seat), livestock deaths (head), crops affected area (hm^2). If there is a rainstorm and flood disaster in a county (city) area, the number of flood disasters in the county (city) is recorded as 1. According to the daily precipitation data of 33 meteorological stations in Northern Xinjiang from 1981 to 2019 provided by the Meteorological Bureau of Xinjiang Uygur Autonomous Region, the number of heavy rain days (12.1- 24.0mm) and the number of annual rainstorm days (⩾24.1mm) was counted.

2.3 Methods

Because the disaster elements that constitute disaster events include 5, they have different units, and the strength of different disasters cannot be compared. In order to compare the strength of disaster events, it is necessary to construct an actual disaster damage exponent (Z_i) that can comprehensively express the five disaster factors. The weight of each disaster element was determined by the ratio method, and then the dimensionless linear combination method was used to obtain Z_i [24,25].

Suppose that each disaster factor consists of N sample, N=1394, so the disaster factor evaluation matrix $X_{N\times 5}$ can be obtained. The calculation formula of the actual disaster damage exponent Z_i is:

$$Z_i = \sum_{j=1}^{5} a_j \frac{X_{i,j}}{\bar{X}_j} \quad “(1)$$

In the above equation, i=1,2, ⋯, N, j =1,2, ⋯, 5, X_{ja}, $\bar{X}_j$, a_j represent the maximum value of j, average, and weight of the first disaster element. The calculation formula of a_j:

$$a_j = \frac{\sum_{i=1}^{n} X_{i,j}}{\sum_{j=1}^{5} \sum_{i=1}^{n} \frac{X_{i,j}}{X_{ja}}} \quad (2)$$

The aforementioned calculation formula (2) reveals that the maximum value is utilized to establish the weight, which ensures the equivalence of the five disaster elements. The average value is used to calculate the actual disaster damage exponent so that the actual disaster damage exponent has a discrete type.

After the calculation of formula (1), the weight coefficient, the average, and the maximum value of five disaster factors can be noted in Table 1.

The closeness of the two can be determined by the size of the correlation coefficient between the actual disaster damage exponent and the disaster elements. Disaster damage exponent and the number of deaths, destroyed homes, collapsed sheds, livestock deaths, and crops affected area between the correlation coefficient of 0.23, 0.90, 0.89, 0.46, and 0.29, respectively, all passed the significance level of 0.01, which shows that the disaster damage exponent can not only express comprehensive five disaster elements, and the size of the damage exponent reflects the strength of the disaster event.

Table 1. Weight coefficient, average and maximum value of disaster factors.

	Deaths (persons)	Destroyed homes (houses)	Collapsed sheds (seats)	Livestock deaths (heads)	Crops affected area (hm^2)
Weight coefficient	0.18	0.33	0.25	0.09	0.16
Average value	0.3	148.7	31.3	470.1	940.9
Maximum value	24	6010	1650	70000	80000

The percentile method determines the damage exponent grade [26]. Percentile is a kind of position exponent. According to the range of threshold change, the disaster is divided into four grades (specific results are listed in Table 2).

Table 2. Grading criteria of rainstorm and flood disasters in Northern Xinjiang.

Percentile r (%)	Disaster exponent Z_i	Disaster grade
r ≤ 50	$Z_i \leq 0.13173$	Mild (Grade 1)
50.1 ≤ r ≤ 75	$0.13174 \leq Z_i \leq 0.56716$	Moderate (Grade 2)
75.1 ≤ r ≤ 90	$0.56717 \leq Z_i \leq 1.72884$	Severe (Grade 3)
r ≥ 90.1	$Z_i \geq 1.72885$	Extremely severe (Grade 4)

3. Results

3.1 Spatial distribution of flood disaster in Northern Xinjiang

In 38 counties (cities) in Northern Xinjiang, from 1981 to 2019, the frequency and intensity of flood disasters showed obvious regional differences. And the cumulative number of disasters that occurred on average over these 39 years in each region was as follows: Boltala Mongolian Autonomous Prefecture (70), Altay region (47), Yili Valley (45), northern Tianshan Mountains (25), Tacheng Area (21), which showed that the disaster events occurred most in Bortala Mongolian Autonomous Prefecture, and the least occurred in Tacheng Area; among them, Wenquan County had the most flood disasters, with a total of 103 occurrences (Figure 2a). Regional average annual damage exponents were as follows: Yili Valley (2.354), Altay (0.819), Tcheng (0.450), northern Tianshan (0.384), Bortala Mongolian Autonomous Prefecture (0.379). The intensity of disaster events in Yili Valley is the strongest, and Bortala Mongolian Autonomous Prefecture is the weakest. With the damage exponent of 3.195, Yining County has the highest disaster intensity out of the 38 counties (cities) (Figure 2b).

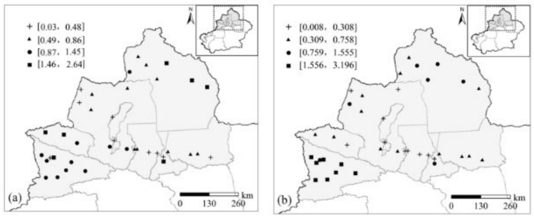

Fig. 2. Spatial distribution of annual average occurrence frequency and annual average disaster exponent of rainstorm and flood disasters in Northern Xinjiang. a) average annual occurrences (times), b) average annual damage exponent.

The number of flood disasters ranging from Grades 1 to 4 also demonstrated apparent regional variances. Grades 1 and 2 occur most frequently in Bortala Mongolia Autonomous Prefecture and least frequently in Tacheng Area; Grades 3 and 4 occur most frequently in Yili Valley; Flood disasters of Grade 3 occur least frequently in the northern side of Tianshan Mountains; Grade 4 occur least frequently in Bortala Mongolia Autonomous Prefecture. The county(cities) with the most occurrences of Grades 1 to 4 are Wenquan County (66 cumulative occurrences in 39 years), Wenquan County (25), Altay City (17), and Gongliu County (12).

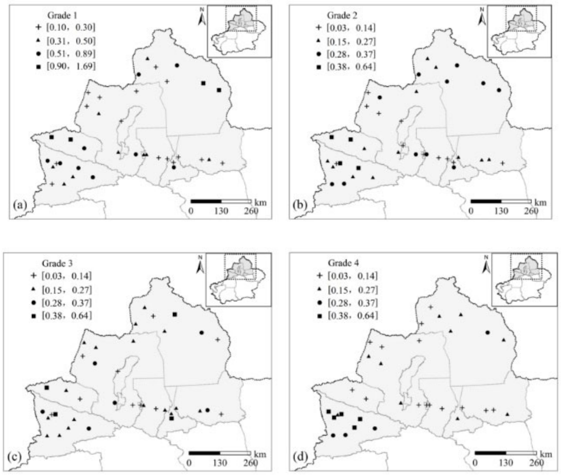

Fig. 3. Spatial distribution of average annual occurrence frequency of Grades1-4 rainstorm and flood disasters in Northern Xinjiang.

3.2 Seasonal and monthly distribution of flood disasters in Northern Xinjiang

The occurrence frequency and intensity of flood disasters show diversity. Grade 1 disasters occur mainly from May to August, and Grade 2 and 3 disasters mainly occur from May to July. Grades 1 to 3 disasters show a unimodal distribution, with the peak month occurring in July, while Grade 4 was bimodal, with the peak month in July and the second peak month in April (Figure 4a, b). The intensity of disasters from Grades 1 to 3 showed a unimodal distribution, with the peak month appearing in July; while the intensity of Grade 4 disasters showed a bimodal distribution, with the peak month appearing in April and the second peak month appearing in June (Figure 4c, d). The monthly distribution of the occurrences of Grades 1-4 flood disasters is very consistent with the monthly distribution of heavy rain days and rainstorm days, indicating the occurrence of flood disaster events in Northern Xinjiang may cause by continuous heavy rain and rainstorms.

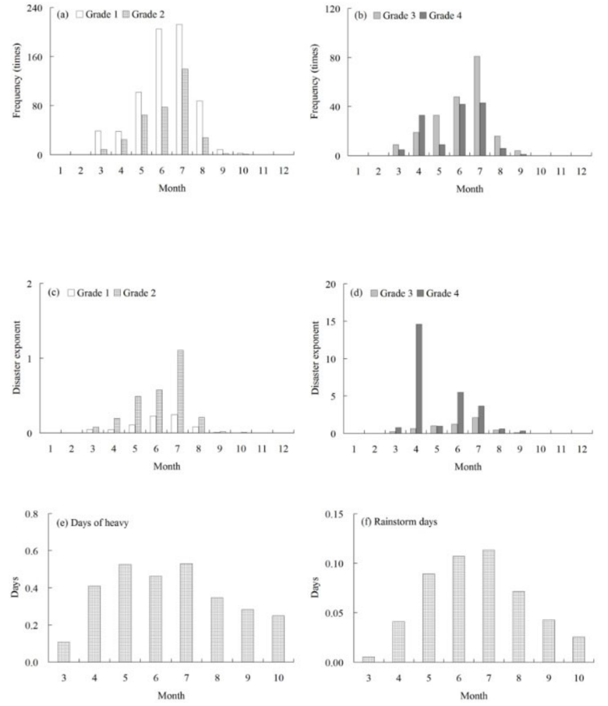

Fig. 4. Seasonal variation of occurrence frequency (a, b) and disaster exponent (c, d) of rainstorm and flood disasters in Northern Xinjiang. Seasonal variation of days of heavy (e) and rainstorm days in Northern Xinjiang.

3.3 Inter-annual occurrence distribution change of flood disaster

According to Figure 5, the annual occurrence of flood disasters in Grade 1 and 2 grew more dramatically from 1981 to 2019, by 5.2 times for Grade 1 and 2.0 times for Grade 2 every 10 years. Flood disasters in Grades 3 and 4 occurred on average 5.4 and 3.6 times yearly, respectively. However, the number fluctuated around the climate average.

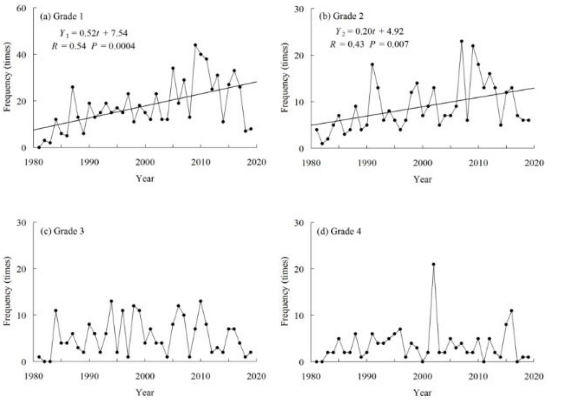

Fig. 5. Inter-annual variations in the number of occurrences of rainstorms and floods of Grades 1-4 in Northern Xinjiang. R indicates the correlation coefficient, and P indicates the Grade of reliability. The straight line indicates a linear trend in the figure.

As illustrated in Figure 6a, from 1981 to 2019, the annual occurrence of flood disasters (Y) in Northern Xinjiang increased by 7.7 times every 10 years, indicating a significant linear increase. The inter-annual variation of the occurrence number of heavy rain days (Rd) and the number of rainstorm days (Bd) from March to October both showed a significant linear increase trend (Fig. 6b, 6c); the correlation coefficient between Y and Rd was 0.39 (P=0.01), and the correlation coefficient between Y and Bd was 0.55 (P=0.0003). Therefore, the annual increase in the number of heavy rain days (Rd) and rainstorm days (Bd) from March to October results in an annual increase in the occurrence of flood disasters.

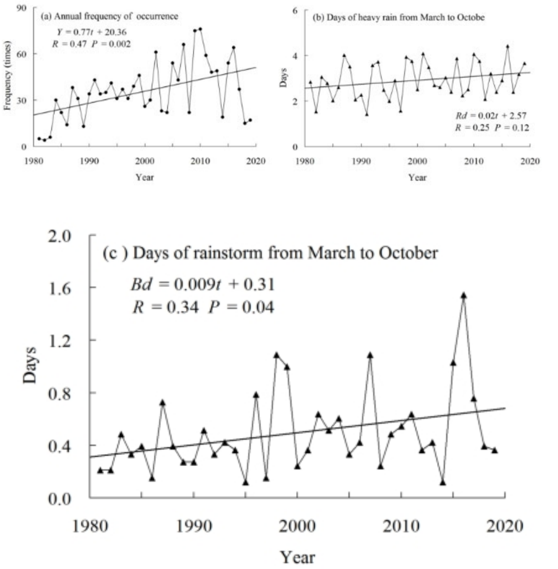

Fig. 6. Annual frequency of rainstorm and flood disasters in Northern Xinjiang (a), interannual variation of heavy rain days (b), and rainstorm days (c) from March to October. R indicates the correlation coefficient, and P indicates the Grade of reliability. The straight line indicates a linear trend in the figure.

4. Discussion and conclusions

This extreme rainstorm caused severe floods and seriously adverse socioeconomic impacts. In some countries exposed to tropical cyclone impacts (notably the United States and China), it is mainly coastal and immediate inland locations that bear the brunt of the storm-related surge and wind losses, while the economic activity of the entire nation spans a much larger area [27]. However, the lack of attention in arid and semi-arid areas and its damage cannot be underestimated.

It is evident that the frequency and intensity of flood disasters in Northern Xinjiang present prominent regional characteristics in terms of spatial distribution. In Bortala Mongolian Autonomous Prefecture, flood disaster events were most frequent, while the severity of these events was highest in the Ili River Valley. For counties (cities), flood disasters in Wenquan County occurred the most, and Yining County had the most vigorous disaster intensity. Grade 1 and 2 flood disasters appear most frequently in Bortala Mongolian Autonomous Prefecture, and Grades 3 and 4 appear most frequently in Ili Valley. And the counties (cities) with the highest frequency of Grade 1 to Grade 4 disasters are respectively Wenquan County, Wenquan County, Altay City, and Gongliu County.

In the seasonal and monthly distribution, disaster occurrence frequency and intensity showed diversity. The occurrence frequency and intensity of Grade 1 to 3 disasters are in unimodal distribution, with peak events occurring in July and the most frequently occurring in July; the frequency and intensity of Grade 4 disasters are in a bimodal distribution, with the most frequent month in July, the second most frequent month in April. And the month with the most vigorous disaster intensity is April, and the second strongest month is June.

Regarding inter-annual changes, the annual occurrence of flood disasters in Northern Xinjiang from 1981 to 2019 showed a significant linear increase, increasing by 7.7 times every 10 years. The annual occurrence of disasters is closely related to the number of heavy rain and rainstorm days from March to October. The annual increase in heavy rain and rainstorm days may result in the annual increase in flood disasters. The annual occurrence number of flood disasters of different grades showed differences. Both Grade 1 and Grade 2 showed a significant linear increase trend, increasing by 5.2 and 2.0 times per 10 years, respectively. However, the occurrence number of Grade 3 and Grade 4 annual occurrences fluctuated around the climate average, showing no linear trend of increase or decrease.

The Chinese government has actively responded to global disaster risk reduction strategies and made active explorations in the discovery of flood risk management. Over the past 30 years, China has recognized that disaster risk reduction measures are investing in a more secure society. Moreover, Chinese authorities are increasingly emphasizing local disaster prevention measures. Local governments can better prepare for disasters and participate more in disaster reduction operations, and disaster prevention and relief have saved many lives [28]. The impact of this shift was particularly evident in the 2020 flood disasters, and China is also ramping up investment in critical infrastructure to enable it to mitigate flooding better. It is still essential to continue efforts in some areas, including developing an in-depth understanding of the laws of disasters, gradually shifting from disaster response and preparation to risk prevention and mitigation, and enhancing emergency response capabilities, which can improve systems for disaster mitigation.

Acknowledgments

This work was supported by the Macao Polytechnic University Research Project Fund (Fund number: RP/FCHS-03/2022) and the Jin Feng Hua Yun Development Fund Project (Fund number: Hyj202201).

Conflict of interest

The authors declare no conflict of interest.

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