Journal of
Water & Climate Change

 Journal of Water and Climate Change Vol 15 No 3, 1076 doi: 10.2166/wcc.2024.480

Discussion on the coupling relationship between flood risk and population vulnerability from climate justice

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ABSTRACT

Facing the increasingly uncertain climate change, people are paying more and more attention to climate justice in urbanization. Climate change has intensified the vulnerability of cities and may have a greater impact on vulnerable groups. Therefore, this research constructed a framework to explore the coupling relationship between flood risk and population vulnerability from the perspective of climate justice. In this framework, the indicators of population vulnerability and population resilience were built. Then, the flood risk was identified through the relationship of inundation potential. Furthermore, the coupling coordination degree model was used to calculate the coupling between population vulnerability and flood risk, and the coupling between population resilience and flood risk. Finally, the driving factors of urbanization contributing to such coupling were analyzed through the Tobit model. The specific conclusions are (i) the study area shows vulnerable groups more likely to live in areas with high flood risk, and (ii) vulnerable groups are susceptible to the impact of population density and development intensity, while relatively wealthy groups are susceptible to the impact of the level of economic development and urban built environment. The results contribute to a better understanding of spatial inequalities in flood risk and population vulnerability, and climate injustice.

Key words: climate justice, coupling coordination degree model, flood risk, population vulnerability, urbanization

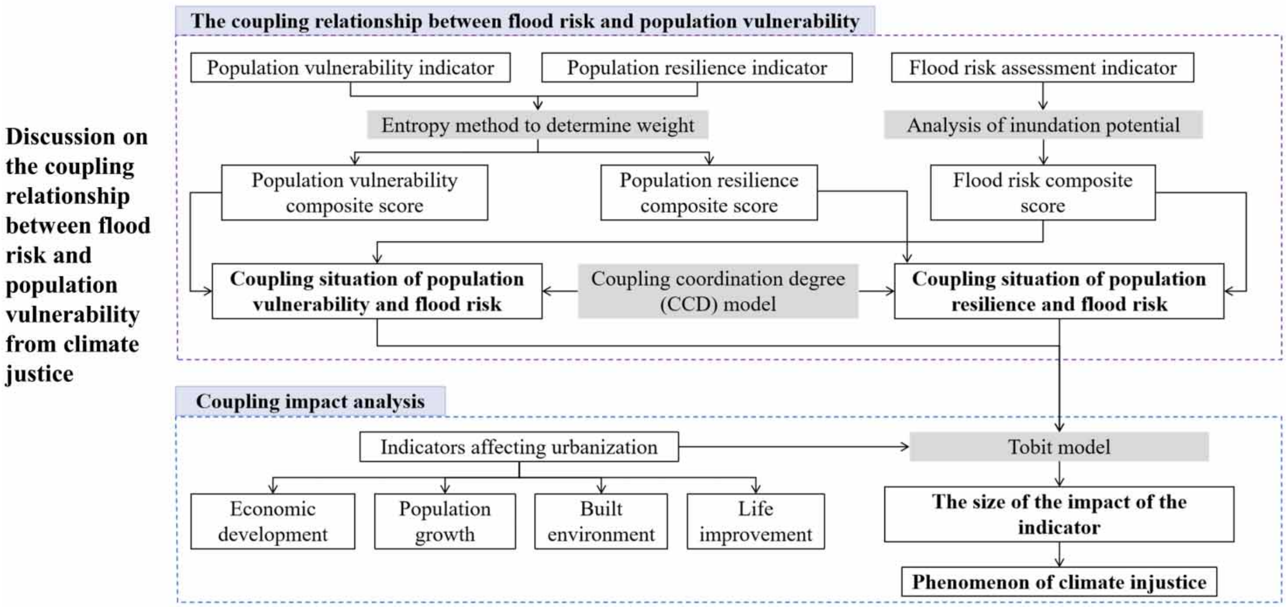
HIGHLIGHTS

- This research constructs a framework for the coupling relationship between flood risk and population vulnerability.
- Vulnerable groups are more likely to live in areas with high flood risk.
- This research provides a new understanding of climate justice and injustice.
- This study clarifies the geographic and statistical relationship between flood risk and population vulnerability.

GRAPHICAL ABSTRACT

Highlights

(1) This research constructs a framework for the coupling relationship between flood risk and population vulnerability.
(2) Vulnerable groups are more likely to live in areas with high flood risk.
(3) This study clarifies the geographic and statistical relationship between flood risk and population vulnerability.
(4) Vulnerable groups often live in areas with low population density and development intensity.



1. INTRODUCTION

The accelerated urbanization has created an increasingly complex social ecosystem containing the complicated relationship among ecology, politics, economy, and society, which makes the impact of urbanization increasingly unpredictable. Research by van den Berg & Keenan (2019) shows that the unequal development of urbanization is a major cause of climate vulnerability, which makes vulnerable groups more susceptible to the impacts of climate change. In addition, climate change has intensified the complexity of urbanization. It deepens the existing vulnerability and poses greater risks to society, the economy, and the environment (Shokry *et al.* 2020; Su 2020). Therefore, we must view the impact of climate change on social vulnerability as a complex and persistent hazard. Moreover, the combined influence of climate justice, flood risk, and population vulnerability has rarely been studied (Mahmoud & Gan 2018; Zhou *et al.* 2019).

Climate change tends to intensify the global hydrological cycle. The most obvious impact is to make the spatial and temporal distribution of precipitation more uneven and bring more extreme rainfall. This further harms the lives and properties of residents and causes more losses (Chang & Su 2021). At the same time, the socioeconomic status of different social groups produced by social differentiation determines the degree to which people are affected by climate change. The research on climate justice showed that climate change, especially the flood hazard it brings, may have a greater impact on vulnerable groups (the elderly, children, and marginalized population) (Holland 2017; Yang *et al.* 2021). From the perspective of climate justice, the main goal is to mitigate the disadvantaged position of vulnerable groups in the world when disasters occur. However, vulnerable groups often prioritize economic benefits rather than flood risk (Running 2015). They pay more attention to the daily living environment, such as violence, unemployment, and crime instead of the impact of climate change (Lizarralde *et al.* 2021). Also, wealthier regions and privileged citizens can benefit from better environmental conditions. This also highlights the lack of economic opportunities for vulnerable groups in the environment where they live. However, nature has a good memory. When facing future climate change, vulnerable groups may pay a greater price and may become even poorer due to the impact of climate-related floods.

The combined influence of urbanization and flood risk has had a disproportionate negative impact on the vulnerable groups in the city. To reduce the flood risk of the entire city, it is usually necessary to restrict the construction of flood plains or relocate existing buildings. However, for vulnerable groups, settling in these areas can meet their needs for livelihood and work, and it is an effective way to get rid of poverty. Therefore, flood-hit areas are often the only settlements that vulnerable groups can afford (van den Berg & Keenan 2019). People still know very little about how social differentiation affects flood risk. Some researchers believe that the wealthier people are, the less susceptible they are to climate change, and the most marginalized groups are more easily hit by climate changes such as floods (climate change alters the distribution and intensity of rainfall, often causing greater and more frequent floods). There are also some researchers who point out that the poor are more resistant to floods because they are more mobile and have fewer assets, and thus they suffer fewer losses and can more easily recover from the disasters. However, the rich people may be more vulnerable to flood since their resources are bound to the specific location of the land (Friend & Moench 2013). Nevertheless, the uneven distribution of flood risk and population vulnerability highlights the increasing importance of the research on climate justice. This research analyzed the coupling relationship between flood risk and population vulnerability, so as to reveal the spatial inequality between disasters and vulnerable groups and to promote the understanding of climate justice.

The unequal development of urbanization has made certain groups in the society more vulnerable. For example, many vulnerable groups living in cities do not have access to reliable and affordable basic services (Juhola *et al.* 2016). Vulnerable groups are unlikely to prioritize long-term floods caused by climate change over economic growth. They also do not support restrictions on economic activities and believe the climate policies that restrict their own development are fundamentally unfair (Parks & Roberts 2006; Norgaard 2012). Relatively wealthy people are more likely to separate environmental issues from economic issues and actively participate in the climate change agenda. For example, wealthier families build flood-prevention walls around their houses to withstand the damage from floods. In addition, high land prices in non-flooded areas have further intensified climate injustice because the rich are able to bear higher housing costs and relocate to safer areas. Therefore, vulnerable groups are forced to relocate to high-risk areas where land prices are low (Mavromatidi *et al.* 2018). It can be seen that vulnerable groups are often marginalized and are ignored in the evaluation and policy intervention. Thus, a highly adaptable system in urbanization is not necessarily fair, nor is it beneficial to vulnerable groups (Friend & Moench 2013). It is believed that understanding the relationship between flood risk and population vulnerability in urbanization is of great significance, which can promote climate justice.

Flood risk and vulnerable groups are often characterized by their location in urban space (Su *et al.* 2021). Coupled thinking can provide an analysis framework for the multi-scale complex connection between flood risk and population vulnerability, so that the reasons for the coupled spatial relationship between flood risk and population vulnerability under urbanization can be quantified. Coupling originated in physics, which is the concept of the interaction between two or more systems (Cui *et al.* 2019). In recent years, this concept has been applied to the urbanization–environment system, such as the study on the coupling relationship among industry, environmental pollution, housing, and population (Cai *et al.* 2021). Therefore, the coupling coordination degree (CCD) model was used in this study to measure whether there is a coupling relationship between flood risk and population vulnerability in a certain area, so as to further reveal the coordination degree between flood risk and vulnerable groups. To understand why the vulnerable groups are spatially coupled with flood risk, it is necessary to explore the driving factors of the relationship between them. Based on the results of coupling, this research used the Tobit model to analyze the factors of urbanization contributing to this relationship. This study explored the spatial and statistical connections between flood risk and population vulnerability and provides a theoretical basis for further research on climate justice.

Although cities are paying increasing attention to climate justice, there seems to be no acceptable empirical method to test the climate justice between flood risk and population vulnerability. This research may contribute to this field. We try to achieve the following goals by providing a new framework for the coupling between flood risk and population vulnerability: (I) to establish a model for the coupling between flood risk and population vulnerability to investigate the main driving factors of climate injustice and (ii) to make the geographic and statistical relationships between flood risk and population vulnerability clear since these relationships have triggered the unbalanced and unfair urban development. In short, this research provides a new understanding of climate justice and injustice, so that the problems the vulnerable groups cannot handle can be discovered and solved.

2. METHODOLOGY

2.1. Research area

Due to its geographical location and geographical environment, Taiwan is one of the areas most vulnerable to natural disasters on the earth. The most obvious natural disaster is flood, and more than two-thirds of the disasters are related to floods. The downstream area of Taichung City was used as the research object (Figure 1). This area has low elevation and often faces problems such as poor drainage system, regional flooding, and seawater intrusion, coupled with the increase in extreme rainfall brought by climate change; the loss of people and property during floods has been aggravated. Therefore, this area can be used for exploring the relationship between flood risk and population vulnerability.

2.2. Research framework

This study provides information about the direct correlation between population vulnerability and flood risk, which can facilitate the understanding of climate justice. Urbanization has driven different groups to transfer to different flood disaster risk areas. This research constructed a new framework for the coupling between flood risk and population vulnerability. It can be divided into two parts (Figure 2). In the first part, the main purpose is to establish an assessment model for the coupling between flood risk and population vulnerability. First, population vulnerability and population resilience were defined and expressed by appropriate indicators. Since the indicators have different influence, weight needs to be assigned. The entropy method can eliminate the artificial subjectivity through the information entropy, so that the weighting of the indicators is more objective. Secondly, the comprehensive flood risk score of each administrative district can be obtained according to the different flooding depth of inundation potential. Furthermore, the CCD model was used to calculate the coupling between population vulnerability and flood risk, and the coupling between population resilience and flood risk. This result can be used as an explanatory variable for the study of why vulnerable groups and flood risk are spatially coupled in the next step. The second part mainly involves the analysis of the coupling effect. This research studied the indicators that affect coupling from the perspective of urbanization and used the Tobit model to analyze the factors of urbanization contributing to the coupling relationship between population vulnerability and flood risk. Then, the influence of the impact indicators can be obtained, which can be used as a reference for the governance of climate injustice. Through the concept of climate justice, it was learned that vulnerable groups often become victims of climate change unconsciously, which provides a theoretical basis for further research on climate justice.

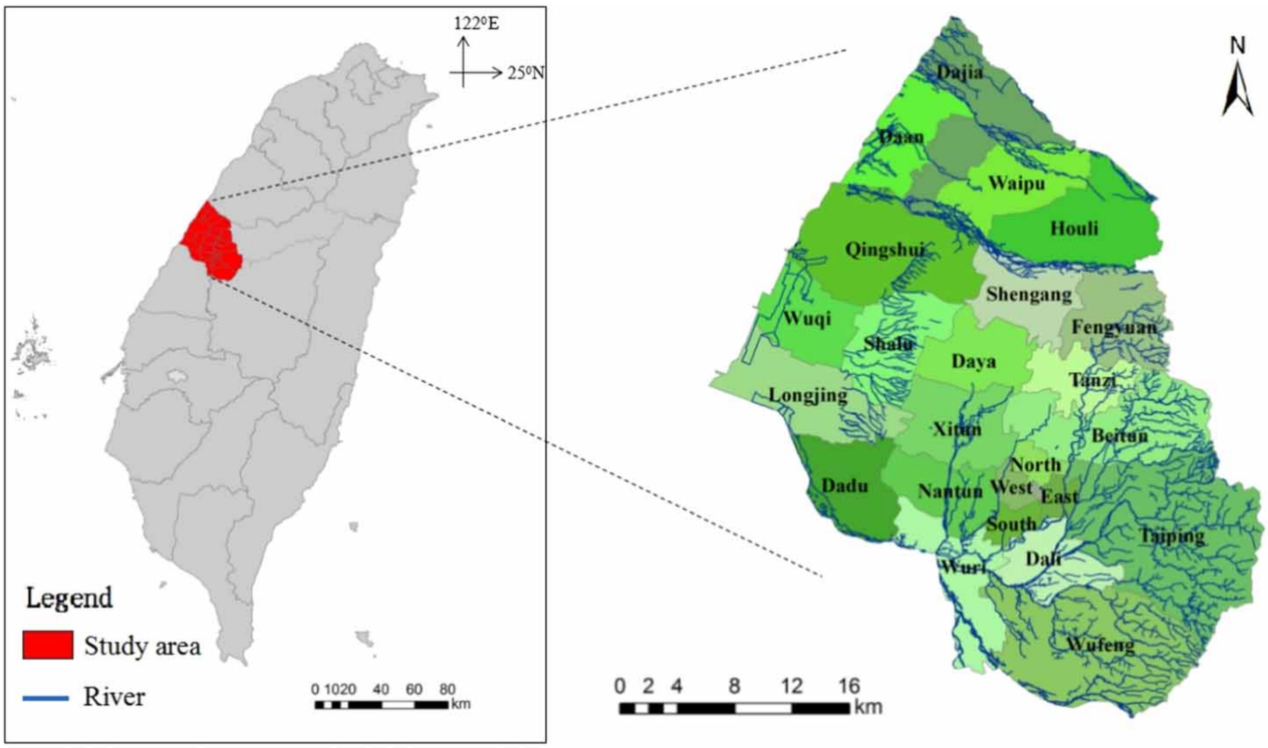


Figure 1 | Research area.

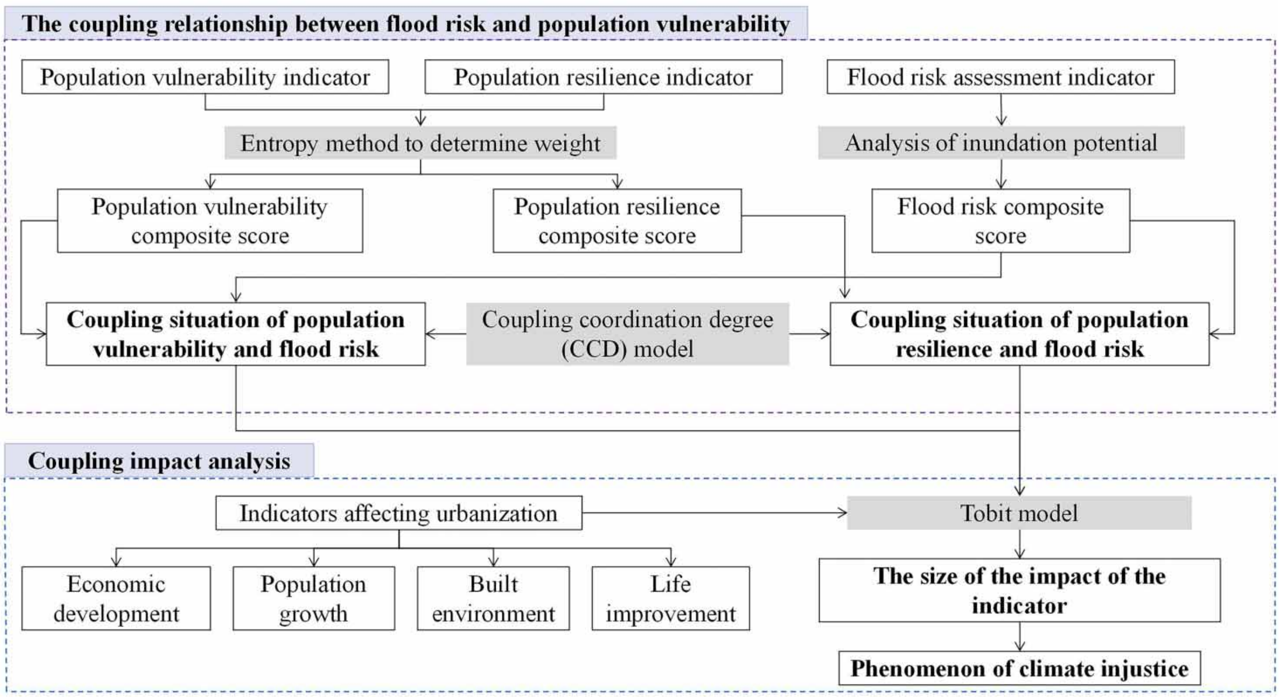


Figure 2 | Research framework for coupling.

2.3. The evaluation system for population vulnerability

In this research, the concept of population vulnerability was included into the scope of disaster management. To verify the spatial coupling relationship between flood risk and population vulnerability, the composition of population vulnerability needs to be defined, but vulnerability is relative. It is believed that those with low income are more vulnerable to climate change than wealthy people. Age, health, race, income, and education level will all affect the vulnerability of the population (Mavromatidi *et al.* 2018; Wilk *et al.* 2018; Drakes *et al.* 2021). Factors such as the elderly, children, illiterate, number of divorces, low-income population, aboriginal, and physical and mental disabilities are regarded as the indicators of population vulnerability based on the indicators published in the 'Taiwan Demographic Bulletin'. Population resilience indicators are expressed by young and middle-aged population and high-income population. Specific indicators are shown in Table 1 (the calculation method of the weight value is introduced in the entropy method below).

Since the units of the indicators are different, to facilitate comparison, the indicators were standardized (the values of all indicators are between 0 and 1; when the indicator is normalized to 0, we use 0.001 instead), as shown in Equation (1).

$$X'_{ij} = \frac{X_{ij} - X_{\min}}{X_{\max} - X_{\min}}. \tag{1}$$

In the evaluation system for population vulnerability, each indicator plays a different role and makes a different contribution. Therefore, it is necessary to determine the weight of each indicator. The entropy method overcomes the limitation of subjective judgment (Zhang *et al.* 2019). It shows good performance in managing the information of the system. It is the information entropy that measures the degree of disorder within the system. The larger the information entropy, the higher the degree of disorder of the information; the smaller the utility value of the information, the smaller the weight of the indicator (Lei *et al.* 2021). This research used the entropy method to determine the weight of the indicators of population

Table 1 | Measurement indicators for population vulnerability and population resilience

	Indicators	Description	Weight	Data source
Population vulnerability	Elder	This group is expressed by the number of people aged over 75. With limited mobility, these people may encounter difficulties in the event of a flood.	0.1422	Statistical bulletin of each administrative district
	Child	This group is expressed by the number of people under 5 years. Since this age group does not have the ability to make independent judgment, they need to be taken care of.	0.1428	
	Illiterate	The low level of education also means weak corresponding escape skills and property level and the limited access to disaster information.	0.1456	
	Number of divorces	The high proportion of divorce will increase the proportion of single-parent families. When a disaster occurs, they usually do not have enough funds to support their families.	0.1414	
	Low-income population	When a disaster occurs, they usually do not have enough funds for disaster recovery.	0.1418	
	Aboriginal	Indigenous people are often disadvantaged and marginalized population in the society.	0.1427	
	Physical and mental disabilities	Physical disability causes limited mobility.	0.1436	
Population resilience	Young and middle-aged population	With strong initiative, they can make a quick response to disasters.	0.5024	
	High-income population	They are able to move to a relatively safe area and have sufficient funds for post-disaster recovery. The high-income group in this study mainly refers to those with a master's degree or a doctoral degree.	0.4976	

vulnerability and population resilience, as shown in Equation (2).

$$Y_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{m} X'_{ij}}$$
$$H_j = \frac{1}{\ln m}\sum_{i=1}^{m} Y_{ij}\ln Y_{ij} \tag{2}$$
$$\eta_j = \frac{1 - H_j}{n - \sum_{i=1}^{n} H_j}$$

where X'_{ij} represents the standard value of indicator j in the ith administrative district, m and n represent the number of administrative districts and indicators, respectively, Y_{ij} means the proportion of indicator j in the ith administrative district, H_j is the information entropy of indicator j, and η_j is the weight of the indicator j (the specific calculated weights are displayed in the last column of Table 1).

2.4. The evaluation system for flood risk

Flood risk reflects the possibility of being affected by floods, that is, the higher the flood risk level, the easier the flooding in the area. In this study, flood risk is expressed by the inundation potential diagram. The flooding potential simulation of the Taichung City Government Water Conservancy Bureau mainly takes into account factors such as rivers, hydraulic structures (pumping stations, seawalls, flood detention facilities, etc.), stormwater sewer systems (rainwater manholes, stormwater pipelines, etc.), and the results of treatment plans for flood-prone areas. Its flooding conditions were caused by the heaviest rainfall to occur in 200 years (Chang *et al.* 2021). Specifically, the data of the flooding range in the 200-year return period were adopted to calculate the flood risk (the flood potential map of the 200-year return period is used because Taiwan's current highest flood control standard is once in 200 years). Taichung's specific inundation potential is shown in Figure 3(a). According to the flooding standards of the Taichung Water Conservancy Department, we divide the flooding depth into five

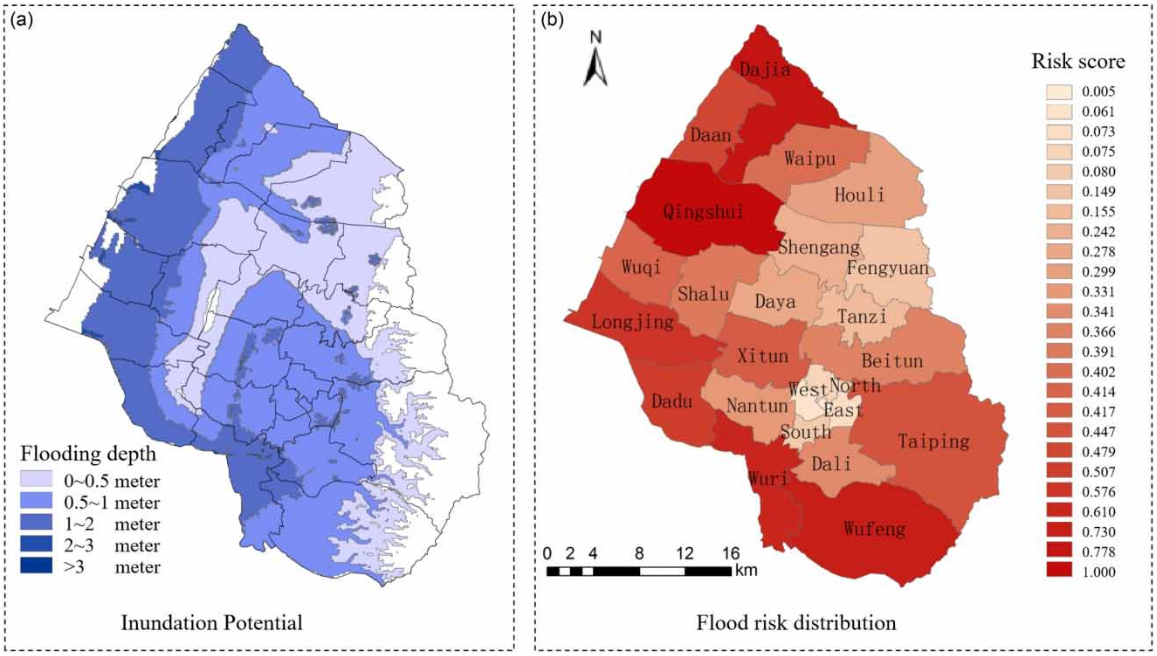


Figure 3 | Inundation potential and flood risk score of the administrative districts in Taichung.

standards: 0–0.5, 0.5–1, 1–2, 2–3, and more than 3 m. Then, scores from 1 to 5 are used to represent the degree of hazard at different flooding depths (see Figure 3(a) for details). The calculation method of flood risk evaluation in each administrative district is shown in Equation (3). According to Equations (1) and (3), the final flood risk score of each administrative region can be obtained (such as Figure 3(b)).

$$S_i = \sum_{i=1}^{m} R_j \times A_{ij} \tag{3}$$

where S_i represents the flood risk score of the ith administrative district, R_j is the degree of hazard of different flooding depth in the 200-year return period, and A_{ij} is the flooded area in the ith administrative district in the jth return period (unit is m^2). The flood risk score of each administrative district was standardized (Equation (1)) to facilitate the subsequent analysis of the CCD between flood risk and population vulnerability.

2.5. CCD model

Based on the theory of coupling, the interaction between flood risk and population vulnerability was defined as the coupling between two systems. The CCD model uses coupling degree and CCD to evaluate the coupling state between research objects (Cai *et al.* 2021). The basic idea is to first apply the comprehensive power function to obtain the comprehensive efficiency of each administrative district; then, the coupling degree is calculated to measure the degree of interaction and mutual influence; finally, the coordination between the two systems is evaluated by the CCD. The comprehensive power values of population vulnerability and flood risk can be calculated by Equations (2) and (3), and the distribution is represented by U_1 and U_2. Then, the coupling degree model can be expressed by Equation (4).

$$\begin{aligned} U_1 &= \frac{\eta_j X_{ij} - (\eta_j X_{ij})_{\min}}{(\eta_j X_{ij})_{\max} - (\eta_j X_{ij})_{\min}} \\ U_2 &= \frac{S_i - S_{\min}}{S_{\max} - S_{\min}} \\ C &= \sqrt{\frac{U_1 \times U_2}{(U_1 + U_2)^2}} \end{aligned} \tag{4}$$

where C is the coupling degree, and the larger the value of C, the stronger the coupling between population vulnerability and flood risk. CCD is expressed by Equation (5) as follows:

$$D = \sqrt{C \times (aU_1 + bU_2)} \tag{5}$$

where $aU_1 + bU_2$ is the comprehensive impact of population vulnerability and flood risk. α and β have the same value, that is, 0.5 (He *et al.* 2017) (population vulnerability and flood risk are equally important); D is the coordination degree, and the larger the value of D, the higher the degree of coordination, which means there is a strong spatial relationship between population vulnerability and flood risk. The same is true for the result of coupling between population resilience and flood risk. To judge the relationship between the two relative to climate justice, Equation (6) was constructed as follows:

$$\tau = \frac{U_2}{U_1} \tag{6}$$

Based on past experience, setting the threshold to 0.7 can better reflect the spatial matching of flood risk and population vulnerability (Liu *et al.* 2022). When $0 < \tau \leq 0.7$, it means that the flood risk is less than the population vulnerability, which is a relative reflection of environmental justice. When $0.7 < \tau \leq 1.4$, it means that the flood risk and population vulnerability appear in space at the same time, which is relative to the environmental injustice. When $\tau > 1.4$, it means that the population vulnerability is less than the flood risk, and the vulnerable groups have not migrated to the floodplains relatively, which also reflects environmental justice relatively.

2.6. Tobit model analysis

Based on the coupling between population vulnerability and flood risk, this research explored the reasons for such coupling from the perspective of urbanization. Urbanization has changed the original living environment, causing many people to actively or passively adjust their living environment to adapt to the impact of urbanization. Chen *et al.* (2018) and Xia *et al.* (2020) show that urbanization is affected by four aspects: economic development, population growth, built environment, and life improvement. Economic development indicators are represented by per capita income, agricultural output value, industrial output value, and commercial output value (Gu *et al.* 2020; Patri *et al.* 2022), reflecting the economic development of each region. Previous studies on population growth indicators used population density to reflect the population congestion in the region and natural population growth rate to highlight the population structure of the region (Clar *et al.* 2023). The built environment indicator is the physical space that reflects the level of urbanization. Previous studies used per capita public land, housing quality, per capita road area, and spatial development intensity (Chen *et al.* 2018; Xia *et al.* 2020; Bernardini *et al.* 2024) to highlight the security level of the physical space. The life improvement indicator mainly focuses on the impact of social conditions on people's lives. Xia *et al.* (2020) believe that government capacity, housing price, and medical institutions are the three major indicators that affect the quality of life. In summary, the specific impact indicators of the coupling in this study are summarized in Table 2.

Since the value of the CCD between population vulnerability and flood risk is 0–1, the dependent variable is limited or truncated. The Tobit model can handle this feature (Equation (7)), and it can effectively reduce the error of parameter estimation (Yan *et al.* 2013; Toloo & Tichý 2015). Therefore, this study uses the Tobit model to obtain more accurate results.

$$\begin{array}{ll} D_i^* = \beta x_i + \varepsilon_i, & i = 1, 2, \ldots, n, \\ D_i = D_i^* & \text{if } D_i^* > 0, \\ D_i = 0 & \text{if } D_i^* \leq 0, \end{array} \tag{7}$$

where D_i^* is a potential variable. In this article, it refers to the value of the CCD of each administrative district. β is the vector of estimable parameter; D_i represents the value of the CCD between population vulnerability and flood risk, which is also the dependent variable of this article; x_i is the influence indicator in Table 2, which is also the independent variable of this article; ε_i is a random interference item. Through the Tobit model, the impact size of the indicators affecting coupling can be found, so that the cause of climate injustice can be discovered.

Table 2 | Impact indicators of the coupling between population vulnerability and flood risk

Dimension	Indicator	Indicator description	Source
Economic development	Per capita income	Per capita income reflects the level of economic development in the area	Statistical bulletins of various administrative regions and land use survey data in Taiwan
	Agricultural output value	Expressed by agricultural land area	
	Industrial output value	Expressed by number of factories	
	Commercial output value	Expressed by number of merchants	
Population growth	Population density	The population of the administrative district/the area of the administrative district	
	Natural population growth rate	New born population/population of administrative district	
Built environment	Per capita public land	Public land area/administrative district area	
	Housing quality	The average age of residential houses is used to indicate that the larger the average age of residential houses, the more old buildings there are	
	Per capita road area	Road construction area/administrative area	
	Spatial development intensity	Overall development area/administrative district area	
Life improvement	Government capacity	Expressed by fiscal expenditure	
	House price	The housing price of 30–50 pings is used as the measurement indicator.	
	Medical institutions	Expressed by the number of medical personnel practicing.	

3. CASE STUDY

3.1. Analysis of the coupling between flood risk and population vulnerability (resilience)

It can be seen from the second column of Table 3 and Figure 3(b) that flood disaster risk is mainly distributed in coastal areas and areas on both sides of the river. The Qingshui district has the highest flood risk. This district is located in the lower reaches of the river and in the coastal area, and thus it is easily affected by flooding and seawater intrusion, but the population vulnerability of this district is at an average level. Other districts with high risk value include the Wuri, Wufeng, and Dajia districts, all of which have a risk value greater than 0.6. These districts are also mainly located in coastal areas and areas on both sides of rivers. It can be seen that the development of coastal areas and areas on both sides of rivers is vulnerable to flooding. The districts with low risk are mainly located in the central areas of the city, including Central, West, East, North, and South districts, all of which have a risk value of less than 0.1. This shows that the main land development in Taichung City avoids areas with high flood risk, which is conducive to the development of the city and the protection of personnel. In general, the overall flood risk value of Taichung City is 0.368, which is at a relatively low level.

From the perspective of population vulnerability (the third column of Table 3), the average population vulnerability of Taichung is 0.366, which is at a relatively low level. However, the Taiping, Beitun, and Dali districts have relatively high population vulnerability, indicating that compared with other administrative districts, these districts have more vulnerable groups. Similarly, the administrative districts located in the central area of the city do not have high population vulnerability, and the values are all less than 0.5.

From the perspective of the CCD (the fifth column in Table 3), the overall CCD of Taichung City is 0.391, indicating that the flood risk and population vulnerability are not highly coupled in space, and the coupling is at a low level. However, there are still several districts where the CCD exceeds 0.5, including the Beitun, Xitun, Taiping, and Qingshui districts, demonstrating that these districts are in a relatively coordinated state. From the perspective of the relative climate justice, the districts where flood risk is as high as population vulnerability are the Shengang, Daya, Nantun, and Shalu districts. Therefore, these districts were regarded as the climate injustice districts because they need to face flood risk and population vulnerability simultaneously. Other districts only need to deal with one of the two problems. For example, the flood risk value of the Fengyuan district is only 0.149, while the population vulnerability reaches 0.576. Although the population vulnerability is

Table 3 | The results of coupling between flood risk and population vulnerability

	Risk score	Vulnerability score	Coupling degree	CCD	Relative climate justice relationship	
Central district	0.005	0.010	0.472	0.061	0.501	Justice
West district	0.061	0.303	0.374	0.261	0.202	Justice
East district	0.073	0.256	0.415	0.261	0.283	Justice
North district	0.075	0.495	0.338	0.310	0.151	Justice
South district	0.080	0.363	0.385	0.292	0.220	Justice
Fengyuan district	0.149	0.576	0.404	0.383	0.259	Justice
Tanzi district	0.155	0.374	0.455	0.347	0.415	Justice
Shengang district	0.242	0.234	0.500	0.345	1.034	Injustice
Daya district	0.278	0.314	0.499	0.384	0.886	Injustice
Houli district	0.299	0.207	0.492	0.353	1.443	Justice
Nantun district	0.331	0.425	0.496	0.433	0.778	Injustice
Dali district	0.341	0.723	0.467	0.498	0.472	Justice
Beitun district	0.366	0.913	0.452	0.538	0.401	Justice
Shalu district	0.391	0.351	0.499	0.430	1.115	Injustice
Waipu district	0.402	0.104	0.404	0.320	3.853	Justice
Wuqi district	0.414	0.216	0.475	0.387	1.912	Justice
Xitun district	0.417	0.644	0.488	0.509	0.648	Justice
Taiping district	0.447	0.823	0.478	0.551	0.543	Justice
Daan district	0.479	0.042	0.273	0.267	11.307	Justice
Dadu district	0.507	0.268	0.476	0.430	1.890	Justice
Longjing district	0.576	0.312	0.477	0.461	1.846	Justice
Wuri district	0.610	0.277	0.463	0.453	2.205	Justice
Wufeng district	0.730	0.246	0.434	0.460	2.963	Justice
Dajia district	0.778	0.300	0.448	0.492	2.595	Justice
Qingshui district	1.000	0.365	0.443	0.550	2.740	Justice
Average	0.368	0.366	0.444	0.391		

high, the flood risk value is small; therefore, this district can effectively avoid disaster losses. Another example is the Wufeng district which has a very high flood risk (0.730), but its population vulnerability is only 0.246; thus, when a disaster occurs, the personnel and property losses can be effectively avoided.

Furthermore, the results of coupling between flood risk and population resilience were analyzed and compared with the coupling relationship between flood risk and population vulnerability. It can be seen from Table 4 that the population resilience of Taichung City is not high, at only 0.323. Only Nantun, Beitun, Xitun, and Dali districts have a population resilience higher than 0.6. The overall CCD is 0.366, indicating that the flood risk and population resilience of each district in Taichung City are not concentrated at the same spatial location at the same time. In other words, a relatively resilient population effectively avoids flood risk areas. However, Beitun, Xitun, and Taiping districts have the CCD greater than 0.5, indicating that the resilient population in these districts pays more attention to economic development than other districts and relatively ignores the problem of flood risk. From the perspective of the relative climate justice relationship, wealthy people will relatively avoid areas with flood risk, and the population resilience group can better reflect climate justice. However, climate injustice can still be observed in the Daya and Taiping districts. The relatively resilient population in these districts prefers flood risk areas to find opportunities for economic development.

In general, the CCD between flood risk and population vulnerability is 6.5% higher than that between flood risk and population resilience, indicating that vulnerable groups are more likely to live in areas with high flood risk than those who are rich.

Table 4 | The results of coupling between flood risk and population resilience

	Resilience score	Coupling degree	CCD	Relative climate justice relationship	
Central district	0.008	0.489	0.057	0.658	Justice
West district	0.379	0.346	0.276	0.161	Justice
East district	0.214	0.435	0.250	0.340	Justice
North district	0.489	0.339	0.309	0.153	Justice
South district	0.364	0.384	0.292	0.220	Justice
Fengyuan district	0.496	0.422	0.369	0.301	Justice
Tanzi district	0.320	0.469	0.334	0.485	Justice
Shengang district	0.157	0.488	0.312	1.543	Justice
Daya district	0.268	0.500	0.369	1.038	Injustice
Houli district	0.113	0.446	0.303	2.643	Justice
Nantun district	0.623	0.476	0.477	0.531	Justice
Dali district	0.666	0.473	0.488	0.512	Justice
Beitun district	1.000	0.443	0.550	0.366	Justice
Shalu district	0.257	0.489	0.398	1.519	Justice
Waipu district	0.048	0.309	0.264	8.350	Justice
Wuqi district	0.142	0.436	0.348	2.921	Justice
Xitun district	0.824	0.472	0.541	0.506	Justice
Taiping district	0.594	0.495	0.508	0.752	Injustice
Daan district	0.007	0.117	0.168	71.472	Justice
Dadu district	0.132	0.405	0.360	3.836	Justice
Longjing district	0.211	0.443	0.418	2.731	Justice
Wuri district	0.206	0.434	0.421	2.965	Justice
Wufeng district	0.158	0.383	0.412	4.604	Justice
Dajia district	0.184	0.393	0.435	4.224	Justice
Qingshui district	0.226	0.388	0.488	4.423	Justice
Average	0.323	0.419	0.366		

This makes the area face the dual problems of flood risk and population vulnerability at the same time, which further raises man-made risks and indirectly reflects climate injustice. In Taichung City, there are four districts with injustice in both flood risk and population vulnerability, two more districts than the districts with population resilience injustice. This also indirectly shows that the resilient population tends to choose areas with low flood risk, and vulnerable groups are forced to transfer to areas with high flood risk.

3.2. Analysis of the driving factors for the spatial coupling between flood risk and population vulnerability (resilience)

In this study, the value of CCD was used as the dependent variable, and the indicators of urbanization were used as the independent variables. The analysis results of the Tobit model are shown in Table 5. The standard deviations of the model are all less than 0.4, and the R^2 values are 0.78 and 0.82, respectively, indicating that the Tobit model has a better fitting effect. It can be found from the results that the coupling between flood risk and population vulnerability is quite different from the coupling between flood risk and population resilience. The main driving factors for the coupling between flood risk and population vulnerability are government abilities and population growth. In addition, the coefficients of population density, housing quality, and spatial development intensity of the city are negative, suggesting that in areas with great population density, housing quality, and spatial development intensity, the vulnerable groups are likely to leave. In other words, vulnerable groups tend to

Table 5 | Analysis results of driving factors

		Vulnerability		Resilience	
Dimension	**Variable**	**Coefficient**	**Std. Error**	**Coefficient**	**Std. Error**
Economic development	Per capita income	0.000243	0.000257	0.000273	0.000236
	Agricultural output value	0.000035	0.000045	0.065872	0.320039
	Industrial output value	0.000032	0.000040	0.028218	0.034679
	Commercial output value	0.000004	0.000012	0.000049	0.000079
Population growth	Population density	−0.000744	0.001186	0.000006	0.000016
	Natural population growth rate	0.017211	0.014936	0.000038	0.000041
Built environment	Per capita public land	0.000451	0.001356	0.000028	0.000037
	Housing quality	−0.001005	0.004396	0.000006	0.000011
	Per capita road area	0.000333	0.000796	−0.000840	0.001085
	Spatial development intensity	−0.005204	0.349676	0.013644	0.013671
Life improvement	Government capacity	0.025630	0.037890	0.000271	0.001241
	House price	0.000036	0.000087	−0.004067	0.004023
	Medical institutions	0.000010	0.000017	0.000200	0.000728
R^2		0.78		0.82	
Log-likelihood		38.41		40.62	

migrate to rural areas with low population density or areas with weak development intensity, and the more average the housing quality in an area, the easier it is for the vulnerable groups to gather. The coupling between flood risk and population resilience is more susceptible to economic development and the built environment. The economic growth and the improvement of the built environment can attract wealthier people. However, the results showed that the coefficient of per capita road area and housing prices is negative, indicating that wealthy people are also susceptible to the impact of housing prices and road noise. The analysis of driving factors in this research is helpful for handling the problems that the disadvantaged or wealthy groups cannot discover and solve.

4. DISCUSSION

In the face of the increasingly uncertain climatic conditions, how people pay more attention to climate justice in the urban environment has attracted increasing attention. Especially, people are paying increasing attention to the unequal distribution of flood risk (Steele *et al.* 2015). Our research results have identified the areas where flood risk and population vulnerability are highly spatially coupled, which can provide a realistic basis for the analysis of climate injustice.

The combined effects of urbanization and climate change have exerted a disproportionate negative impact on those vulnerable groups in the city. Our research results showed that the CCD between flood risk and population vulnerability is 6.5% higher than the CCD between flood risk and population resilience, suggesting that vulnerable groups are more susceptible to flood risk than wealthy groups. This makes some areas face the dual risks of flood disaster and population vulnerability simultaneously. Such double-vulnerability greatly increases the risk of water-borne diseases of vulnerable groups and threatens their property and even their lives.

The coupling results showed that urbanization has made historically marginalized populations more vulnerable and less secure, so that these populations are more likely to move to areas with high flood risk, and at the same time, more privileged residents will benefit from the built environment in the city. It can be seen from the analysis of the driving factors of coupling that vulnerable groups prefer economically favorable areas where the local government has strong abilities to take care of the vulnerable groups. The high prices of land and the high intensity of spatial development will further intensify this coupling. The consequence is that vulnerable groups will stay away from the areas with better urban built environment since many do not have access to reliable and affordable basic services. The rich are more affected by economic development and the built environment of the city, and they prefer to live in areas with low flood risk. The results provide a new understanding of urban climate justice and the spatial distribution of injustice.

People know little about the position of vulnerable groups in climate justice and the potential relationship between flood risk and population vulnerability. It seems that there is no acceptable empirical method to test the relationship between vulnerable groups and climate justice. Previous studies mainly focus on how flood risk causes great social vulnerability (Yang *et al.* 2021), but the relationship between flood risk and population vulnerability has rarely been discussed from the perspective of spatial coupling. The difference between this research and related studies is that it constructed a coupling and coordination relationship between flood risk and population vulnerability from the perspective of climate justice. In this framework, the indicators of population vulnerability and population resilience were established, and the entropy method was used to objectively evaluate the weight of each indicator. In addition, the CCD model was used to compare the relationship between flood risk and population vulnerability with the relationship between flood risk and population resilience, thereby revealing their spatial differences. Finally, the driving factors of coupling were used to reveal how the vulnerable groups and the rich strengthen climate injustice in the process of urbanization. This framework helps better understand the spatial inequality in flood risk and population vulnerability and the phenomenon of climate injustice, and can also help explore the factors of urbanization leading to unbalanced and unfair results. The results establish the spatial and statistical link between flood risk and population vulnerability, which can provide a theoretical basis for future urban planning, spatial design, government policy implementation, and governance.

There are still some limitations in this research. (i) It explored the relationship between flood risk and population vulnerability from a regional perspective, but the scale of urban design was not included. Subsequent research can combine urban land development and functional zoning to make the phenomenon of climate injustice concrete in space. (ii) The entropy method in this study does not consider the correlation between criteria. Since it only assigns weights based on entropy (variability), it cannot resolve redundant information. Subsequent research can further refine the weights of indicators in combination with the Criteria Importance Through Intercriteria Correlation (CRITIC) method (Manikanta *et al.* 2023).

5. CONCLUSIONS

Climate change has intensified the vulnerability of cities and may have a great impact on vulnerable groups. Our research results have verified this hypothesis. The results make clear the geographic and statistical relationships between flood risk and population vulnerability and illustrate how these relationships have shaped the unbalanced and unfair urban development. The specific conclusions can be summarized as follows:

(I) This research constructed a framework to explore the coupling relationship between flood risk and population vulnerability from the perspective of climate justice. The framework studied which are the real disadvantaged and wealthy groups and applied the information entropy method to objectively assign the weight of the indicators. The flood risk was identified using the relationship of inundation potential. Furthermore, the CCD model was adopted to calculate the coupling between population vulnerability and flood risk, and the driving factors of coupling were analyzed using the Tobit model.

(II) The research results showed that vulnerable groups in Taichung City are more likely to live in areas with high flood risk, 6.5% higher than wealthy groups. Therefore, the areas with high risk often face the double crisis of flood risk and population vulnerability. In Taichung City, there are four administrative districts with injustice in both flood risk and population vulnerability, which double the result of population resilience. This also indirectly reflects the potential connection between social vulnerability and environmental injustice.

(III) Judging from the analysis results of the Tobit model, vulnerable groups tend to move to rural areas with low population density or areas with low development intensity, and the ability of the government is a major consideration for the settlement of vulnerable groups. Relatively wealthy groups are easily affected by the level of economic development and the built environment of the city and tend to settle in areas with low flood risk. This result can help solve the problems that the disadvantaged or wealthy groups cannot discover and solve, which is vital to the future pursuit of climate justice.

After the Paris Climate Agreement was established, increasing attention has been paid to fair and just process, which requires the identification of the risk relationship between the characteristics of vulnerable population and climate change (Hughes & Hoffmann 2020). The advancement of urbanization and a highly adaptable system are not necessarily fair, nor are they beneficial to vulnerable groups. Although our research results revealed the phenomenon of climate injustice to a certain extent, a broader knowledge system involving social vulnerability, poverty, political economy, and different social powers (Friend & Moench 2013) needs to be established to promote the true understanding and resolution of climate justice.

AUTHOR CONTRIBUTIONS

ZJ contributed to the conceptualization, methodology, reviewing the writing – reviewing, writing the original draft, visualization, and data curation. QS contributed to the conceptualization, methodology, software, data curation, writing the original draft, visualization, and reviewing and editing the writing. YC contributed to reviewing and editing the writing, software, and data curation.

FUNDING

This study was supported by Projects of Fujian Social Science Foundation (No. FJ2022C097), Projects of Fuzhou Philosophy and Social Science Foundation (No. 2023FZC32), Projects of Fujian Natural Resources Science and Technology Innovation (No. KY-020000-04-2022-035), Projects of National Natural Science Foundation of China (No. 52008110), and Projects of Fujian Natural Science Foundation (No. 2020J05195).

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 6 August 2023; accepted in revised form 26 December 2023. Available online 16 February 2024