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Spatio-temporal detection of agricultural disaster vulnerability in the world and implications for developing climate-resilient agriculture

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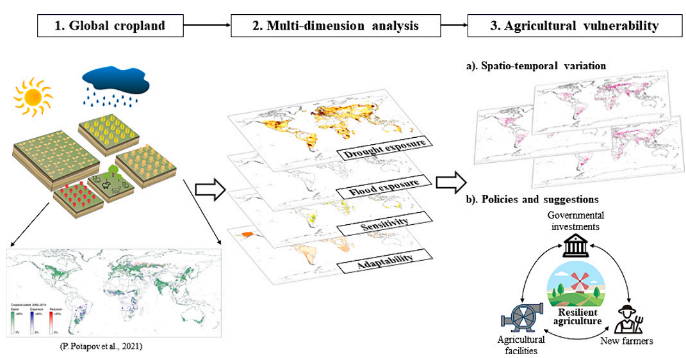
HIGHLIGHTS

- A new theoretical framework is proposed to understand the relationship between climate change, agricultural system and socio-economic system.
- Agricultural vulnerability is comprehensively assessed by multiple consistent factors.
- To enhance the agricultural resilience will contribute to more sustainable future agriculture.

GRAPHICAL ABSTRACT



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ABSTRACT

Drought and floods seriously affect agriculture across the world. It is of great importance to lower down the agricultural vulnerability to disasters to build climate-resilient agriculture. The paper aims to investigate the spatio-temporal changes of agricultural vulnerability to drought and floods in the world in the period 2003–2019. Research results show that (1) the agricultural vulnerability to drought and floods is at a low level across the globe owning to the dual effects of decreasing exposure and increasing adaptability; (2) the northern parts of United States, northeastern parts of China, and the border between Russia and Kazakhstan are identified as most vulnerable areas to drought and floods; and (3) spatio-temporal mismatch of precipitation is the main factor to cause floods and drought while better adaption is beneficial to minimize the adverse effects of disasters. Based on analysis on the drivers and spatial patterns of drought and floods risk in all dimensions, tailored measures and policies are put forwards to make adaptive strategies of agriculture to climate change.

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1. Introduction

The 78th UN General Assembly released the halfway assessment of the Sustainable Development Goals (SDGs) and the results were not optimistic as expected. It shows that only 15 % of goals are on track, while 48 % are moderately to severely off track, and 37 % are either making no progress at all or regressing in comparison to the 2015 starting line (United Nations, 2023). Among all the challenges, climate change exerts far-reaching and broad coverage impacts on the key SDG targets such as no poverty, zero hunger and reduced inequalities etc. The global food security situation will become more difficult as the world's population is estimated to reach 9.5 billion by 2050 and about 70 % more food needs to be yielded to feed these people (FAO, 2016). However, the observed climate change events such as drought, heat waves and floods are already affecting agriculture and food production especially in rural communities with large populations of small-scale producers who are highly dependent on rain-fed agriculture for their livelihoods and food. Climate change is also expected to reduce yields of staple crops by up to 30 % due to lower productivity and crop failure (Jain et al., 2015).

Climate change and its induced disaster events have arisen public concerns to the world's food security issues. Almost half of the world's population are living in regions that are highly vulnerable to climate change. According to Intergovernmental Panel on Climate Change (IPCC), the chances of deaths caused by floods, droughts and storms were 15 times higher in vulnerable regions than other places of the world during the last decade (IPCC, 2023). In addition, an estimation of $3.8 trillion loss of crops and livestock production were caused owing to climate change events over the past 30 years (FAO, 2023). Climate change has also adversely affected human physical health around the world (IPCC, 2023). It is projected that 600 million people will be chronically undernourished in 2030, pointing to the immense challenge of achieving the SDGs targets to eradicate hunger (FAO et al., 2023). IPCC (2021) further estimated that the output of the four major crops (corn, wheat, rice, and soybeans) will decrease by 10 % by 2100, and around 10 % of the world's crops and livestock areas are no longer suitable for production by 2050.

At present, people try to develop climate resilient agriculture through various ways in order to minimize the impact of climate change. As one of sustainable land management approaches, greenhouse agriculture which evolves from simple covered rows of open-fields crops to highly sophisticated agriculture facilities is an illustrative example of controlling environmental conditions for farming given the external temperature and humidity variations (Ten Napel et al., 2006; Shamshiri et al., 2018). Another example is the improved on-farm water management and storage such as drip irrigation and deep-water irrigation which have shown to diminish farmers' vulnerability to weather conditions and make production and incomes more stable (Salazar and Rand, 2016). What's more, crop yields have increased substantially throughout the past century, which are attributed to cultivar improvements as well as advances in farming technology and practice (Robert et al., 2014).

In particular, both floods and drought are major natural disasters induced by climate change. Drought is conceived as an exceptional and sustained lack of water caused by a deviation from normal conditions over a certain region (Tallaksen and Van Lanen, 2004; Van Loon et al., 2016). However, the surplus of water is the direct cause of floods. Drought has been regarded as the major factor in agricultural production loss. Over 34 % of crops and livestock production loss in least developed countries (LDCs) and low and middle income countries (LMICs) is traced to drought, arriving at $ 37 billion losses (FAO, 2021). And evidences show that there are 70 % loss of cereal crops in the Mediterranean and national livestock herd declined by 15 % in Africa (United Nations, 2023). Floods are the second gravest disaster in agricultural production, responsible for $ 21 billion of crops and livestock losses between 2008 and 2018 in LDCs and LMICs (FAO, 2021). Over 18 % of the total areas was directly inundated, and the estimated losses of rice production were approximately 1.8 million tons, representing an 80 % loss of the expected total rice yield in Pakistan's Sindh Province in 2022.

Thinking of the global food security and the potential challenges of climate change, it becomes necessary to know the vulnerable places where agriculture and food production are subjected to climate change disasters. This helps to take specific measures to counteract climate events and ensure food security. Thus, the research focuses on agriculture's response to climate change and its adaptive strategy. It aims to detect the spatio-temporal evolution of agricultural vulnerability to climate disasters (drought and floods) across the world. Policy implications for developing climate-resilient agriculture are made based on the research findings. The structure of the paper is as follows: the second section creates a theoretical framework to illustrate the interactions between climate change and agriculture and socio-economic systems. In the third section, the paper introduces research methodology and data source. The fourth section presents the spatio-temporal pattern of the agricultural vulnerability to natural disasters in the world and in the typical countries. The paper closes by discussing ways of developing climate-resilient agriculture.

2. Theoretical framework

Agricultural system is a complex inter-related matrix composed of soil, plants, fertilizer, labor and capital, etc. It is controlled by family inputs and influenced by various factors such as changes in environmental or socio-economic conditions which cannot be anticipated. Food security means that all people at all times have access to adequate amounts of nutritious and safe food. However, climate change poses threats on the sustainable food production. In terms of trends, global warming will affect agricultural activities gradually in the future: by the end of the 21th century, temperature is expected to rise by 1.4 to 5.8 °C while atmospheric CO_2 concentration could reach three to four times the pre-industrial levels (IPCC, 2014). Natural disasters induced by climate change have spawned a large-scale food crisis and the number of people facing food insecurity has been increasing quickly nowadays. Extreme weather and its induced climate events were the main causes of severe food insecurity for 56.8 million people in 12 countries worldwide in 2022 (FSIN, 2023).

Vulnerability which dates back to the Latin word '*vulnus*' is a very dynamic concept and describes the relationship between the object and the environment. Based on the seminal work by IPCC, the vulnerability concept benefits from a highly operational framework including exposure, sensitivity and adaptability to describe the relationship between the studied system and its environment (Adger, 2006; Luers et al., 2003; Urruty et al., 2016). As shown in Fig. 1, there are close linkages between climate change, agricultural system and socio-economic system. Climate change has caused a series of natural disasters across the globe, such as floods, drought, typhoon and heat waves etc. These have led to widespread adverse impacts on agricultural production, human health and socio-economic stability. Agricultural system is composed of biotechnical and social factors, and is dedicated to the supply of food, livelihoods, ecosystem and landscapes (Renting et al., 2009). It is exposed to unpredictable perturbations (exposure), which inevitably cause the changeable stability over time of the availability, access and utilization dimensions at all times (sensitivity), so adaptation options which are effective in reducing climate risks are necessary (adaptability). In practice, adaptability is seen as the set of natural, financial, social, technical or institutional conditions that agricultural systems can mobilize for coping with constraints and overcoming them (Brooks and Adger, 2005).

It is important to encompass both internal and external factors facing uncertainty. For instance, improving the self-adaptability of the agricultural system by popularizing climatic resilient crops and animal breeding is an illustrative example. Besides, it is necessary to intensify

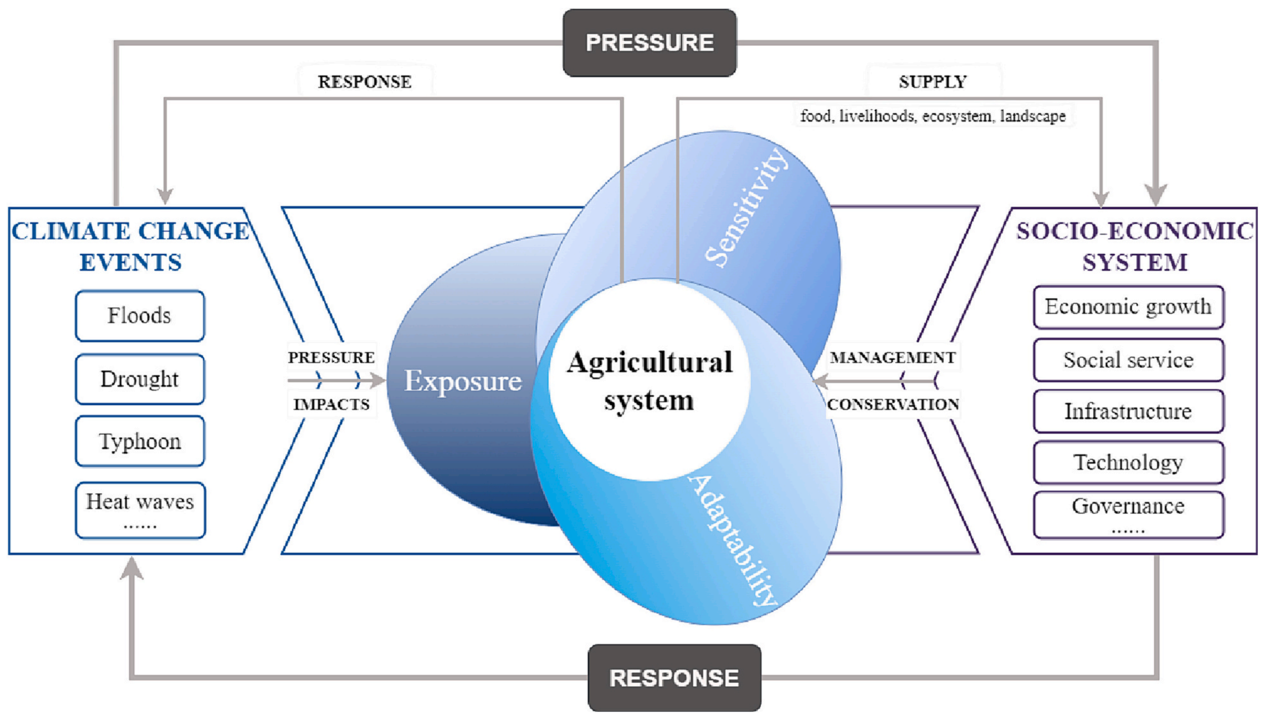

Fig. 1. The theoretical framework about natural disasters.

the construction of disaster prevention and relief system. In pre-disaster, remote sensing, GPS and navigation etc., are widely applied in weather monitoring, warning and information disseminating. The constructions of agricultural infrastructures, such as drainage, irrigation sensors and roads, are attached great importance to prevent disasters and shorten rescue time. In the meanwhile, providing convenient check for affected crops is necessary in post-disaster. Climate change risks show a complex trend, with multiple disasters occurring simultaneously and affecting multiple systems. Therefore, the multi-sectoral solutions are undertaken that can cut across systems and yield greater benefits for human well-being, social equity and justice, and ecosystem and planetary health.

Climate change is considered as the increasingly important factor of agricultural development at the national level (Dronin and Kirilenko, 2013). There have been continuous efforts to assess the capacity of agricultural systems to cope with natural events. To date, there are studies focusing on incremental adjustments like promotion of single adaptation responses to improve agricultural resilience, that may enable better management of climate risks and opportunities in the near-term (Rickards and Howden, 2012; Vermeulen et al., 2013; Vermeulen et al., 2018). While it acts as a disincentive for other types of change that may lead to much more negative outcomes over the longer term. Hence, agricultural vulnerability is seen as the manifestation of agricultural sensitivity and adaptability to climate change (Li et al., 2023). This paper makes use of the "exposure-sensitivity-adaptability" vulnerability framework by setting multiple indicators to investigate response of agricultural system attributes and socio-economic factors to drought and floods. On the basis, policy implications to make adaptive strategies of agriculture to climate change are put forwards (Fig. 1).

3. Methodology and data source

3.1. Methodology

Vulnerability varies with time and space scales and it depends on economic, social, geographic, environmental and other factors. Thus, it is impossible to use a single indicator model to assess vulnerability (Næss et al., 2006). Following IPCC (2007), we consider the agricultural vulnerability to climate disasters as a function of exposure (that is, the frequency, intensity and duration of disturbances affecting agricultural systems), sensitivity (that is, the degree to which agricultural systems are affected by disturbances) and adaptability (that is, the ability of the studied system to deal with disturbances and increase the variability that it can cope with). Vulnerability is usually understood as a concept which focuses on the assessment of impact on climate events on agricultural production under human intervention from socio-economic system (Urruty et al., 2016). According to the concept of vulnerability proposed by IPCC, the paper creates agricultural vulnerability index model by the following formula:

$$\mathrm{A.vulner} = \frac{\mathrm{E^*S}}{\mathrm{AD}} \tag{1}$$

This article makes use of multiplication-division which can better reflect the interaction among influencing factors. That is a positive correlation between vulnerability and exposure & sensitivity, and a negative correlation between vulnerability and adaptability. The introduction of specific indicators is shown in Table 1. As a valuable tool in risk management (de Ruiter et al., 2017; De Lange et al., 2010), the model can be widely used to describe agricultural sensitivity under specific environments (exposure) and socio-economic conditions (adaptability). This method helps to enrich evaluation methods of agricultural vulnerability.

3.1.1. Disaster exposure

Exposure refers to the extent to which agricultural systems are adversely affected by climate change (IPCC, 2022). The standardized precipitation index (SPI) is one of most applied drought indices and can represent precipitation deficits or surpluses. The paper focuses on drought characteristics extracted from SPI (duration and intensity[1]) to depict drought exposure of agricultural system. Drought duration is defined as the number of months and the drought intensity is the mean values between drought initiation and termination time (Su et al., 2021).

[1] Drought duration (DD) and drought intensity (DF).

Table 1
The introduction of indicators.

Primary indicators	Secondary indicators	Explanation	Literature reference
Exposure	SPI	SPI is the most popular metric for drought monitoring, and it is used to assess precipitation anomaly. The smaller the index, the drier the region and the higher the exposure.	Dabanlı et al., 2017; Nadi and Soqanloo, 2024; Kourtis et al., 2023
	NDFI	NDFI is a change detection method characterized by efficient processing and less manual intervention, which can quickly identify flood scope. The smaller the index, the lower the exposure.	Xue et al., 2022; Wan and Billa, 2018; Xia et al., 2023
Sensitivity	NDVI	NDVI is one of the important parameters to detect the vegetation growth and coverage. Higher index means higher vegetation density and lower sensitivity.	Gu et al., 2007; Gopinath et al., 2015; Shrestha et al., 2017; Marchetti et al., 2016
Adaptability	Agriculture, forestry, fishing (% of central government)	Agriculture, forestry, fishing (% of central government) reflects the priority of agriculture within country. The higher the proportion, the greater the importance attached to agriculture and the higher the adaptability.	Wang et al., 2020
	Rural access index	Rural access index represents the convenience of regional transport. The convenient transportation can shorten the disaster-relief time. The higher the index, the higher the adaptability.	Liu et al., 2022; Zhang et al., 2023
	Corruption perception index	Corruption perception index represents political stability. The higher the index, the cleaner it is, meaning the country has higher adaptability for disaster-relief.	Erum and Hussain, 2019
	Per capita GDP	The higher the Per capita GDP, the better the economy. The more money can be invested in post disaster recovery, meaning higher adaptability.	Gurusamy and Vasudeo, 2023; Habib, 2022

In addition, SPI is divided into five types: no drought, mild drought, moderate drought, severe drought and extreme drought. At the same time, NDFI (Normalized Difference Flood Index) is used to depict floods exposure of agricultural system, extracted by the Google Earth Engine (GEE).

$$E = -0.5*[T_i(\mathrm{DD})*max_i(\mathrm{DF})] \quad (2)$$

where $T_i(\mathrm{DD})$ is the drought during in a year, between 0 and 12; and $max_i(\mathrm{DF})$ is the highest SPI in a year, less than -0.5.

3.1.2. Sensitivity to disaster

NDVI (The Normalized Difference Vegetation Index) measures the "greenness" of ground cover and is used as a proxy to indicate the density and health of vegetation. NDVI values range from $+1$ to -1, with high positive values corresponding to dense and healthy vegetation, and low and/or negative NDVI values indicating poor vegetation conditions or sparse vegetative cover.[2] It has been extensively used to assess vegetation's response to extreme climate events like continuous drought and floods in large-scale (Liu et al., 2018; Fu and Burgher, 2015). The reciprocal of NDVI is applied to express sensitivity.

$$\mathrm{S} = \frac{1}{\mathrm{NDVI}} \quad (3)$$

3.1.3. Adaptability to disaster

Adaptation refers to changes made by human to actual or expected climate change in order to avoid harm and take advantage of beneficial opportunities (Rudolph et al., 2020). In this study, adaptability is seen as a function of agriculture, forestry, fishing (% of central government), rural access index, corruption perception index (CPI) and per capita GDP.[3] The entropy method is used to determine weights of different indicators and calculate adaptability. The higher the value, the stronger the adaptability.

$$\mathrm{AD} = \sum W_i Z_i \quad (4)$$

where W_i is the weights for each normalized data set between 0 and 1, which is calculated by the entropy method. Z_i is the four indicators mentioned above.

3.1.3.1. Agriculture, forestry, fishing (% of central government). Agriculture, forestry, fishing (% of central government) is the proportion of expenditure on agriculture, forestry, and fishery to total government expenditure. It can be used to depict the government's concern on agriculture, and higher values indicate more concerns and investments from the government.

3.1.3.2. Rural access index. RAI measures the proportion of the rural population who live within 2 km of an all-season road (World Bank Group, 2016). In particular, higher values of RAI indicate shorter time for disaster-relief material and population transportation for reconstruction.

3.1.3.3. Corruption perception index. CPI uses a scale of 0–100 (where 100 is the cleanest and 0 is the most corrupt). Countries and territories are ranked based on their perceived levels of public sector corruption. High values indicate better economic support for emergency rescue.

3.1.3.4. Per capita GDP. Per capita GDP is an economic metric that breaks down a country's economic output per person. Higher values indicate better economic support and social resilience for rescue.

3.2. Data source

The study period of the paper is 2003, 2011 and 2019. The main data used in this study includes cropland data, with a spatial resolution of 30 m, which is derived from Global Land Analysis and Discovery.[4] The SPI-

[2] https://www.fao.org/giews/earthobservation/asis/index_2.jsp?lang=zh.
[3] Agriculture, forestry, fishing (% of central government) [AFF], rural access index (RAI), corruption perception index (CPI) and per capita GDP (PC-GDP).
[4] https://glad.umd.edu/dataset/croplands.

3 data is from Global Drought Observatory[5] is used to depicted exposure. NDVI, with a spatial resolution of 1000 m, refers to National Aeronautics and Space Administration (NASA).[6] The agriculture-forestry-fishing (% of central government) is from FAO.[7] The rural access index is from World Bank.[8] The corruption perception index is from the Transparency International.[9] Per capital GDP data refers to Invest pedia.[10]

4. Research results

4.1. Disasters exposure

4.1.1. Global drought exposure

Fig. 2 shows the world map of drought exposure computed at the sub-national cropland level with SPI-3 in 2003, 2011 and 2019. Over the globe, the global drought exposure has decreased overall but increased locally and is higher in the northern U.S., the central Europe, Africa, and the southeast China.

An in-depth scrutiny of the spatial distribution within regions exhibiting intensified vulnerability to drought warrants our attention. Southern Australia and Southeast Brazil are selected as cases for analysis. South and Southeast Brazil produce together more than 70 % of the crops in the country (Parré and Guilhoto, 2001). However, the increasing drought exposure is mainly due to the stronger drought intensity caused by low precipitation (Supplement 1).The high exposure has a negative impact on agricultural production in Brazil. Australia's farming system feeds a domestic population of some 22 million people, while exporting enough food to feed another 40 million (Lawrence et al., 2013). However, Australia has become even drier accompanied by increasing drought duration (it reached 8 months in 2019, supplement 2).

4.1.2. Global floods exposure

Fig. 3 presents the map of global floods exposure based on the NDFI in 2003, 2011 and 2019. On the whole, the flood scope on cropland is smaller than the drought and the floods exposure has changed little. The floods exposure mainly distributed in the border between the northern parts of United States, the border between Russia and Kazakhstan, and the northeastern parts of China.

Floods pose threats on agricultural development, triggering crops reduction and quality deterioration (Venkatappa et al., 2021), so the northern parts of United States and the northeast parts of China have been earmarked as examples. The northern parts of United States are one of the main agricultural producing regions, with main crops including wheat, corn and soybeans (Auch et al., 2017). However, frequent rainfall in the area results in river overflow (e.g. Mississippi River and the Great Lakes), further spawning farmland inundation and severe loss of soybeans. According to United States Department of Agriculture, the net income of farms is predicted that it will decline to $69.4 billion.[11] The northeastern parts of China are a major grain production region and own one of the three major black soil belts in the world. But the river network in Northeast China is densely, meaning unstable food supplement once the rainy season arrives (from July to September) (Zhao, 2010).

4.2. Sensitivity to disaster

Fig. 4 shows the global sensitivity maps derived using NDVI for 2003, 2011 and 2019. It is obvious that the sensitivity has changed little and poor vegetation is mainly seen in southern parts of Canada, middle western United States, northeast parts of China, Iran and so on.

High sensitivity is in the agro-pastoral ecotone of northern China. It is the prominent area for agricultural production, but it is also the most typical ecological fragile area characterized by desertification land, low precipitation and frequent disasters, all of which caused more sensitive agricultural production environment. Thus, measures should be taken to improve ecological environment and increase crop yields.

As the global grain producer, the central parts of United States experienced extensive vegetation transformations owing to broadly climate change in recent years (Mihunov et al., 2018). Frequent disasters directly result in grain reduction and make it become the more sensitive region. In 2012, there were overall $40,000 to $50,000 loss in sweet corn caused by drought in Indiana in north-central America (China Business News, 2012).

4.3. Adaptability to disasters

Fig. 5 shows the world map of adaptation calculated with four indicators of AFF, RAI, CPI, and PC-GDP in 2003, 2011 and 2019. The global adaptability has increased overall but decreased locally and it is higher in the United States and the western Europe than others.

The reason why adaptability in the United States is so strong is largely due to the higher PC-GDP and RAI. The PC-GDP was 63,953.69 US$ in 2019, ranking at the forefront of the world, which means that farmers have ability to deal with agricultural production risks and improve their competitiveness in international trade (Li and Li, 2014). The RAI arrived at 87.48 in 2019, second only to some European countries. The perfect transportation network reflects government's long-term support for agriculture, guaranteeing delivery of relief materials post disasters in time.

Peer lower down western Europe, and Ireland is selected as an example. The PC-GDP was 81,560.40 US$ in 2019, and the growth rate was 96.51 % compared to 2003. The RAI has been consistently greater than 90 during the study period. Those prove that the ability to cope with risks has rapidly advanced in Ireland. There are well developed risk management organizations, where agricultural professionals continuously monitor agricultural change and provide corresponding supports. In addition, the interaction and cooperation between agricultural professionals, enterprises, researchers, and some organic farmers are common. These not only enhance farmers' agricultural professional skills, but also enable them to take precautions for encountering disasters such as drought and floods and greatly raising their climate adaptability (Duram, 2010).

4.4. Vulnerability to disasters

4.4.1. Drought vulnerability

Fig. 6 presents the map of global drought vulnerability. Research indicates that the global drought vulnerability is at a low level overall and the change of drought vulnerability in most regions is not obvious, except for the southern parts of US, the eastern parts of China and so on.

Drought vulnerability in the southern parts of United States was increasing first and then decreasing. This is mainly because the core of exposure shifts from south to north and the drought intensity and coverage reached its peak in 2011. Moreover, the adaptability fell to the bottom (0.452[12]), the exaggerated change of these indicators leading to strong drought vulnerability in 2011. As the world's largest grain producer and exporter, drought occurred frequently in the United States which would cause a double-digit percentage drop in winter wheat production in the south-central Plains (Luo and Yu, 2022), and some measures should be taken to meet drought disasters at once.

The same as the southern parts of United States, drought

[5] https://edo.jrc.ec.europa.eu/gdo/php/index.php?id=2001.
[6] https://appeears.earthdatacloud.nasa.gov/task/area.
[7] https://fenixservices.fao.org/faostat/static/documents/IG/IG_e.pdf.
[8] https://datacatalog.worldbank.org/search/dataset/0038250.
[9] https://www.transparency.de/cpi.
[10] https://www.investopedia.com/terms/p/per-capita-gdp.asp.
[11] https://www.usda.gov/.

[12] The adaptability was 0.666 in 2003 and 0.607 in 2019.

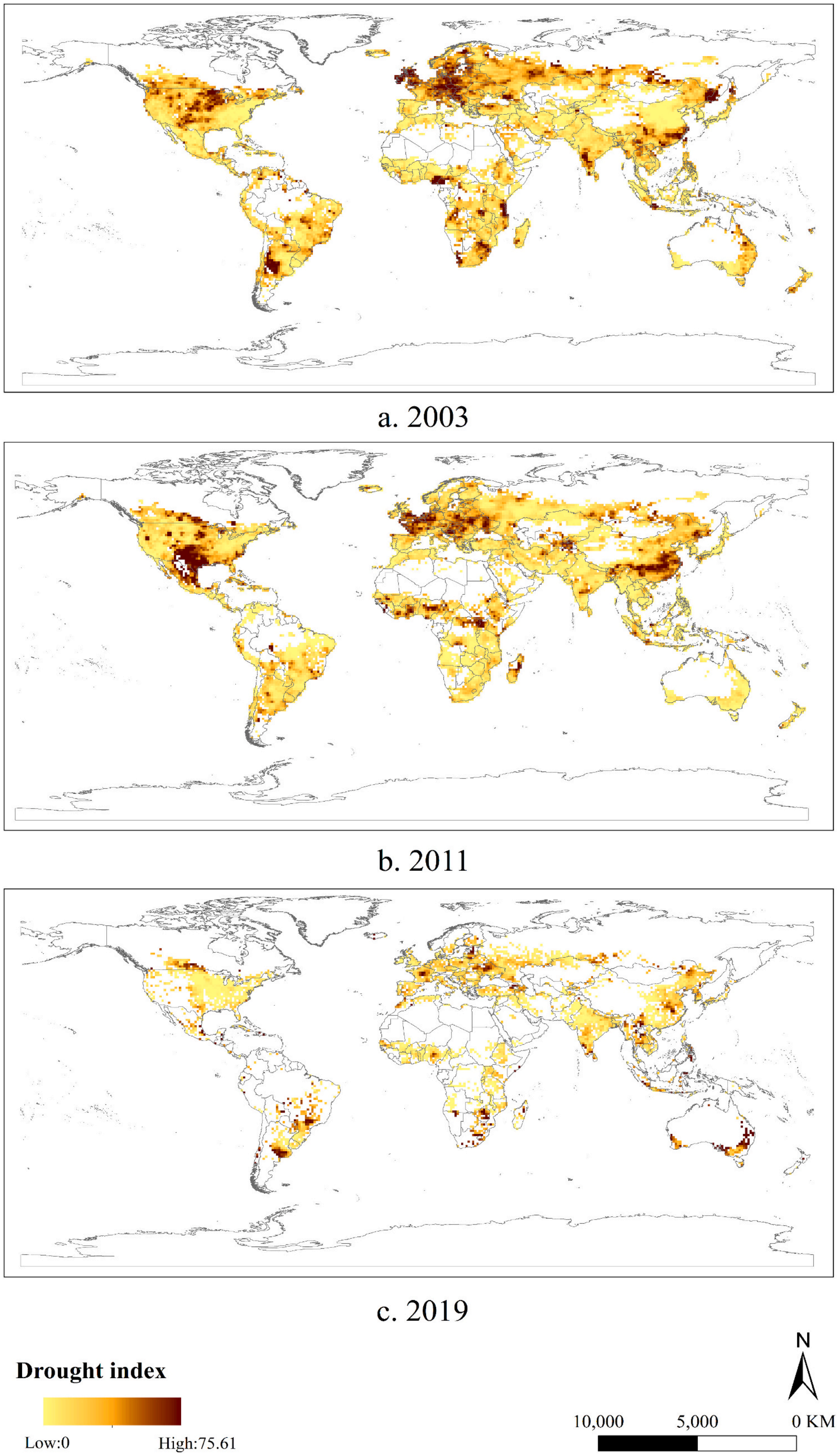

Fig. 2. Global distribution of drought exposure.

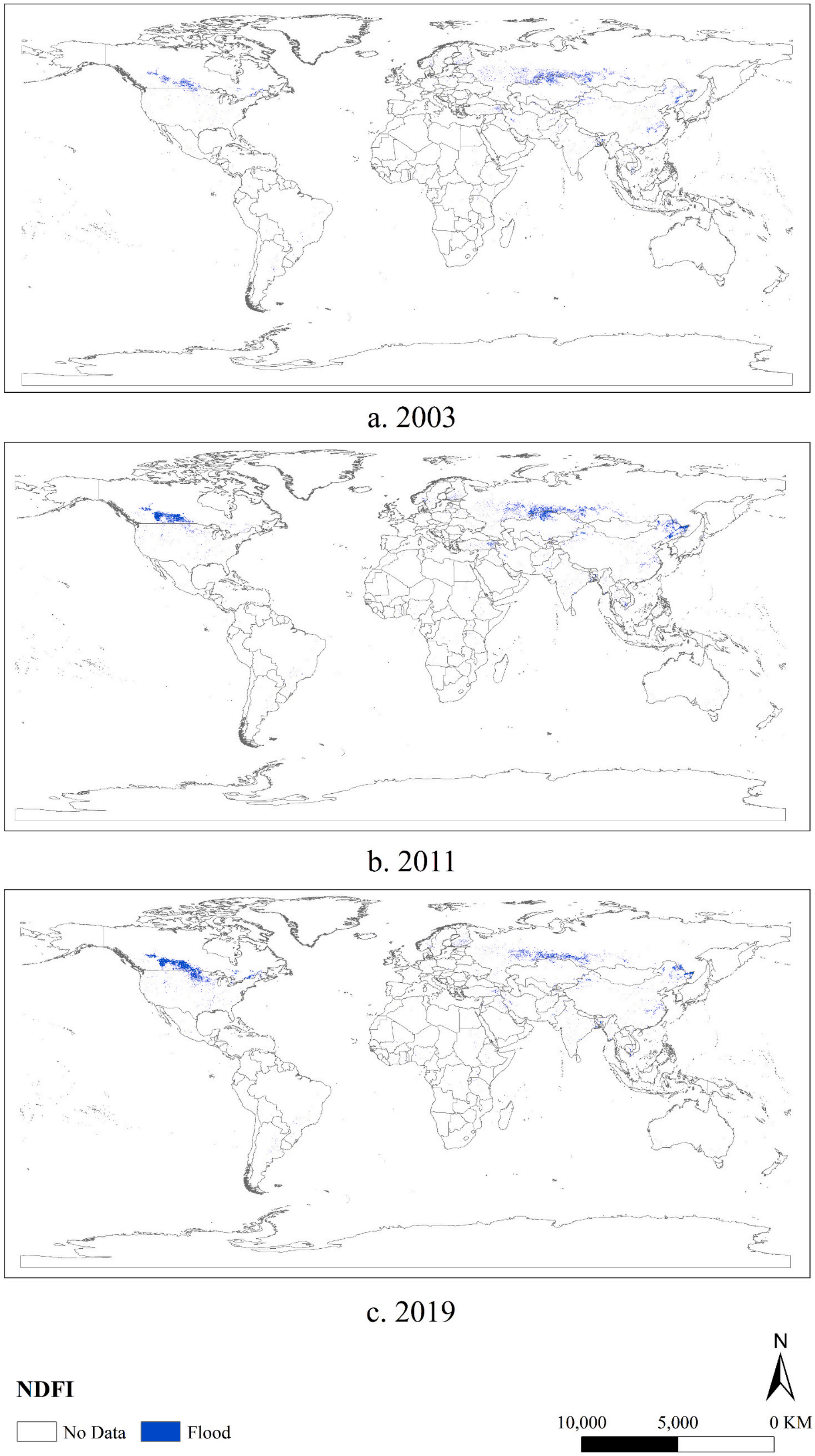

Fig. 3. Global distribution of floods exposure.

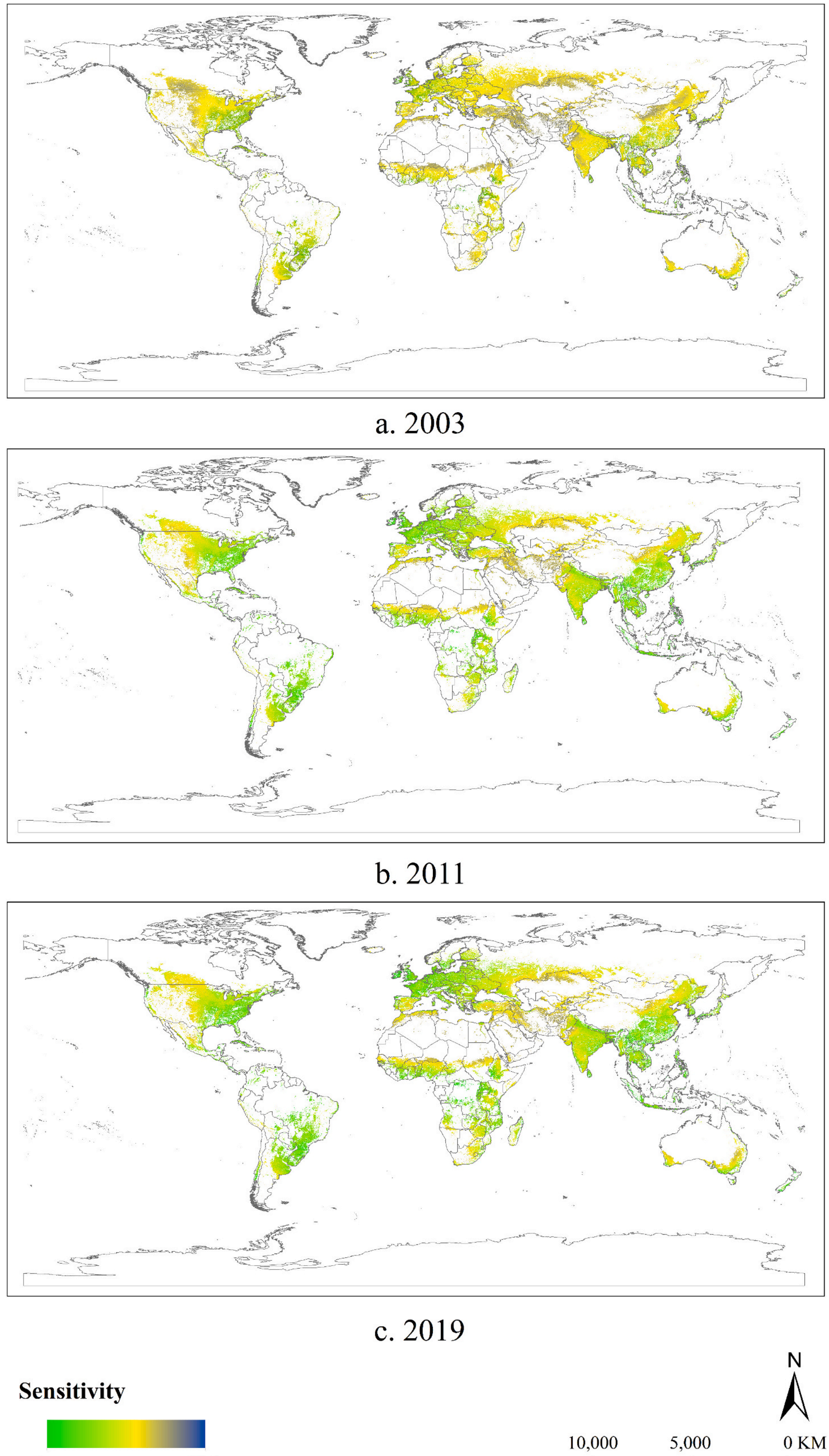

Fig. 4. Global distribution of sensitivity.

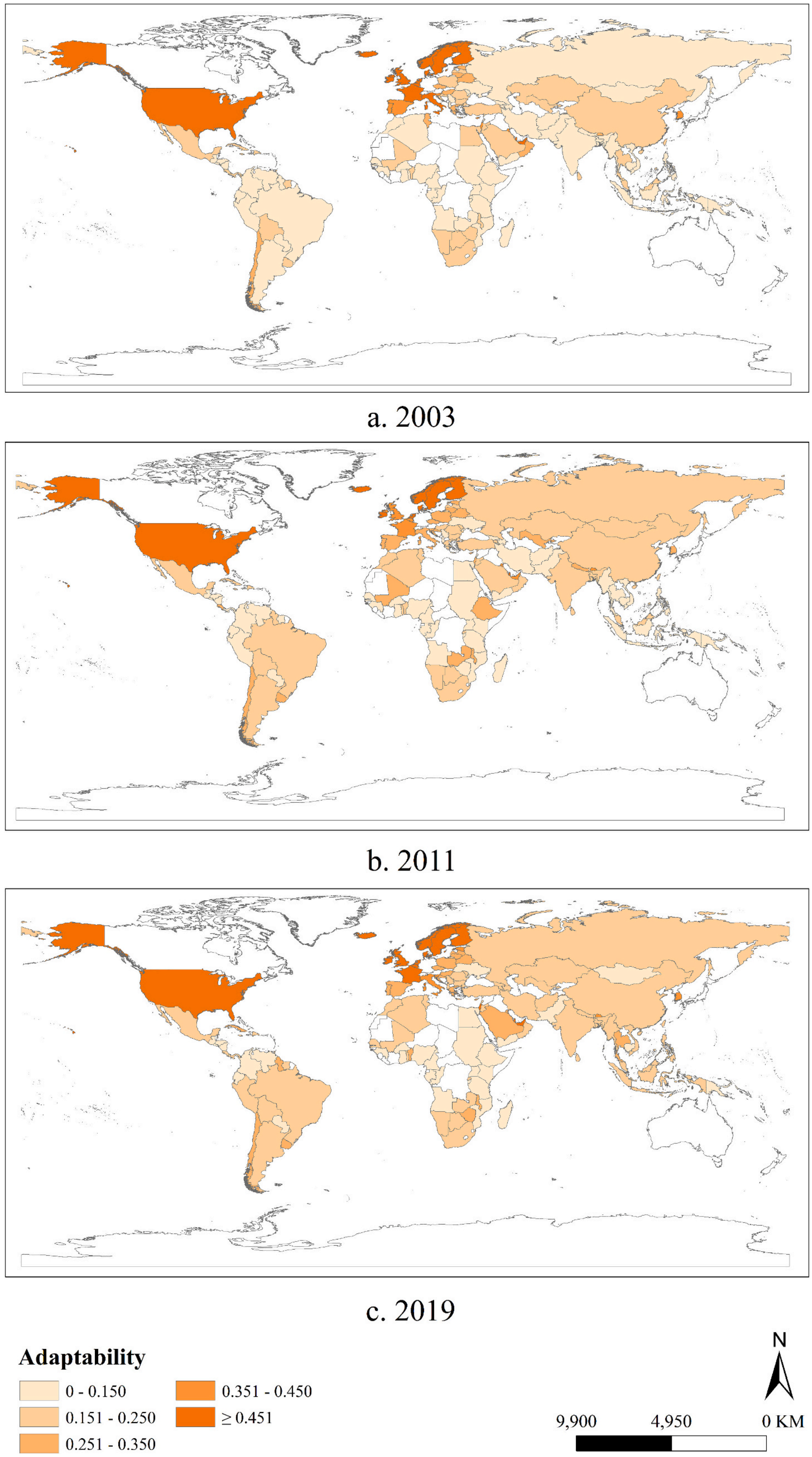

Fig. 5. Global distribution of adaptability.

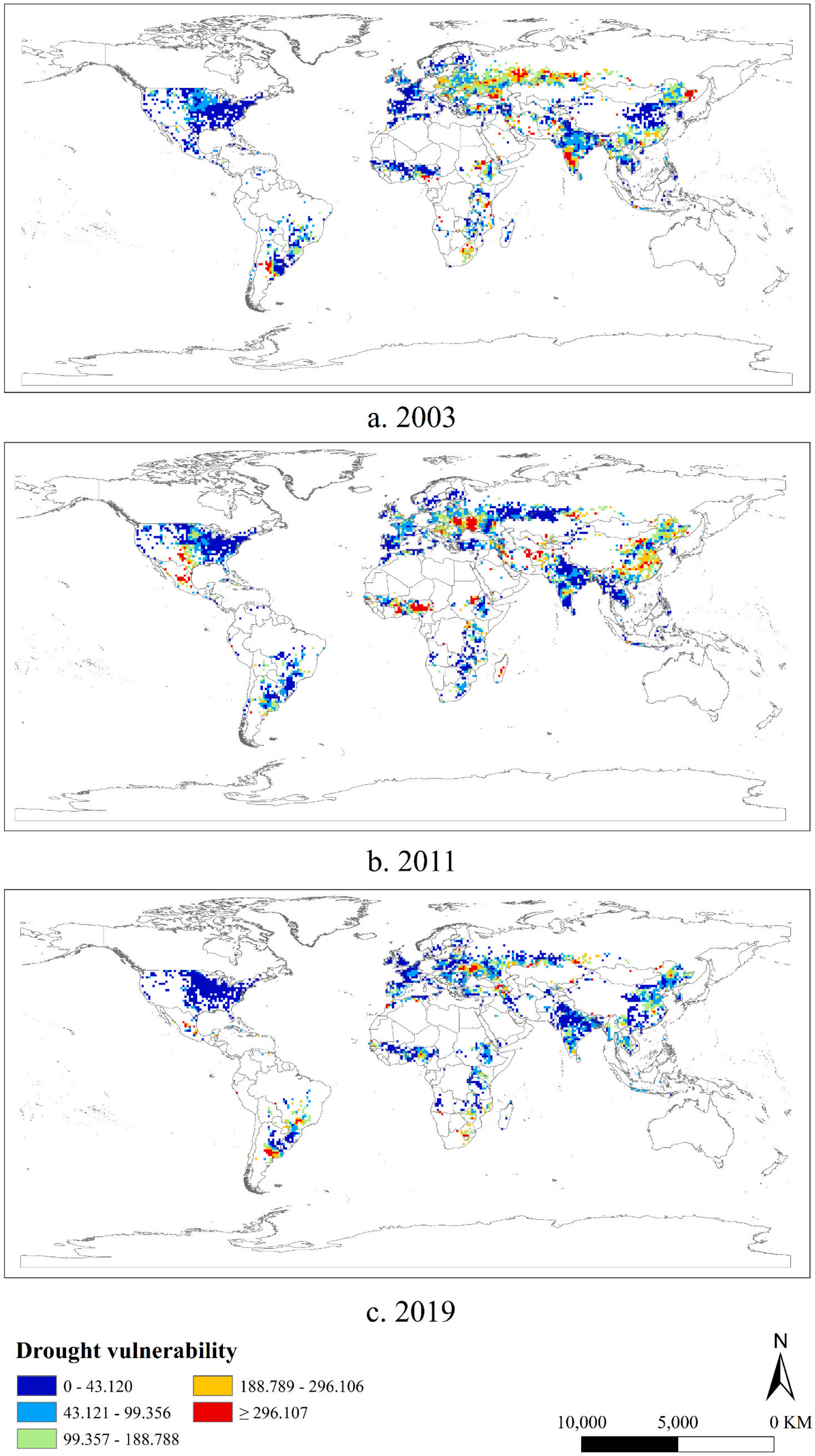

Fig. 6. Global distribution of drought vulnerability.

vulnerability in eastern parts of China also experienced the process of first ascending and then descending. This is mainly due to increased drought exposure caused by higher intensity and longer duration of drought in 2011. The eastern China guarantees the country's food security to a large extent, however, agricultural drought events in the Yellow River basin are more frequent in recent years, and grain production fell by about 2.3 million tons (Li et al., 2021).

4.4.2. Floods vulnerability

In Fig. 7, we present the map of global floods vulnerability computed with the agricultural vulnerability model. Our results show that there are no significant changes in floods vulnerability during the study period. However, the floods vulnerability in the northern parts of United States, northeastern parts of China, and the border between Russia and Kazakhstan is higher than other areas.

Floods, as the most frequent and highest crisis among the natural disasters caused by global climate change (Zhang and Wang, 2022), greatly affects agricultural production. It can be seen that there is a clear increase in the northern parts of United States, which is mainly because the rising precipitation frequency caused a potential floods risk on agriculture in north United States (Scaff et al., 2019). The U.S. Department of Agriculture (USDA) reported that the corn and wheat production decreased by 12 % and 11 % respectively in 2019, due to the severe floods. Peer lower down Asia, and the spatial aggregation effect of floods vulnerability in the northeastern parts of China is more obvious, along with the diversion of the core of floods disaster on agriculture from the southwest to northeast (Guan et al., 2021).

4.5. Typical countries analysis

Fig. 8 shows the drought and floods vulnerability across the globe. Countries affected by two disasters can be identified through the superposition analysis. In fact, drought and floods disasters repel each other. And it can be seen that more than 90 % of regions cannot coexist with drought and floods in Fig. 8. However, there are a few countries presenting dual vulnerability and spreading across the globe. Taking the northeast parts of United States, the border between Russia and Kazakhstan, the northeast parts of China and the southeast parts of Africa showing drought and floods vulnerability as examples to investigate the similarity and differences between major influence factors.

It has been observed that there are the dual threats of drought and floods in the northeast parts of United State. It is evident that the aggravated intensity and duration of the drought led to higher drought vulnerability in 2003 and 2011, but the drought vulnerability has decreased in 2019 with the core of drought gradually shifting from south to north. While the floods vulnerability increased during the study period as well (Fig. 9a1–a3). The US government has not invested enough in agriculture with the AFF accounting for only 1.18 % in 2019. As far as floods are concerned, inland deluge often occurred in the United States due to insufficient drainage infrastructure and lack of disaster resistance consciousness among farmers in agriculture regions (Schillerberg et al., 2019; Gina and Jeffrey, 2022).

High levels of drought and floods risk for agricultural systems are observed in the border between Russia and Kazakhstan (Fig. 9b1–b3), while the drought and floods vulnerability show a marked decline in the period 2003–2019. Relevant studies indicate that, the number of hydrological and meteorological hazards in the border between Russia and Kazakhstan has been growing every year. Yet it has been a significant decline since the mid-20th century, especially after 2010. According to the relevant data, the government attached no importance to agriculture before 2010, with insufficient investments and lower farmers' income resulting in its lower adaptability (the AFF in Russia was less than 1.3 %, PC-GDP was only 2998$ in Russia and 2000$ in Kazakhstan in 2003). However, the PC-GDP has experienced a substantial increase in Russia and Kazakhstan in 2019, arriving at 11,617$ and 9686$ respectively. The decreasing floods vulnerability highlights that relevant measures to increase the coping capacity, such as controlling flooding in the mouths of regulated rivers with an effective system of floods and ice jam protection (Frolova et al., 2017), are necessary for reducing flood risks.

The northeast parts of China, a region in China known for black land, is a place showing severe drought and floods vulnerability. There has been an initial increase followed by a subsequent decline in drought vulnerability since 2011, with the widest coverage of drought in 2011 (Fig. 9c1–c3). Following data analysis, higher intensity and longer duration of drought led to high drought exposure in 2003 and 2011, with lower adaptability (AFF and PC-GDP are 2.3 % and 1387$ in 2003, lower than other countries). Under the dual effects of high exposure and low adaptability, drought vulnerability in northeast China was serious. By contrast, the PC-GDP reached 10,110$ by 2019 meaning that farmers have the ability to cope with disasters. The trend of floods vulnerability is similar to drought in 2003–2019. And the decline of floods vulnerability in 2019 is inseparable from the government's attention and support to agriculture. It is predicted that the spatial distribution of drought and floods show high vulnerability from 2020 to 2050 in the northeast China (Li et al., 2022). Therefore, the regional government has intensified the prevention of drought and floods disasters to reduce the agricultural losses by reasonably adjusting the crop structure and popularizing the drought and floods resistant sowing technology.

Finally, peer lower down Africa. The drought in southern parts of Africa is particularly severer compared to floods, due to the higher drought intensity, longer duration and lower RAI (21 %) in 2003. As the most concentration of poverty and malnutrition in the world, most people survive and access food only through agriculture. The single livelihoods and backward agricultural facilities result in the lower adaptability for people facing disasters. Previous studies have shown that increasing drought frequency hindered rice production in Mozambique (Fig. 9d1–d3). But hermetic storage adopted by farmers in Mozambique can improve food security and income generation in the country, thus reducing the risk of drought slightly (Guenha et al., 2014).

Generally speaking, some underlying factors contributing to the observed pattern can be found. Strong exposure and low adaptability will lead to high agricultural vulnerability like the Europe (Fig. 8). Higher drought intensity and duration trigger severe droughts and the lack of agricultural economic investments aggravates agricultural vulnerability. It is predicted that the agriculture losses caused by drought may reach 65 billion euros by 2100 in European Union.[13] On the contrary, better adaptability can help reduce and overcome negative effects of climate change, such as China. China has attached great importance to improve agricultural adaptability all the time. On the one hand, increasing investments in agricultural systems and strengthening rural construction aim to enhance the ability to withstand climate disasters. On the other hand, a series of policies in climate change adaptation are adopted to build a climate adaptive agricultural system. According to Ministry of Agricultural and Rural Affairs of China, the investments of agricultural and rural fixed assets arrived at 4237billion yuan in 2019, increased by 5.1 times compared to 2016.[14]

5. Discussion and conclusion

At present, the mid-term evaluation results of SDGs are not optimistic, and most of them have stagnated or regressed, alerting all humanity. The sustainable agriculture is directly related to the SDGs — notably SDG 1 (no poverty), SDG 2 (zero hunger), SDG 3 (good health and well-being) and SDG 15 (life on land). Under the adverse effects of natural disasters and uncertain risks, it is crucial to enhance the agricultural resilience. This paper found that the global agricultural

[13] https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/global-warming-could-more-double-costs-caused-drought-europe-study-finds-2021-05-10_en.

[14] https://www.moa.gov.cn/.

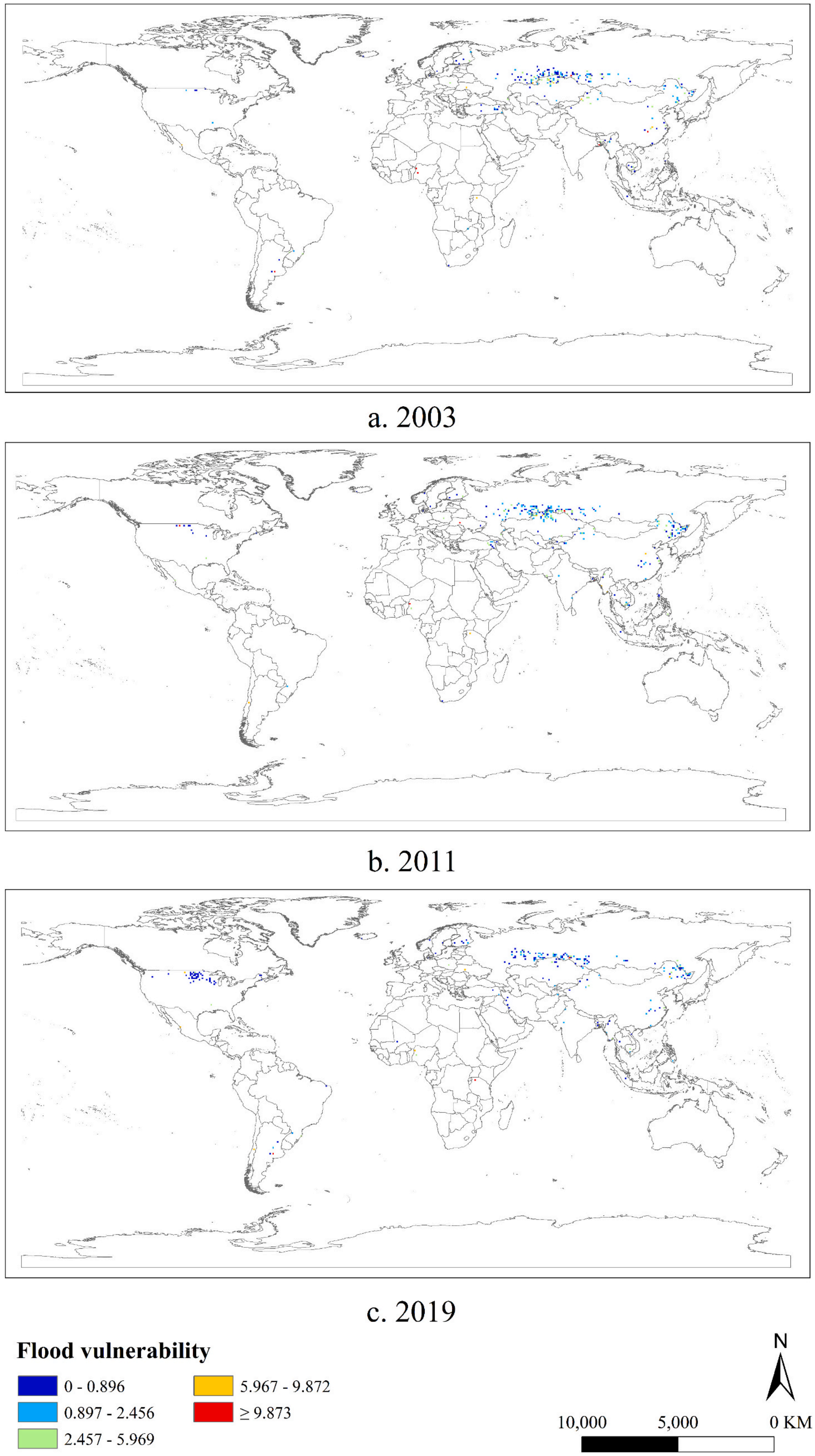

Fig. 7. Global distribution of floods vulnerability.

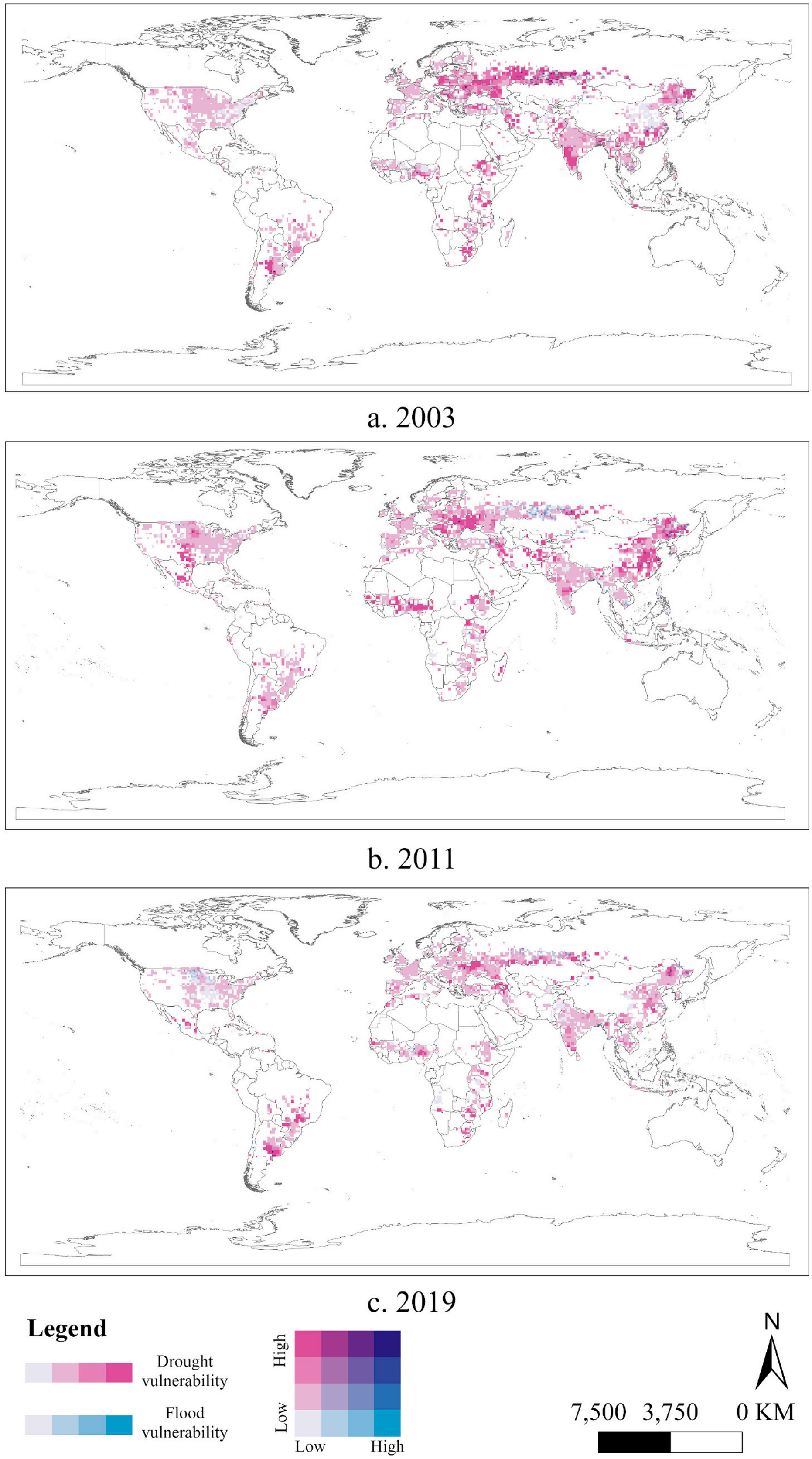

Fig. 8. Global distribution of comprehensive vulnerability.

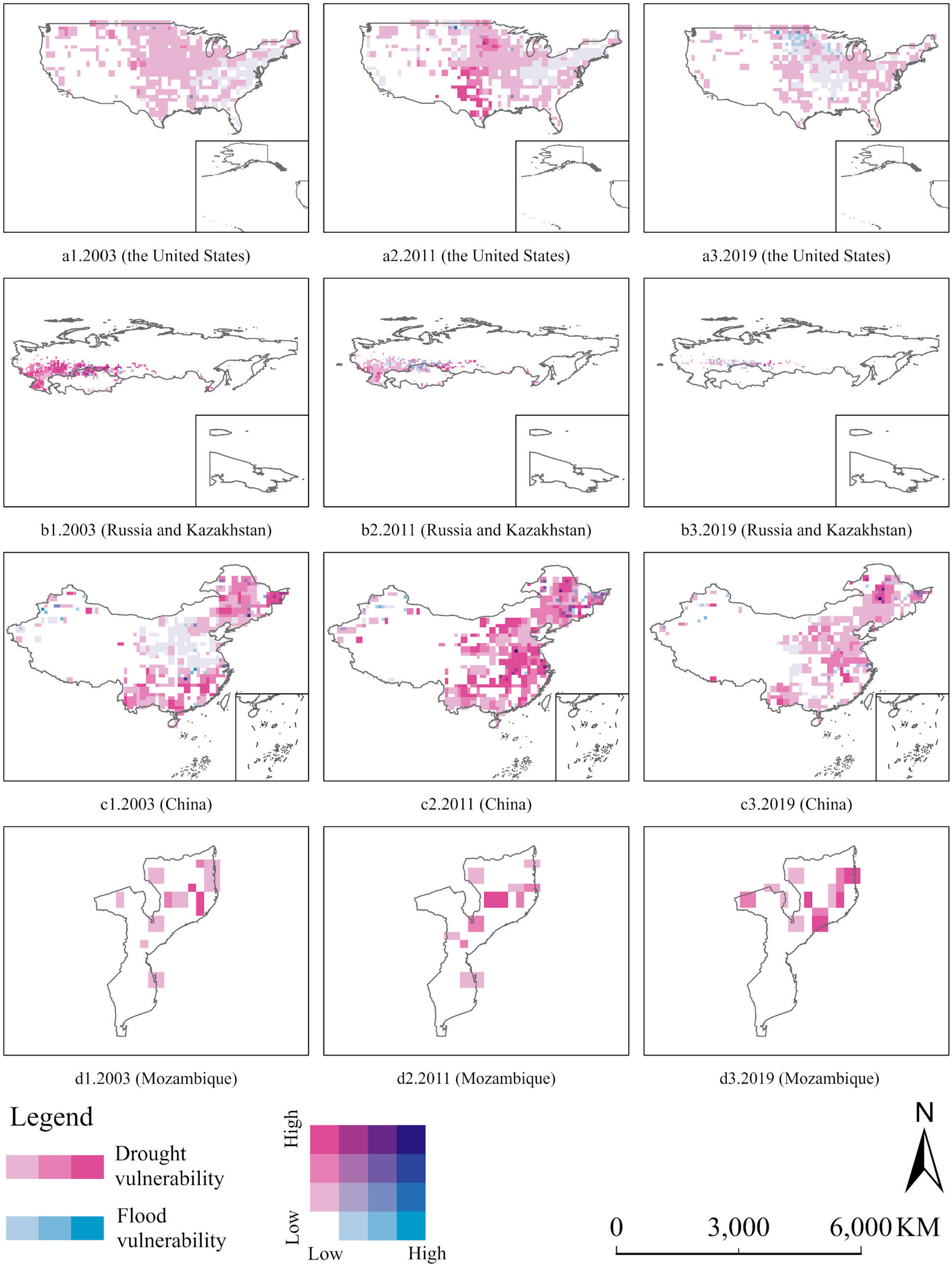

Fig. 9. The comprehensive vulnerability of typical countries.

vulnerability to drought and floods are at a low level overall on account of decreasing disasters exposure and increasing adaptability of disasters prevention measures taken by humans. However, it is estimated that the risk of various disasters will inevitably increase and threaten ecosystems and human society if the global temperature rise reaches 1.5 °C in the near future (IPCC, 2023). It means that resilient agriculture is essential to be developed. And decreasing agricultural vulnerability is the critical step to eliminate hunger and ensure food security for providing healthy and productive lives. As the prime connection between people and nature, agriculture can help achieve multiple SDGs (FAO, 2018). Therefore, some suggestions are put forwards to effectively decrease vulnerability and improve the agricultural adaptability.

First, it is necessary to carry out agricultural zoning based on the topography, hydrology, soil and local climate conditions, which aims to adjust crop breeds and planting structures to increase diversity. For instance, climate intelligent crops containing high nutrient are planted. As the most vulnerable regions in drought, crops with climate resilience like grains, sweet potatoes and sugar beets etc., are supposed to promote in Africa and the eastern Europe, which are conducive to enhance food production during the dry season. Cultivating drought-resistant crops by genetic engineering is a feasible solution to improve climate adaptability like Beleia and HYT333 showing high drought-resistant wheat, which have been widely planted in the drought vulnerable of Middle East and effectively improved crop yield and quality.

In addition, we suggest to intensify the precision construction of disaster prevention and relief system on the grounds of climate adaptation map, which can be used for assessing and predicting the probability of climate events. For example, water-saving irrigation engineering and water transfer engineering construction can be spread in areas with frequent drought. Dryland farming is being promoted in arid and semiarid area showing high vulnerability in China. And reservoirs and farmland drainage systems are reinforced in areas with severe floods disasters. Besides, post-disasters reconstruction deserved more concerns and investments. Many efforts, such as accelerating the restoration of damaged farmland and agricultural facilities, and strengthening agricultural technology guidance, are put forwards to ensure agricultural production. Nation Flood Insurance Program is a good example to spread risks and reduce losses of farmers, which deserved to be popularized in vulnerable regions.

Finally, new type nutritional food systems are critical to increase the adaptive capacity of agricultural systems. The implementation of technical components is designed to help farmers adjust day-to-day operations. For example, several tools are already available to inform farmers about pest outbreaks, soil water availability or nitrogen nutrition index, and farmers can respond to variability by adjusting pesticide, irrigation or fertilizer uses. In particularly, precision agriculture is supposed to carried out in vulnerable countries to raise productivity and adaptability facing harmful perturbations.

Nowadays, the increased high-temperature extremes, shifted rainfall patterns, and intensified human activities bring adverse impacts on the sustainable agriculture, aggravating the agricultural vulnerability. However, still there are shortages of research on the assessment of agricultural vulnerability in the Shared Socioeconomic Pathways (SSPs), which can help to promote comprehensive analysis of climate change and evaluate climate policies. Therefore, further research should be conducted on agricultural vulnerability assessment in different climate scenarios.

In this paper, we measured agricultural vulnerability to climate disasters (drought and floods) in the world in the period 2003–2019 and investigated its driving factors. The conclusions are as follows.

(1) The agricultural vulnerability to drought and floods is at low level across the globe and vulnerability decreased during the study time under the dual effects of decreasing exposure and increasing adaptability.
(2) Spatio-temporal mismatch of precipitation and geographical conditions are critical indicators to floods and drought, but better adaptions are beneficial to minimize adverse effects of disasters and ensure food security in post-disaster reconstruction.

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CRediT authorship contribution statement

Wenjing Cheng: Visualization, Methodology, Formal analysis, Data curation. **Yuheng Li:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Wenjie Zuo:** Resources, Data curation. **Guoming Du:** Writing – review & editing, Methodology. **Monika Stanny:** Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

Adger, W.N., 2006. Vulnerability. Glob. Environ. Change 16, 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006.
Auch, R.F., Xian, G., Laingen, C.R., et al., 2017. Human drivers, biophysical changes, and climatic variation affecting contemporary cropping proportions in the northern prairie of the U.S. J. Land Use Sci. 1–27.
Brooks N., Adger WN., (2005) Assessing and enhancing adaptive capacity. In: Lim B, Spanger-Siegfried E (eds) Adaptation policy frameworks for climate change: developing strategies, policies and measures. Cambridge University Press, Cambridge, pp 165–182Return to ref Adger , 2005 in article.
China Business News, 2012. The Drought of the Century in the U.S. [EB/OL] [2023-10-20]. https://www.yicai.com/news/1913732.html.
Dabanlı, İ., Mishra, A.K., Şen, Z., 2017. Long-term spatio-temporal drought variability in Turkey. J. Hydrol. 552, 779–792. https://doi.org/10.1016/j.jhydrol.2017.07.038.
De Lange, H.J., Sala, S., Vighi, M., Faber, J.H., 2010. Ecological vulnerability in risk assessment — a review and perspectives. Sci. Total Environ. 408 (18), 3871–3879. https://doi.org/10.1016/j.scitotenv.2009.11.009.
Dronin, N.M., Kirilenko, A.P., 2013. Weathering the soviet countryside: the impact of climate and agricultural policies on Russian grain yields, 1958–2010. Sov. Post Sov. Rev. 40 (1), 115–143.
Duram, L.A., 2010. A pragmatic assessment of government support for organic agriculture in Ireland. Ir. Geogr. 43 (3), 249–263. https://doi.org/10.1080/00750778.2011.583138.
Erum, N., Hussain, S., 2019. Corruption, natural resources and economic growth: evidence from OIC countries. Resour. Policy 63, 101429. https://doi.org/10.1016/j.resourpol.2019.101429.
FAO, 2018. Transforming food and agriculture to achieve the SDGs: 20 interconnected actions to guide decision-makers. https://www.fao.org/3/I9900EN/i9900en.pdf.
FAO, 2021. The Impact of Disasters and Crises on Agriculture and Food Security: 2021. https://doi.org/10.4060/cb3673en.
FAO, IFAD, UNICEF, WFP, WHO, 2023. The State of Food Security and Nutrition in the World 2023. Urbanization, Agrifood Systems Transformation and Healthy Diets Across the Rural-Urban Continuum. FAO, Rome. https://doi.org/10.4060/cc3017en.
Food and Agriculture Organization of the United Nations (FAO), 2016. Increasing the Resilience of Agricultural Livelihoods (FAO Emergencies and Resilience).
Food and Agriculture Organization of the United Nations (FAO), 2023. First-ever Global Estimation of the Impact of Disasters on Agriculture.
Food Security Information Network (FSIN), 2023. Global Report on Food Crises 2023.
Frolova, L.N., Kireeva, B.M., Magrickiy, V.D., et al., 2017. Hydrological hazards in Russia: origin, classification, changes and risk assessment[J]. Nat. Hazards 88 (1).
Fu, B.H., Burgher, I., 2015. Riparian vegetation NDVI dynamics and its relationship with climate, surface water and groundwater. J. Arid Environ. 113, 59–68. https://doi.org/10.1016/j.jaridenv.2014.09.010.

Gina, T., Jeffrey, C., 2022. Evaluating the risk and complexity of pluvial flood damage in the U.S.[J]. Water Econom. Policy 08 (03).
Gopinath, G., Ambili, G.K., Gregory, S.J., et al., 2015. Drought risk mapping of south-western state in the Indian peninsula — a web based application. J. Environ. Manage. https://doi.org/10.1016/j.jenvman.2014.12.040. S0301479714006197.
Gu, Y.X., Brown, J.F., Verdin, J.P., et al., 2007. A five-year analysis of MODIS NDVI and NDWI for grassland drought assessment over the central Great Plains of the United States. Geophys. Res. Lett. 34 (6), L06407. https://doi.org/10.1029/2006gl029127.
Guan, X.J., Zang, Y.W., Meng, Y., et al., 2021. Study on spatiotemporal distribution characteristics of flood and drought disaster impacts on agriculture in China[J]. Int. J. Dis. Risk Reduct. 64.
Guenha, R., Salvador, V.D.B., Rickman, J., et al., 2014. Hermetic storage with plastic sealing to reduce insect infestation and secure paddy seed quality: a powerful strategy for rice farmers in Mozambique[J]. J. Stored Prod. Res. 59.
Gurusamy, B.T., Vasudeo, A.D., 2023. Socio-economic and ecological adaptability across south asian floodplains. J. Environ. Eng. Landsc. Manag. 31 (2), 121–131.
Habib, H., 2022. Climate change, macroeconomic sensitivity and the response of remittances to the North African countries: a panel VAR analyse. Int. J. Sustain. Dev. World Ecol. 29 (5), 401–414.
IPCC, 2007. Appendix I: glossary. In: Parry, M.L., et al. (Eds.), Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 869–883.
IPCC, 2014. Climate change 2014: Impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. In: Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK/New York, NY.
IPCC, 2021. AR6-Climate Change 2021—The Physical Science Basis Summary for Policymakers[R]. Augest. 1–40.
IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA. https://doi.org/10.1017/9781009325844.
IPCC, 2023. Sections. In: Team, Core Writing, Lee, H., Romero, J. (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, pp. 35–115. https://doi.org/10.59327/IPCC/AR6-9789291691647.
Jain, M., Naeem, S., Orlove, B., et al., 2015. Understanding the causes and consequences of differential decision-making in adaptation research: adapting to a delayed monsoon onset in Gujarat, India. Glob. Environ. Change 31, 98–109.
Kourtis, I.M., Vangelis, H., Tigkas, D., et al., 2023. Drought assessment in Greece using SPI and ERA5 climate reanalysis data. Sustainability 15 (22). https://doi.org/10.3390/su152215999.
Lawrence, G., Richards, C., Lyons, K., 2013. Food security in Australia in an era of neoliberalism, productivism and climate change. J. Rural. Stud. 29, 30–39. https://doi.org/10.1016/j.jrurstud.2011.12.005.
Li, J.N., Chou, J.M., Zhao, W.X., et al., 2022. Future drought and flood vulnerability and risk prediction of China's agroecosystem under climate change. Sustainability 14 (16), 10069. https://doi.org/10.3390/su141610069.
Li, W.J., Li, Y.J., 2014. American agricultural subsidy policy evolution and its revelations to China [J]. Res. Agric. Modern. 35 (03), 268–272.
Li, Y., Cheng, W., Zuo, W., et al., 2023. Agricultural vulnerability to drought in China's agro-pastoral ecotone: a case study of Yulin City, Shaanxi Province. Chin. Geogr. Sci. 33, 934–945. https://doi.org/10.1007/s11769-023-1386-5.
Li, Y.Y., Chang, J.X., Fan, J.J., et al., 2021. Agricultural drought evolution characteristics and driving mechanisms in the Yellow River Basin under climate and land use changes[J]. Trans. Chin. Soc. Agric. Eng. 37 (19), 84–93.
Liu, L.Z., Yang, X., Zhou, H.K., et al., 2018. Evaluating the utility of solar-induced chlorophyll fluorescence for drought monitoring by comparison with NDVI derived from wheat canopy. Sci. Total Environ. 625, 1208–1217. https://doi.org/10.1016/j.scitotenv.2017.12.268.
Liu, Q., Jiang, J.X., Yang, X., et al., 2022. Poverty vulnerability measurement and its impact factors of farmers: based on the empirical analysis in Qinba Mountains. Geogr. Res. 41 (2), 307–324.
Luers, A.L., Lobell, D.B., Sklar, L.S., et al., 2003. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Glob. Environ. Chang. 13, 255–267. https://doi.org/10.1016/S0959-3780(03)00054-2.
Luo, Q., Yu, B., 2022. Many parts of the world are suffering from severe drought climate [J]. Ecol. Econ. 38 (08), 5–8.
Marchetti, Z.Y., Minotti, P.G., Ramonell, C.G., et al., 2016. NDVI patterns as indicator of morphodynamic activity in the middle Parana River floodplain. Geomorphology 253, 146–158.
Mihunov, V.V., Lam, N.S.N., Zou, L., et al., 2018. Community resilience to drought hazard in the south-central United States. Ann. Am. Assoc. Geogr. 108, 739–755.
Nadi, M., Soqanloo, S.S., 2024. Modification of standardized precipitation index in different climates of Iran. Meteorol. Appl. 30 (5) https://doi.org/10.1002/met.2155.
Næss, L.O., Norland, I.T., Lafferty, W.M., et al., 2006. Data and processes linking vulnerability assessment to adaptation decision-making on climate change in Norway. Glob. Environ. Chang. 16 (2), 221–233. https://doi.org/10.1016/j.gloenvcha.2006.01.007.
Parré, J.L., Guilhoto, J.J.M., 2001. A desconcentrac ao regional do agronegocio brasileiro. Rev. Bras. Econ. 55, 223–251.
Renting, H., Rossing, W.A.H., Groot, J.C.J., et al., 2009. Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. J. Environ. Manage. 90 (Supplement 2), S112–S123. https://doi.org/10.1016/j.jenvman.2008.11.014.
Rickards, L., Howden, S.M., 2012. Transformational adaptation: agriculture and climate change. Crop Pasture Sci. 63, 240–250. https://doi.org/10.1071/CP11172.
Robert, P., Koester, Jeffrey A., Skoneczka, Troy R., et al., 2014. Historical gains in soybean (*Glycine max* Merr.) seed yield are driven by linear increases in light interception, energy conversion, and partitioning efficiencies. J. Exp. Bot. 65 (12), 3311–3321. https://doi.org/10.1093/jxb/eru187. July.
Rudolph, L., Maizlish, N., North, S., et al., 2020. A public health learning collaborative on climate change for urban health departments, 2016–2018. Public Health Rep. 135 (2), 189–201. https://doi.org/10.1177/0033354920902468.
de Ruiter, M.C., Ward, P.J., Daniell, J.E., Aerts, J.C.J.H., 2017. Review article: a comparison of flood and earthquake vulnerability assessment indicators. Nat. Hazards Earth Syst. Sci. 17, 1231–1251. https://doi.org/10.5194/nhess-17-1231-2017.
Salazar, C., Rand, J., 2016. Production risk and adoption of irrigation technology: evidence from small-scale farmers in Chile. Lat. Am. Econ. Rev. 25, 2. https://doi.org/10.1007/s40503-016-0032-3.
Scaff, L., Prein, F.A., Li, Y., et al., 2019. Simulating the convective precipitation diurnal cycle in North America's current and future climate[J]. Climate Dynam. 55 (1).
Schillerberg, A.T., Tian, D., Miao, R., 2019. Spatiotemporal patterns of maize and winter wheat yields in the United States: predictability and impact from climate oscillations [J]. Agric. For. Meteorol. 275.
Shamshiri, R.R., Kalantari, F., Ting, K.C., et al., 2018. Int. J. Agric. Biol. Eng. 11 (1), 1–22. https://doi.org/10.25165/j.ijabe.20181101.3210. Jan.
Shrestha, R., Di, L.P., Yu, E.G., et al., 2017. Regression model to estimate flood impact on corn yield using MODIS NDVI and USDA cropland data layer. J. Intergr. Agric. 16 (2), 398–407. https://doi.org/10.1016/S2095-3119(16)61502-2.
Su, B.D., Huang, J.L., Mondal, S.K., et al., 2021. Insight from CMIP6 SSP-RCP scenarios for future drought characteristics in China. Atmos. Res. 250 https://doi.org/10.1016/j.atmosres.2020.105375.
Tallaksen, L.M., Van Lanen, H.A. (Eds.), 2004. Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater. Elsevier, Amsterdam.
Ten Napel, J., Bianchi, F.J.J.A., Bestman, M.W.P., 2006. Utilising intrinsic robustness in agricultural production systems. In: Invention for a Sustainable Development of Agriculture. Zoetermeer, TransForum, pp. 32–54.
United Nations, 2023. Global drought snapshot 2023. https://www.unccd.int/sites/default/files/2023-12/Global%20drought%20snapshot%202023.pdf.
Urruty, N., Tailliez-Lefebvre, D., Huyghe, C., 2016. Stability, robustness, vulnerability and resilience of agricultural systems. A review. Agron. Sustain. Dev. 36, 15. https://doi.org/10.1007/s13593-015-0347-5.
Van Loon, A.F., Gleeson, T., Clark, J., Van Dijk, A.I.J.M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A.J., Tallaksen, L.M., Uijlenhoet, R., Hannah, D.M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., Van Lanen, H.A.J., 2016. Drought in the Anthropocene. Nat. Geosci. 9, 89–91.
Venkatappa, M., Sasaki, N., Han, P., et al., 2021. Impacts of droughts and floods on croplands and crop production in Southeast Asia—an application of Google Earth engine[J]. Sci. Total Environ. 795, 148829.
Vermeulen, S.J., Challinor, A.J., Thornton, P.K., Campbell, B.M., Eriyagama, N., Vervoort, J., et al., 2013. Addressing uncertainty in adaptation planning for agriculture. Proc. Natl. Acad. Sci. U. S. A. 110, 8357–8362. https://doi.org/10.1073/pnas.1219441110.
Vermeulen, S.J., Dinesh, D., Howden, S.M., Cramer, L., Thornton, P.K., 2018. Transformation in practice: a review of empirical cases of transformational adaptation in agriculture under climate change. Front. Sustain. Food Syst. 2, 65. https://doi.org/10.3389/fsufs.2018.00065.
Wan, K.M., Billa, L., 2018. Post-flood land use damage estimation using improved normalized difference flood index (NDFI3) on Landsat 8 datasets: December 2014 floods, Kelantan, Malaysia. Arab. J. Geosci. 11 (15), 434. https://doi.org/10.1007/s12517-018-3775-0.
Wang, P., Qiao, W.H., Wang, Y.Y., et al., 2020. Urban drought vulnerability assessment? A framework to integrate socio-economic, physical, and policy index in a vulnerability contribution analysis. Sustain. Cities Soc. 54 https://doi.org/10.1016/j.scs.2019.102004.
World Bank Group, 2016. Measuring Rural Access: Using New Technologies. ©World Bank, Washington, DC. http://hdl.handle.net/10986/25187. License: CC BY 3.0 IGO.
Xia, Z.H., Wan, J., Xue, F.Q., et al., 2023. Remote sensing monitoring method of flood disaster based on prior knowledge constraints: a case study of Jianghan Plain. Resour. Environ. Yangtze Basin 32 (7), 1447–1455.
Xue, F.Q., Gao, W., Yin, C., et al., 2022. Flood monitoring by integrating normalized difference flood index and probability distribution of water bodies. IEEE J. Sel. Top. Appl. Earth Observ. Remote Sens. 15, 4170–4179.
Zhang, J.X., Wang, H.M., Huang, J., et al., 2023. A study on dynamic simulation and improvement strategies of flood resilience for urban road system. J. Environ. Manage. 344 https://doi.org/10.1016/j.jenvman.2023.118770.
Zhang, M., Wang, J., 2022. Global flood disaster research graph analysis based on literature mining[J]. Appl. Sci. 12 (6).
Zhao, X.L., 2010. Influence of climate change on agriculture in Northeast China in recent 50 years[J]. J. Northeast. Agric. Univ. 41 (09), 144–149.