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RESEARCH ARTICLE

Drought risk to soybean in Northeastern China: History and future

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ABSTRACT

Soybean (*Glycine max* (L.) Merr.) is not only a globally significant oilseed crop but also a critical component of food security and global oil supply stability, making its resilience to climate variability an issue of paramount importance. This study examines the drought disaster risk associated with soybean production in Northeastern China under the influence of climate change, aiming to provide a scientific basis for soybean production management. Soybean is a globally significant oilseed crop, highly sensitive to climate conditions, particularly drought. In recent years, as global warming has increased the frequency of drought events, serious threats have emerged to soybean yield and quality. By analyzing historical meteorological observation data and future climate scenarios, this research assesses the frequency, intensity, and disaster risk of drought during different growth stages of soybeans. The results indicate significant heterogeneity in future drought frequency and intensity across different soybean growth stages. Drought frequency is expected to decrease overall during the sowing to emergence stage, although some western regions will remain at high risk. Conversely, the drought risk is projected to significantly increase during the branching to flowering and flowering to maturity stages, especially in the northern and western regions. Different climate scenarios also show varying levels of future drought risk. The study further reveals that, despite an overall reduction in drought intensity across most regions compared to historical periods, especially in the distant future (2061-2100), localized risks remain a concern. Through this drought risk assessment, the study offers theoretical support for enhancing drought resilience and developing disaster prevention and mitigation strategies for soybean production in China.

Key words: China, drought risk, future scenarios, *Glycine max*, growth stages, soybean, spatial patterns.

INTRODUCTION

Soybean (*Glycine max* (L.) Merr.) is one of the world's major oilseed crops, second only to rice, wheat, and maize in terms of global economic importance (Huang et al., 2021). It holds significant social, economic, and cultural value, and plays a crucial role in agricultural production, strongly influencing the stability of global edible oil supplies (Mazarei et al., 2023). In recent years, global warming has led to more frequent extreme weather events. Drought, characterized by high frequency, wide-ranging impact, and long duration, is one of the most severe types of extreme climate events, posing a serious threat to the sustainability of agricultural production (Liu et al., 2020). Soybean production is highly sensitive to drought, which greatly affects both yield and quality, threatening the balance of global oil supply and demand (Iftikhar et al., 2022). Consequently, investigating the drought risk to soybean production has become a focal point in agronomy, geography, and climatology, with significant implications for ensuring stable global edible oil supplies (Raghavendra and Suresh, 2020; Thomasz et al., 2024).

Current research on the effects of drought on soybean production primarily focuses on physiology, biochemical characteristics, growth, yield, quality, and spatial distribution. On the one hand, studies have confirmed that drought stress severely negatively impacts soybean morphology and yield loss (Arya et al., 2021), while also strongly affecting chlorophyll fluorescence and cellular levels of proline and soluble sugars in soybean leaves, leading to cell damage (Basal et al., 2024). On the other hand, soybeans have been shown to mitigate drought's adverse effects by triggering genetic components (Zhao et al., 2024), and humans can enhance soybean drought resistance through shading practices (Asghar et al., 2020). Although most soybean production areas exhibit sensitivity to drought, there is notable spatial heterogeneity in the impact of drought across regions (Zipper et al., 2016). Drought risk assessment for soybean production is another key area of focus, forming an essential part of agricultural drought risk research. Current studies largely center on staple crops such as rice, maize, and wheat (Zhang et al., 2017; 2021; Guo et al., 2021). Methods such as index-based assessments and model-based approaches are typically used. For example, Yue et al. (2018) constructed a wheat drought risk assessment method based on crop models and climate data. Research on soybean drought risk often uses models combined with climate data to assess the risk of drought-induced yield reduction (Wu et al., 2004; Dhakar et al., 2017; Wei et al., 2021). However, these studies have predominantly focused on historical periods (Yang et al., 2017), and there is a lack of research on the forecast of drought disaster risk, which is crucial agricultural climate information for soybean production management.

Northeastern China is the country's primary soybean-producing region, accounting for over 50% of the national soybean output and having one of the largest soybean cultivation areas in China (Cheng et al., 2023). However, due to increasing climate variability, frequent drought events have caused significant damage to soybean production in this region (Xie et al., 2014; Wang et al., 2020). Dynamic monitoring and refined drought early warning systems are urgently needed. Thus, this study focuses on the Northeastern region of China, analyzing the dynamic changes and future projections of drought disaster risk during different soybean growth stages, aiming to provide valuable scientific references for ensuring soybean production security and drought defense in China.

MATERIALS AND METHODS

Study area overview

Northeastern China is located between 38°43' to 53°24' N lat and 115°20' to 135° E long, covering the provinces of Liaoning, Jilin, and Heilongjiang, with a total area of approximately 791 800 km² (Figure 1). The region's topography includes plains, hills, and mountains, with the Changbai Mountains in the east, the Lesser Khingan Range in the north, and the Greater Khingan Range in the west, surrounded by the expansive Northeast Plain. The climate is temperate monsoon, characterized by distinct seasons, with warm, rainy summers and cold, dry winters. The average annual temperature ranges from -0.5 to 10.6 °C, with annual precipitation between 500 and 800 mm. Both temperature and precipitation decrease from southeast to northwest. Northeastern China is one of the world's three major black soil regions, with high agricultural production potential. The region's ample arable land and favorable climate make it highly suitable for soybean (*Glycine max* (L.) Merr.) cultivation. Soybean is one of the main crops in the three northeastern provinces, grown in a single season, and the region enjoys a clear advantage in both production and cultivation area within China (Tian et al., 2020; Yin and Wei, 2023).

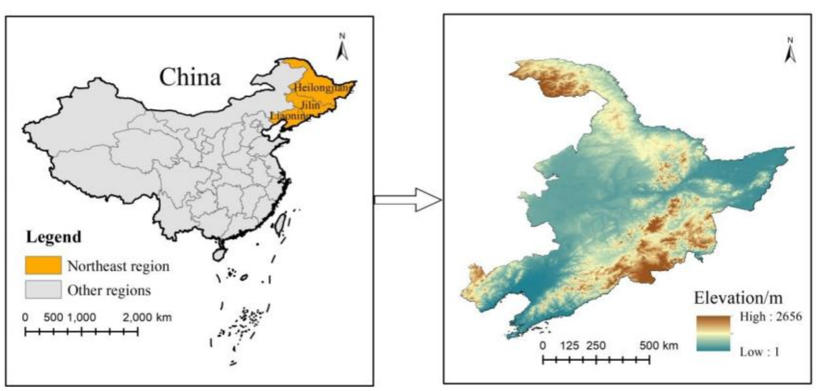

Figure 1. Location and topography of Northeastern China.

Data sources and processing

This study includes historical meteorological observation data and future climate projection data. The historical meteorological data consist of daily observations from 86 stations in Northeastern China from 1961 to 2020, covering daily precipitation, maximum temperature, minimum temperature, average temperature, relative humidity, and average wind speed. Missing data were supplemented using linear regression. For future climate projections, data were obtained from four models in the CMIP6 series—ACCESS-CM2, BCC-CSM2-MR, CMCC-CM2-SR5, and EC-Earth3—which demonstrated strong simulation performance for Northeastern China. These data include daily average temperature, maximum and minimum temperatures, daily precipitation, relative and absolute humidity, solar radiation, and wind speed. Three different climate scenarios, SSP245, SSP370, and SSP585, were selected to represent different socioeconomic development pathways and radiation intensity scenarios. The SSP245, SSP370, and SSP585 scenarios represent moderate development with medium emissions, accelerated development with new radiative forcing, and conventional development with high emissions, respectively (Deng et al., 2023; Dias et al., 2024). The soybean growth period data provided by the China Meteorological Administration, along with previous research (Xie et al., 2014), were used to divide the soybean growth stages into four phases: Sowing to emergence (1 to 20 May), emergence to branching (21 May to 30 June), branching to flowering (1 to 20 July), and flowering to maturity (21 July to 20 September).

Research methods

The crop water deficit index (CWDI) is an indicator that represents the degree of water deficiency in crops, calculated as the difference between crop water demand and actual water supply during different growth stages. It is expressed as a percentage (%) and calculated using the following formula:

$$CWDI = \frac{K_c \cdot ET_0 - S}{K_c \cdot ET_0} \times 100\% \quad (1)$$

where CWDI is the crop water deficit index, and K_c represents the crop coefficient. Based on previous studies (Cheng et al., 2023), K_c for soybeans were assigned as follows: 0.4 for the early growth stage (sowing to emergence), 1.15 for the middle stages (sowing to emergence and branching to flowering), and 0.5 for the late stage (flowering to maturity). The reference evapotranspiration (ET_0) was calculated using the Penman-Monteith formula recommended by the United Nations Food and Agriculture Organization (FAO) (Allen et al., 1998). Based on the CWDI results, drought levels are categorized into four classes: Extreme drought (CWDI > 50%), severe drought (35% < CWDI ≤ 50%), moderate drought (25% < CWDI ≤ 35%), and mild drought (15% < CWDI ≤ 25%). The specific calculation process for the CWDI can be found in the research methods of Cheng et al. (2022).

Drought frequency represents how often drought occurs over a certain period. It was calculated as Equation (2):

$$P = n / N \times 100\% \quad (2)$$

where P is the drought frequency (%), n is the total number of drought years at the station, and N is the total number of years observed. The Kriging interpolation method was used to obtain spatial maps of drought frequency.

Drought intensity represents the severity of drought in a given region and is calculated as Equation (3):

$$T = \sum_{i=1}^{n} T_i / N \quad (3)$$

where T is the drought intensity for a specific period, N is the total number of drought years, and T_i represents the value assigned to each drought category. Values of 1, 2, 3, and 4 were assigned to mild, moderate, severe, and extreme droughts, respectively. The Kriging interpolation method was also used to obtain spatial maps of drought intensity.

The drought disaster risk index (DDRI) is an indicator that combines drought intensity and frequency, providing an objective reflection of the overall drought risk. The calculation formula for the DDRI for different soybean growth stages is as follows:

$$R_e = \sum_{i=1}^{4} D_i / n \cdot H_i \quad (4)$$

where R_e is the drought disaster risk index for each growth stage, D_i is the frequency of drought occurrence for group i, n is the total number of samples, and H_i is the median value of the group.

An integrated drought disaster risk model was developed to evaluate the overall risk across all growth stages:

$$R_t = \sum_{i=1}^{4} R_e \cdot W_i \quad (5)$$

where R_t is the overall drought disaster risk index, R_e is the DDRI for each growth stage, and W_i is the weighting factor for each stage. Given that drought risk during each growth stage strongly affects soybean yield, equal weightings (0.25) were assigned to each growth stage.

Based on the calculated drought disaster risk results, a classification system was established, dividing the risk into five levels (Table 1).

Table 1. Soybean drought disaster risk classification standards by growth stage.

Risk levels	Low risk	Moderate-low risk	Moderate risk	Moderate-high risk	High risk
Sowing to emergence stage	< 20	20 ~ 40	40 ~ 60	60 ~ 80	> 80
Emergence to branching stage	< 5	5 ~ 10	10 ~ 15	15 ~ 20	> 20
Branching to flowering stage	< 5	5 ~ 10	10 ~ 15	15 ~ 20	> 20
Flowering to maturity stage	< 10	10 ~ 20	20 ~ 30	30 ~ 40	> 40
Entire growth stage	< 10	10 ~ 20	20 ~ 30	30 ~ 40	> 40

RESULTS

Average drought frequency and intensity and their variations

During the stages from sowing to emergence and from emergence to branching, the historical period shows a higher drought frequency than the future periods (2021-2060 and 2061-2100) under all scenarios. During the stages from branching to flowering and from flowering to maturity, the drought frequency in the historical period is slightly lower than that of the future period (2021-2060) under the SSP245 and SSP370 scenarios but higher than that under the SSP585 scenario and all scenarios for the future period (2061-2100). Overall, the drought frequency for the future period (2021-2060) is higher than for the future period (2061-2100) under all scenarios (Figure 2a). The general pattern of drought intensity across the four growth stages is similar to that of drought frequency in both the historical and future periods under all scenarios. However, it is noteworthy that during the stages from emergence to branching and from branching to flowering, the drought intensity shows minimal differences between the historical and future periods under all scenarios. During the flowering to maturity stage, the drought intensity in the historical period is significantly lower than that in the future period (2021-2060) under all scenarios and only slightly higher than that in the future period (2061-2100) under all scenarios (Figure 2b).

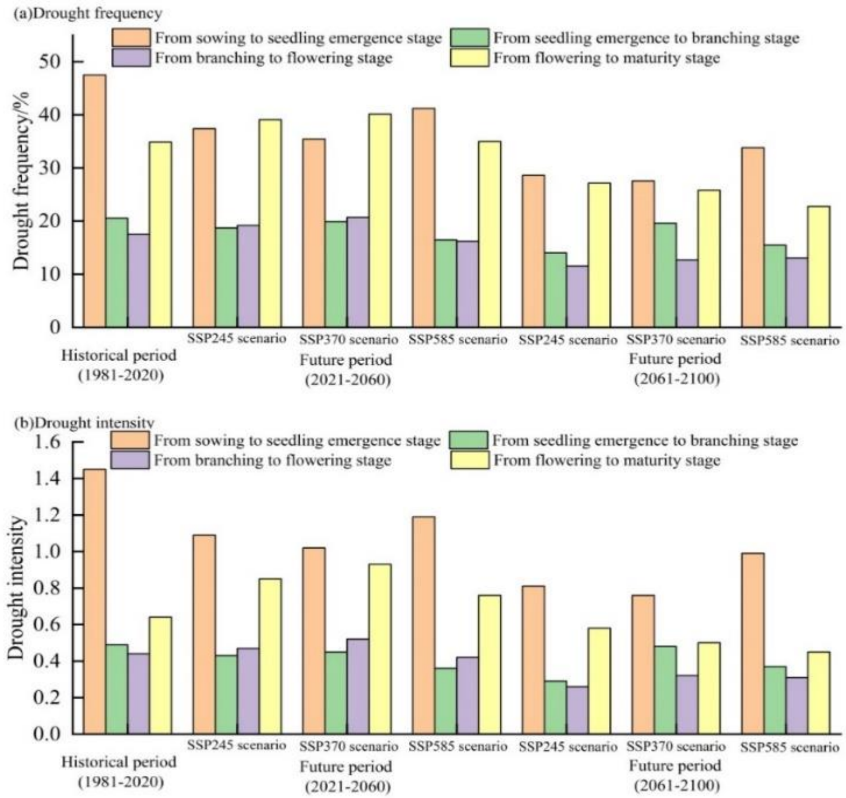

Figure 2. Average drought frequency and intensity during different growth stages of soybeans.

During the stages from sowing to emergence and from emergence to branching, both the historical and future periods exhibit low drought frequency in the eastern region of the study area, while high drought frequency is concentrated in the western region (Figures 3(a)I-(g)I and Figures 3(a)II-(g)II). From the branching to flowering stage, in both the historical and future periods, drought frequency shows a decreasing trend from north to south across the study area (Figures 3(a)III-(g)III). During the flowering to maturity stage, drought frequency is higher in the western and northeastern regions and lower in the southern and central regions during the historical period and the future period (2021-2060) under all scenarios. However, in the future period (2061-2100), high drought frequency areas are mainly concentrated in the western region, with lower frequency in most other regions (Figures 3(a)IV-(g)IV).

From sowing to emergence and from emergence to branching, drought intensity generally increases from east to west in both the historical and future periods (Figures 4(a)I-(g)I and Figures 4(a)II–(g)II). During the stages from branching to flowering and from flowering to maturity, drought intensity increases from the southeast to the northwest across both the historical and future periods under all scenarios. The low-intensity drought areas are more widespread in the future period (2061-2100) compared to the future period (2021-2060), but the high-intensity areas vary greatly between scenarios within the same future period (Figures 4(a)III-(g)III and Figures 4(a)IV-(g)IV).

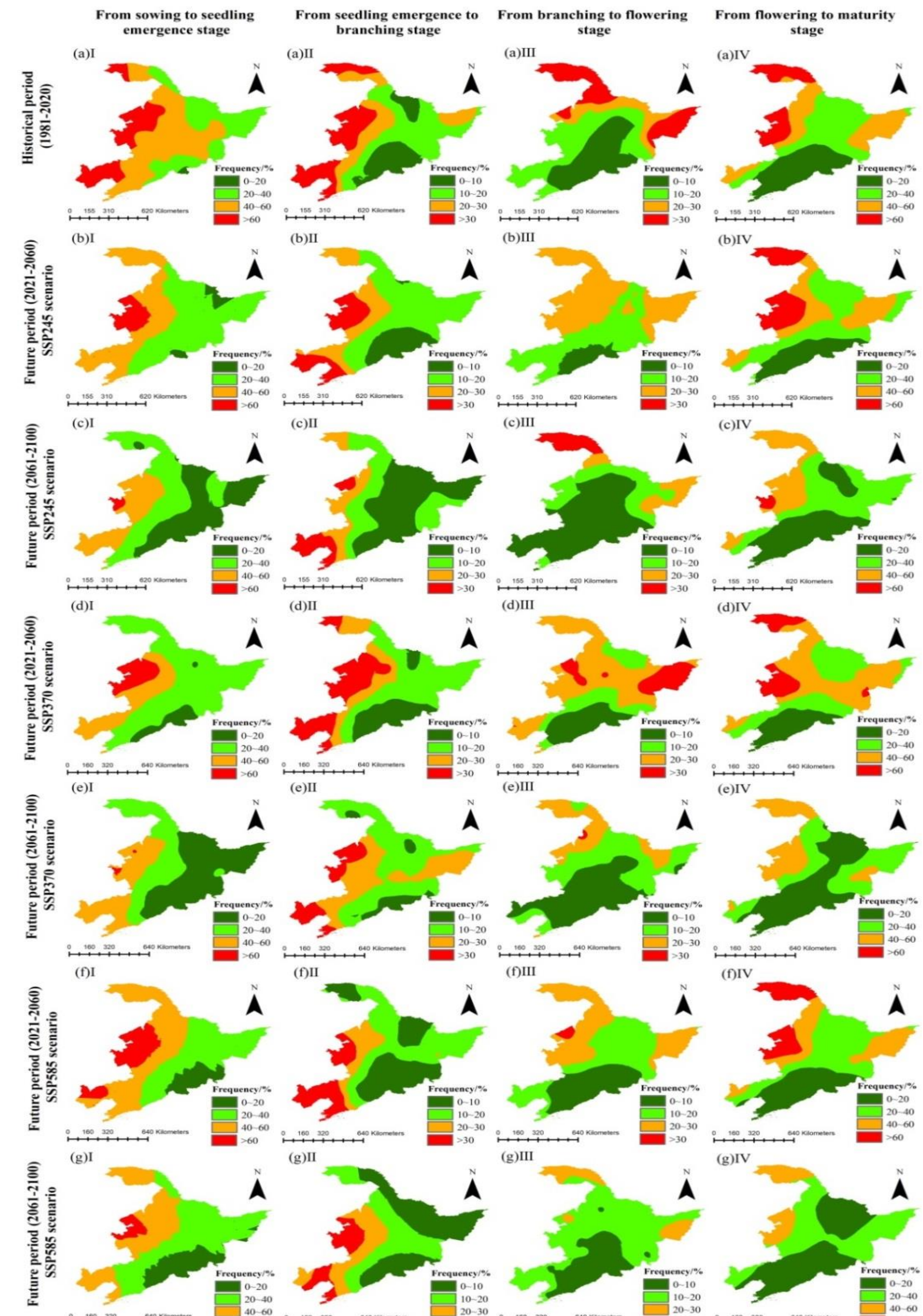

Figure 3. Spatial distribution of drought frequency during different growth stages of soybeans.

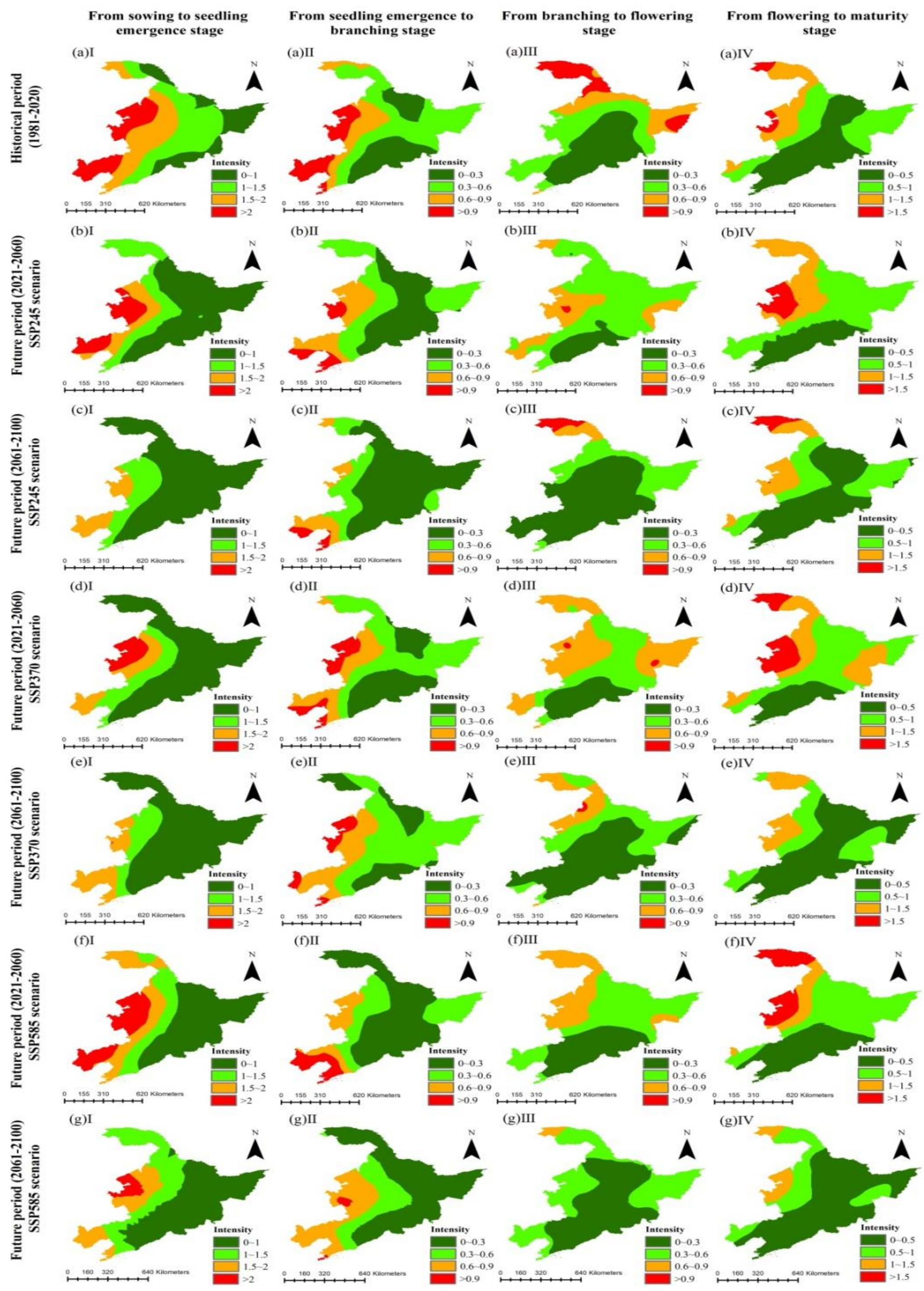

Figure 4. Spatial distribution of drought intensity during different growth stages of soybeans.

Compared to the historical period, both drought frequency and intensity decrease in stages I (sowing to emergence) and II (emergence to branching) across all scenarios in the future periods. The decline in drought frequency and intensity is more pronounced under the SSP245 and SSP370 scenarios during stage I than under the SSP585 scenario. In stage II, the decline is more pronounced under the SSP245 and SSP585 scenarios compared to the SSP370 scenario. In stage III (branching to flowering), drought frequency and intensity increase in the future period (2021-2060) under the SSP245 and SSP370 scenarios but decrease under other scenarios in future periods. During stage IV (flowering to maturity), drought frequency and intensity increase in all scenarios during the future period (2021-2060) but decrease in all scenarios during the future period (2061-2100). The SSP370 and SSP585 scenarios show significant increases and decreases, respectively, during the future periods (2021-2060) and (2061-2100) (Table 2).

Table 2. Changes in drought frequency and intensity across different growth stages of soybeans in future periods compared to the historical period. Stage I: From sowing to seedling emergence stage; Stage II; from seedling emergence to branching stage; Stage III: from branching to flowering stage; Stage IV: from flowering to maturity stage.

Periods	Scenarios	Drought frequency/%				Drought intensity			
		Stage I	Stage II	Stage III	Stage IV	Stage I	Stage II	Stage III	Stage IV
Future period (2021-2060)	SSP245	-10.12	-1.84	1.68	4.23	-0.36	-0.06	0.03	0.21
	SSP370	-12.06	-0.66	3.20	5.27	-0.43	-0.04	0.08	0.29
	SSP585	-6.30	-4.11	-1.30	0.12	-0.26	-0.13	-0.02	0.12
Future period (2061-2100)	SSP245	-18.90	-6.55	-5.97	-7.71	-0.64	-0.20	-0.18	-0.06
	SSP370	-19.94	-0.96	-4.85	-9.05	-0.69	-0.01	-0.12	-0.14
	SSP585	-13.70	-5.07	-4.44	-12.11	-0.46	-0.12	-0.13	-0.19

In stage I (sowing to emergence), most of the study area shows a decreasing trend in drought frequency across future scenarios compared to the historical period, with only a small portion of the western and northwestern regions experiencing an increase (Figure 5(a)I-(f)I). In stage II (emergence to branching), areas showing an increase in drought frequency are more widespread under the SSP245 and SSP370 scenarios in the future period (2021-2060) compared to the SSP585 scenario. However, during the future period (2061-2100), areas of increasing drought frequency are fewer under the SSP245 and SSP585 scenarios than under the SSP370 scenario (Figure 5(a)II-(f)II). During stages III (branching to flowering) and IV (flowering to maturity), areas with increasing drought frequency are more widespread during the future period (2021-2060) than during the future period (2061-2100), whereas areas with decreasing drought frequency are fewer during the future period (2021-2060) compared to the future period (2061-2100) (Figures 5(a)III-(f)III and Figures 5(a)IV-(f)IV).

In stage I (sowing to emergence), most of the study area shows a decreasing trend in drought intensity across all future scenarios compared to the historical period, with only localized areas in the west and northwest showing an increase (Figures 6(a)I-(f)I). In stage II (emergence to branching), most of the study area shows decreasing drought intensity across all future scenarios except for the SSP370 scenario during the future period (2061-2100), where a slight increase is observed in the southern region (Figures 6(a)II-(f)II). During stages III (branching to flowering) and IV (flowering to maturity), drought intensity increases across most of the study area in all future scenarios during the future period (2021-2060), with this trend being more pronounced in the central and southern regions. However, in the future period (2061-2100), drought intensity decreases across most of the study area, except for the southern region, where an increase is observed (Figures 6(a)III-(f)III and Figures 6(a)IV-(f)IV).

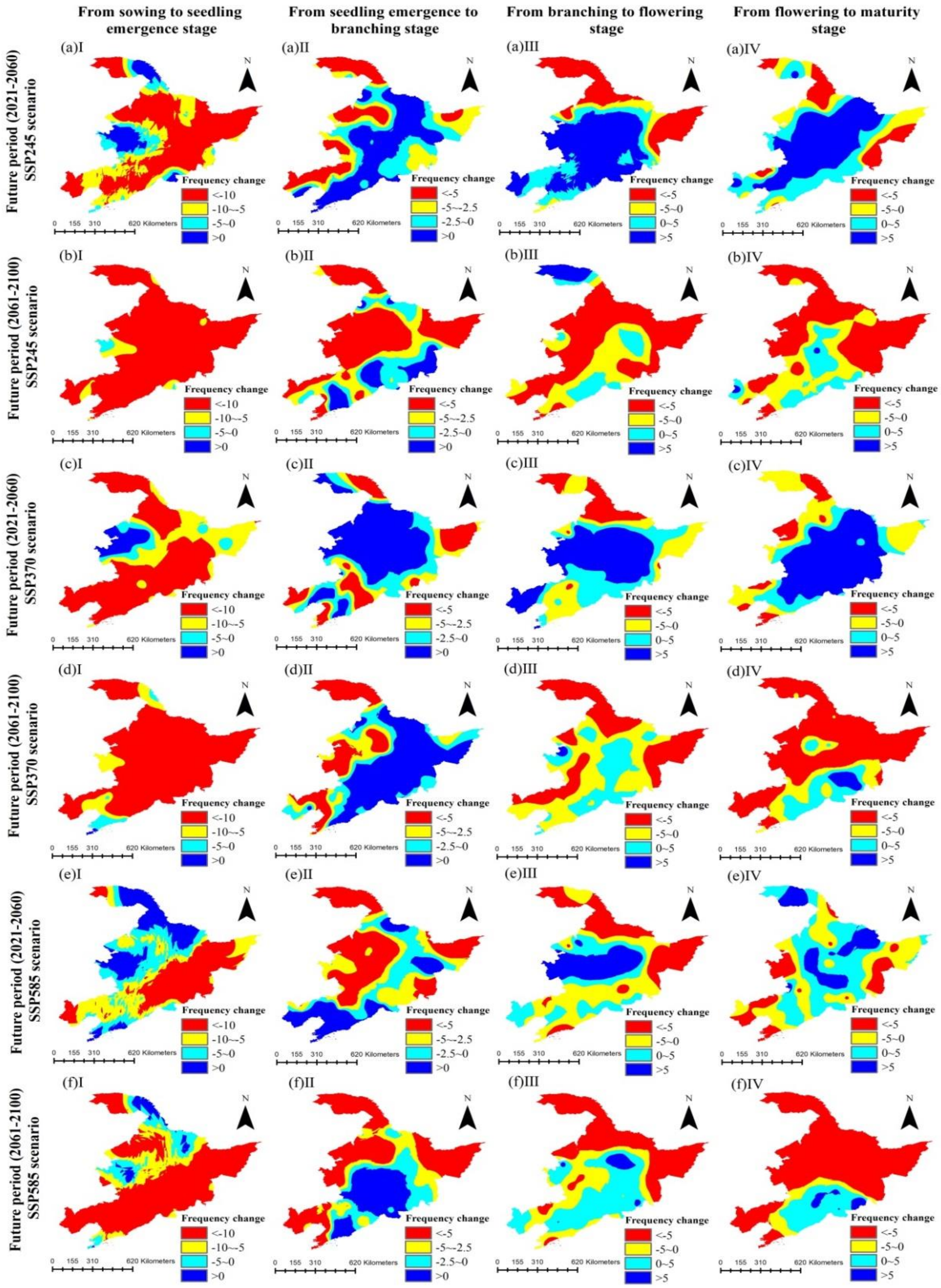

Figure 5. Spatial distribution of changes in drought frequency during different growth stages of soybeans in future periods compared to the historical period.

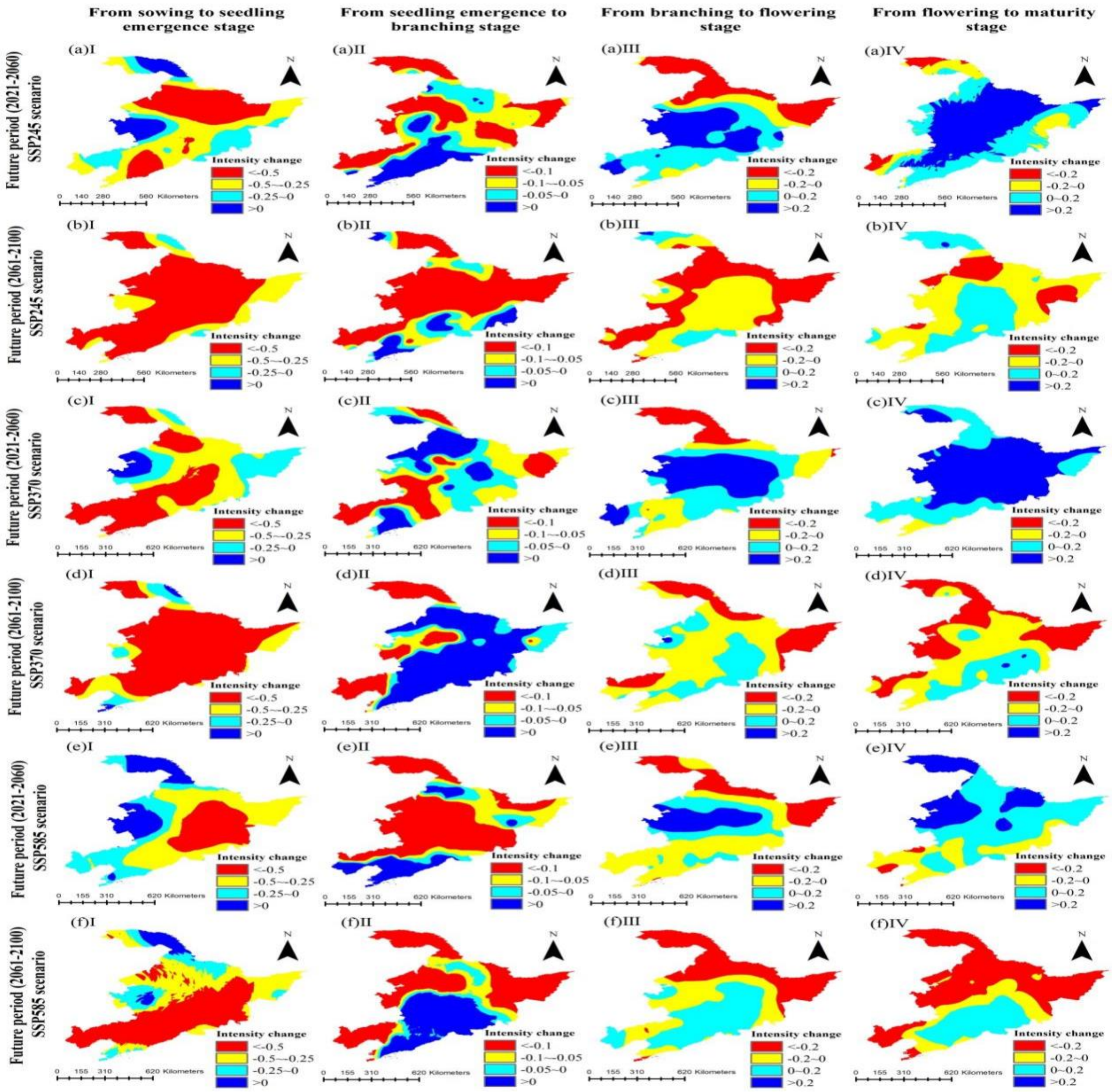

Figure 6. Spatial distribution of changes in drought intensity during different growth stages of soybeans in future periods compared to the historical period.

Assessment of drought disaster risk

From sowing to emergence, drought disaster risk was primarily high during the historical period. In the future period (2021-2060), the SSP245 and SSP370 scenarios show a predominance of low and moderate-low risk, whereas the SSP585 scenario exhibits both high and low risk. In the future period (2061-2100), low risk dominates across all scenarios. From emergence to branching, low risk prevails during both the historical period and future periods across all scenarios except for the future period (2061-2100) under the SSP370 scenario. From branching to flowering, low risk dominates most scenarios during both the historical and future periods, except for the future periods (2021-2060) under the SSP245 and SSP370 scenarios. From flowering to maturity, low risk dominates during the historical period, while high risk dominates during the future period (2021-2060) and low risk dominates during the future period (2061-2100). For the entire growth stage, high, moderate-low, and moderate risks dominate during the historical period and the future period (2021-2060) under the SSP370 scenario. The SSP245 and SSP585 scenarios show a predominance of moderately low risk in the future period (2021-2060), while low risk dominates all scenarios during the future period (2061-2100) (Figure 7).

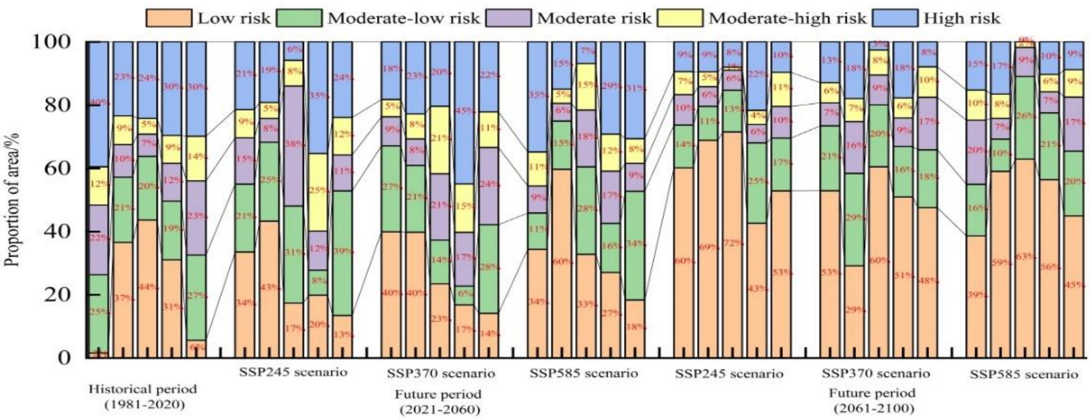

Figure 7. Proportion of area under different drought disaster risk levels during various soybean growth stages in the historical and future periods.

During stages I (sowing to emergence) and II (emergence to branching), the drought disaster risk level is lower in the eastern region and higher in the western region of the study area (Figures 8(a)I-(f)I and Figures 8(a)II-(f)II). In stage III (branching to flowering), high-risk levels dominate in the northwest, while low-risk levels prevail in the central and southern regions (Figures 8(a)III-(f)III). In stage IV (flowering to maturity), the drought disaster risk is higher in the northern regions and lower in the southern regions during both the historical and future periods (2021-2060) under all scenarios. However, during the future period (2061-2100), the overall risk pattern shifts, showing higher risks in the west and lower risks in the east (Figures 8(a)IV-(f)IV). For the entire growth stage, the risk levels increase gradually from the southeast to the northern and western regions during both the historical and future periods under all scenarios (Figures 8(g)I-(f)IV).

Changes in drought disaster risk

From the sowing to emergence stage, compared to the historical period, all future scenarios show an increasing trend in the area of low-risk regions. Except for the moderate-low risk in the SSP370 scenario during the future period (2021-2060), the areas of all other risk levels decrease. During the emergence to branching stage in the same period, the low and moderate-low risk areas increase in the SSP245 and SSP370 scenarios, while moderate, moderate-high, and high-risk areas decrease. In the future periods (2021-2060 SSP585 scenario and 2061-2100 SSP245 and SSP585 scenarios), only low-risk areas expand, with all other risk levels decreasing. For the future period (2061-2100 SSP370 scenario), moderate-low and moderate-risk areas increase, while low, moderate-high, and high-risk areas decrease. From the branching to flowering stage in the future period (2021-2060 SSP245 and SSP585 scenarios), only low and high-risk areas decrease. However, in the SSP370 scenario, low, moderate-low, and high-risk areas all show decreasing trends. In the future period (2061-2100 SSP245 scenario), only the low-risk area increases, whereas most risk levels in the SSP370 and SSP585 scenarios tend to rise. From the flowering to maturity stage during the future period (2021-2060), low and moderate-low risk areas decrease across all scenarios, while moderate, moderate-high, and high-risk areas increase. In the future period (2061-2100), the trends for all risk levels in the SSP245 and SSP585 scenarios are the opposite of those observed during the 2021-2060 period. For the future period (2061-2100 SSP370 scenario), only the low-risk area increases, with all other risk levels decreasing. For the entire growth stage during the future period (2021-2060), low and moderate-low risk areas increase across all scenarios, while other risk levels decrease. However, in the future period (2061-2100), only low-risk areas expand in all scenarios (Table 3).

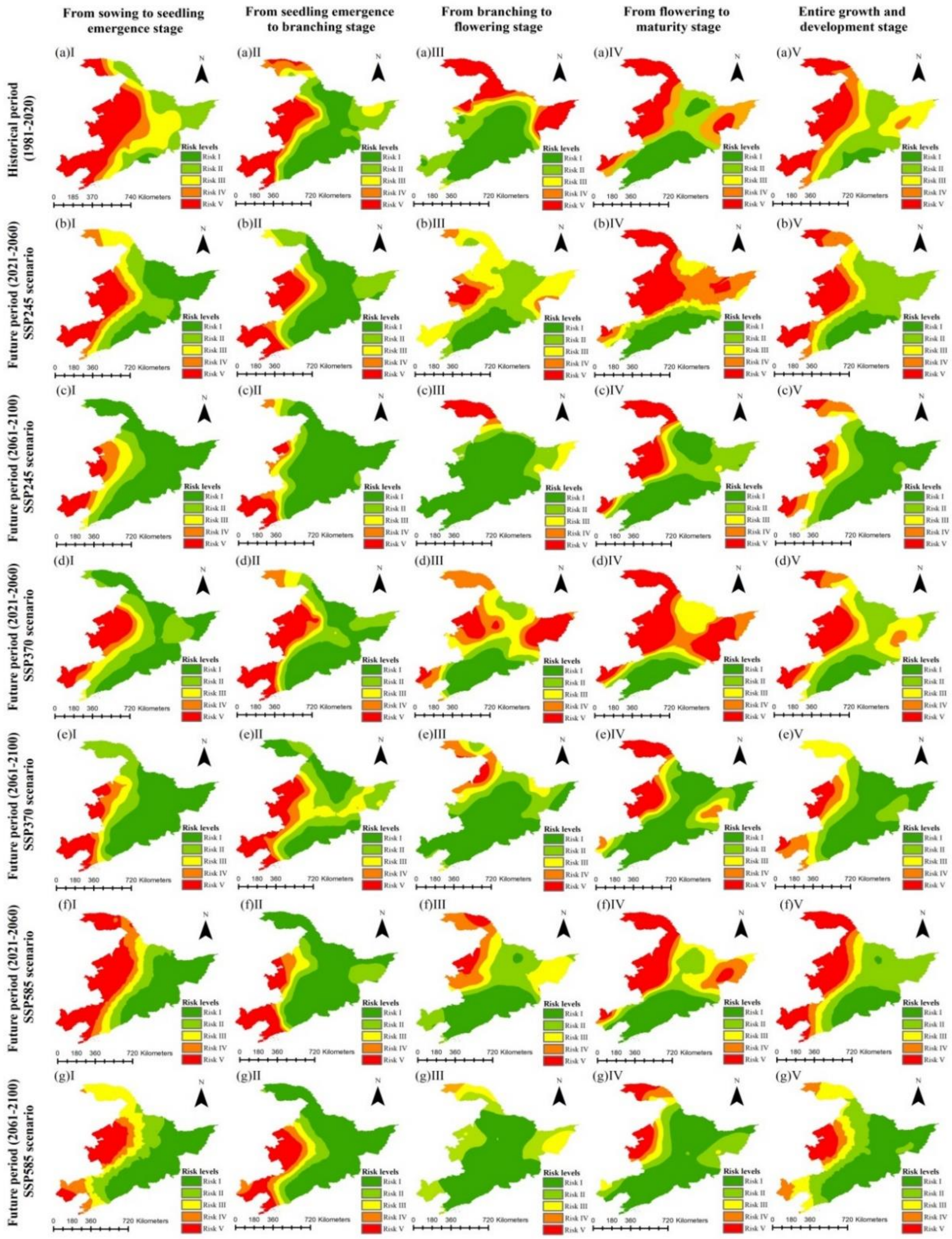

Figure 8. Spatial distribution of drought disaster risk during different growth stages of soybeans in the historical and future periods.

Table 3. Changes in the area (km^2) of drought disaster risk during different soybean growth stages in future periods compared to the historical period. Stage I: From sowing to seedling emergence stage; Stage II: from seedling emergence to branching stage; Stage III: from branching to flowering stage; Stage IV: from flowering to maturity stage; Stage V: entire growth stage.

Periods	Scenarios	Growth stages	Low risk	Moderate-low risk	Moderate risk	Moderate-high risk	High risk
Future period (2021-2060)	SSP245	Stage I	252292	-26051	-58431	-25145	-142664
		Stage II	53041	34139	-21842	-32083	-33255
		Stage III	-207252	83160	244353	24550	-144811
		Stage IV	-88314	-83895	2944	123972	45293
		Stage V	61913	98386	-95744	-17591	-46965
	SSP370	Stage I	302637	19129	-101469	-52289	-168008
		Stage II	25462	3863	-15039	-9467	-4819
		Stage III	-169236	-49787	110186	138913	-30077
		Stage IV	-112454	-99480	39571	51234	121129
		Stage V	67333	8503	-7494	-22590	-60741
	SSP585	Stage I	258978	-105027	-106421	-10593	-36938
		Stage II	182427	-42458	-36894	-36391	-66684
		Stage III	-85637	59407	86391	76597	-136758
		Stage IV	-31580	-23961	35758	22926	3143
		Stage V	100583	58604	-115416	-49866	-6095
Future period (2061-2100)	SSP245	Stage I	462369	-88759	-98122	-38016	-237473
		Stage II	254899	-78289	-31980	-34646	-109984
		Stage III	219929	-55101	-5224	-31748	-127856
		Stage IV	91230	54353	-48495	-34577	-62512
		Stage V	373029	-81037	-106270	-26210	-159512
	SSP370	Stage I	405040	-33493	-116631	-44964	-209951
		Stage II	-58507	67859	48113	-14416	-43050
		Stage III	132790	-4330	19135	22954	-170548
		Stage IV	157028	-20343	-23538	-19617	-93531
		Stage V	331215	-68580	-54037	-35364	-173234
	SSP585	Stage I	292357	-66675	-13924	-20269	-191488
		Stage II	177311	-82343	-29481	-11237	-54250
		Stage III	152145	47190	17258	-25702	-190891
		Stage IV	200020	20431	-42071	-26158	-152223
		Stage V	310499	-51116	-50392	-42916	-166076

From the sowing to emergence stage, compared to the historical period, the drought disaster risk in most regions in all future scenarios tends to decrease, which is particularly evident in the western region (Figures 9(a)I-(f)I). During the emergence to branching stage, except for the future period (2061-2100 SSP370 scenario), drought disaster risk decreases in most regions across most future scenarios (Figures 9(a)II-(f)II). From the branching to flowering stage and from flowering to maturity stage, in the future period (2021-2060), the drought disaster risk in most regions of the study area generally shows an increasing trend in all scenarios, while in the future period (2061-2100), this risk generally shows a decreasing trend in all scenarios (Figures 9(a)III-(f)III and Figures 9(a) IV-(f)VI). For the entire growth stage, during the future period (2021-2060), the drought disaster risk only increases in the western regions, while it decreases in the northern, western, and southern regions. In the future period (2061-2100), the drought disaster risk decreases across all regions of the study area in all scenarios, with the decline particularly evident in the western regions (Figures 9(a)V-(f)V).

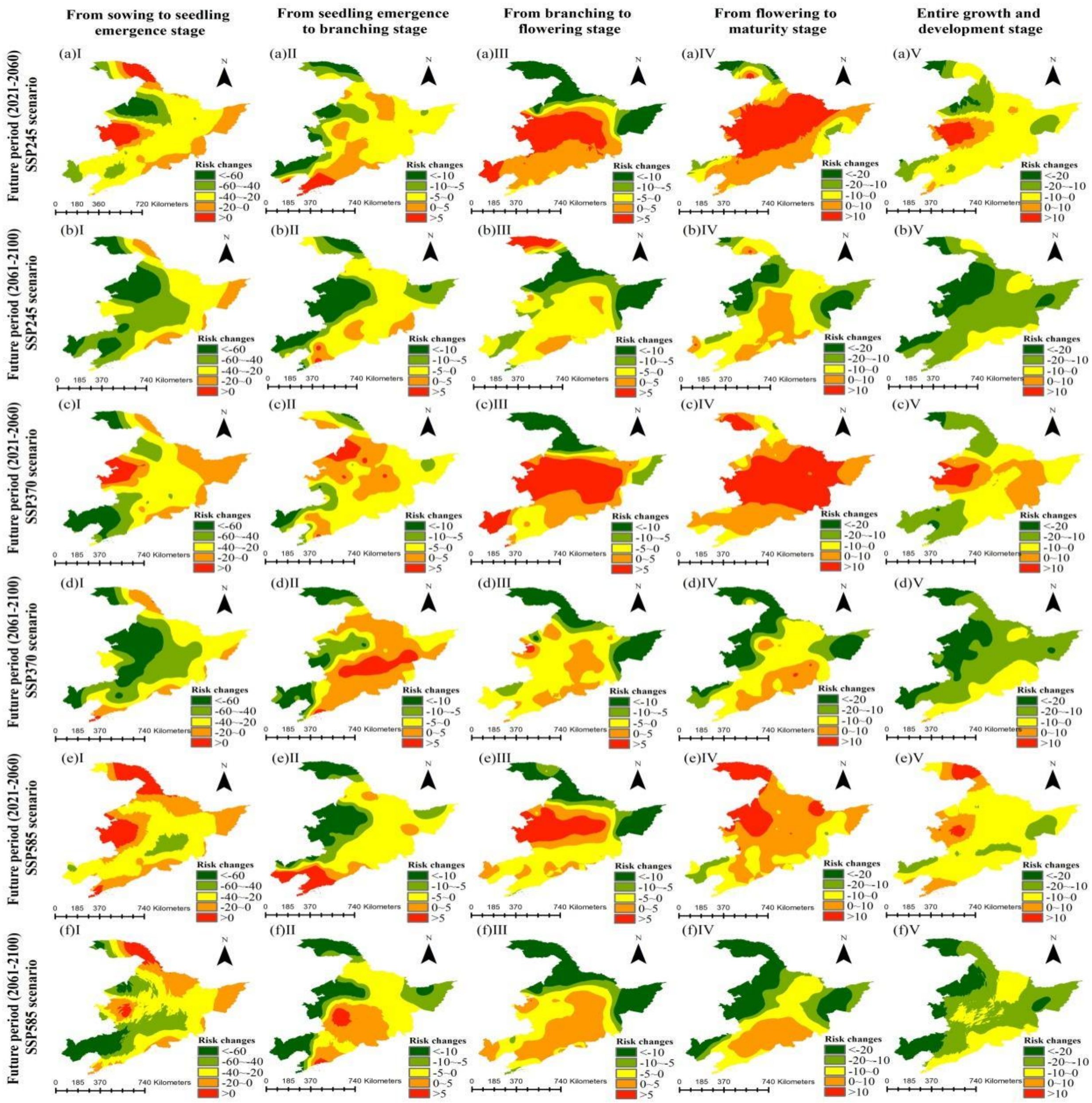

Figure 9. Spatial pattern of changes in drought disaster risk in future periods compared to the historical period.

DISCUSSION

This study investigates the changes in drought frequency and intensity across different growth stages of soybeans during historical and future periods and examines the variation in drought disaster risk under different SSP scenarios. These findings provide valuable insights for assessing the impact of future climate change on agricultural drought.

Comparison of study results with existing literature

The results of this study indicate that there are significant spatiotemporal changes in drought frequency and intensity across various growth stages of soybeans in the future periods (2021-2060 and 2061-2100) compared to the historical period. These changes are closely linked to the global warming trend, and the different greenhouse gas concentration pathways (SSP scenarios) significantly affect the future characteristics of drought. The findings of this study are similar to those of Zhang et al. (2021), who investigated the effects of different future climate scenarios on plant distribution.

However, this study also reveals differences in the changes in drought characteristics across different growth stages. For example, during the sowing-to-emergence and emergence-to-branching stages, future drought frequency and intensity generally show a decreasing trend. This contrasts with the findings of Rattis et al. (2021), who studied climate threats to Brazilian agriculture, suggesting that spatial heterogeneity in extreme climate changes across different regions of the globe may account for these discrepancies. In the stages from branching to flowering and from flowering to maturity, the increase in drought frequency and intensity is more pronounced, potentially related to increased evapotranspiration and changes in precipitation patterns due to climate warming. This indicates that the negative impacts of drought on the late growth stages, where water demand is highest, are still intensifying, which is consistent with Zhao et al. (2019), who found that drought poses a more severe threat to grain crop growth during later stages in China.

Policy recommendations for mitigating drought risk

Based on the study's findings, different drought risks are faced by soybean cultivation at various developmental stages in the future, so differentiated strategies for mitigating these risks are necessary. Four policy recommendations are proposed. (1) Enhance farmland water resource management: The study shows that drought frequency and intensity increase significantly from the branching-to-flowering and flowering-to-maturity stages. Therefore, strengthening the capacity of agricultural irrigation systems is crucial. Water-saving irrigation techniques such as drip and sprinkler irrigation should be promoted to improve water use efficiency. Additionally, regional water resource allocation systems should be established to ensure timely irrigation during high drought periods. (2) Optimize planting time and layout: Adjusting the planting time and layout of soybeans based on the spatial distribution of drought frequency and intensity under different SSP scenarios can effectively avoid high-risk areas and periods. The government can establish regional agricultural production guidelines to help farmers optimize crop planting times according to future climate forecasts, reducing exposure to drought during high-risk periods. (3) Strengthen agricultural meteorological services and climate risk early warning: Agricultural meteorological services play a crucial role in drought risk management. The government should establish a comprehensive agricultural meteorological observation network and provide more accurate climate forecasts, especially during critical periods such as sowing-to-emergence and emergence-to-branching. Climate warnings should be issued, and farmers' capacity to respond to climate change should be enhanced through training and education to improve their ability to handle drought disasters. (4) Introduce drought-resistant crop varieties and innovate biotechnology: The increasing drought risk in the future places higher demands on crops' drought resistance. Policymakers should increase investment in the development and promotion of drought-resistant soybean varieties to enhance crops' tolerance to drought. Utilizing modern biotechnology, such as gene editing, to cultivate soybean varieties more adaptable to extreme drought conditions will help ensure future agricultural production security.

Innovations in the study

This study presents innovations in three areas. (1) Multi-stage drought risk analysis: Unlike most previous studies that focused solely on overall changes in drought frequency and intensity, this study conducts an in-depth analysis of drought characteristics and trends across different developmental stages of soybeans, revealing varying sensitivities to drought at different growth stages. This detailed stage-based analysis helps better understand the impact of future climate change on agricultural production and provides a basis for more precise agricultural drought risk management measures. (2) Spatiotemporal comparison across different SSP scenarios: By comparing SSP245, SSP370, and SSP585 greenhouse gas emission scenarios, this study comprehensively demonstrates the spatiotemporal distribution of drought frequency and intensity in future soybean cultivation regions. This cross-scenario comparative analysis helps policymakers better assess the potential impacts of different emission reduction policies and formulate more scientifically informed response strategies. (3) Comprehensive assessment of drought disaster risk: This study not only analyzes drought frequency and intensity but also introduces the concept of drought disaster risk, assessing the potential harm of future droughts to soybean production. This risk assessment framework combines the probability of drought occurrence with its potential impact on agricultural production, providing a more comprehensive reflection of the threat posed by drought to agriculture and offering scientific evidence for future drought disaster prevention.

Limitations

Despite providing a detailed analysis of future changes in drought risk, this study has some limitations that need further exploration. First, the study is based on SSP scenario simulations, which rely on certain greenhouse gas emission pathways. However, actual future emissions may be influenced by various factors, such as policies, technological advancements, and economic development, leading to uncertainties in the scenarios. Consequently, the conclusions of this study may have some scenario dependence. Second, the impact of drought is not only related to climate conditions but is also influenced by factors such as soil type, vegetation cover, and farmland management practices. This study primarily focuses on the impact of climate change on drought and does not fully consider the effects of other non-climatic factors, which may lead to biases in the drought risk assessment results. Moreover, this study mainly analyzes drought risk through four key developmental stages of soybeans. Still, different regions have varying soybean varieties and agricultural practices, so future research should combine specific regional agricultural management measures to propose more targeted risk response strategies.

CONCLUSIONS

This study focuses on Northeast China and examines the dynamic changes in drought during different growth stages of soybeans under the background of climate warming and evaluates the associated drought disaster risk. By analyzing different climate scenarios for future periods (SSP245, SSP370, SSP585), it was found that drought frequency and intensity generally show a decreasing trend during stages I (sowing to emergence) and II (emergence to branching) in the future, while there is a possibility of increased drought frequency during stages III (branching to flowering) and IV (flowering to maturity), which is evident in the future period (2021-2060). This shift may further exacerbate drought risk during these stages, threatening soybean yields. The future drought disaster risk assessment indicates significant differences in risk levels across growth stages under different climate scenarios. Specifically, areas with high risk during the historical period gradually shift to low risk in the future, but some areas, especially in the western and northern regions, maintain relatively high drought risk under certain scenarios. Overall, the spatial pattern of drought disaster risk in the future shows a gradual increase from the southeast to the west and northwest, particularly during the flowering-to-maturity stage, where this trend is more pronounced. Therefore, future soybean production management must focus on the spatial distribution of drought and the dynamic changes in drought disaster risk, adopting targeted drought prevention measures, especially in high-risk areas, such as improving irrigation technology and optimizing crop planting structures, to enhance soybeans' drought resistance and production stability. This study provides scientific evidence for soybean production in Northeast China and offers a reference for soybean production management in other drought-sensitive regions globally. Future research should further explore drought-resistant genes and breeding techniques in soybeans to mitigate the negative impacts of drought on production and ensure the stability of the global edible oil supply chain.

Author contributions

Methodology: J.Z. Software: J.Z. Validation: Y.J. Formal analysis: Y.J. Investigation: J.Z. Resources: H.H. Data curation: J.Z. Writing-original draft: H.H. Writing-review & editing: H.H. Funding acquisition: H.H. All co-authors reviewed the final version and approved the manuscript before submission.

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