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Impact of Climate Change on the Climatic Suitability of Oilseed Rape (*Brassica napus* L.) Planting in Jiangsu Province, China

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Abstract

Climate change has caused considerable uncertainty to oilseed rape production. However, the climatic suitability for oilseed rape cultivation and its future changing trend remain unclear, specifically in Jiangsu Province—a major oilseed rape producing-region in China. Based on the past 50 years (1969–2018) of daily meteorological data from 13 meteorological stations in the province, this study established a climate suitability assessment model for oilseed rape cultivation. Temperature, precipitation, and sunlight were comprehensively analyzed, with suitable zones delineated through GIS spatial analysis and the natural break method. With the incorporation of SSP2-4.5 climatic scenario simulation data, the study projected the evolving trends of oilseed rape cultivation climatic suitability zones from 2024 to 2050 in the province. The findings reveal that over the past five decades, the climatic suitability for oilseed rape planting in the province has demonstrated the following patterns: temperature suitability increased by 0.02 per decade, precipitation suitability declined by −0.01 per decade, sunlight suitability decreased by −0.01 per decade, and comprehensive suitability rose by 0.01 per decade. High climatic suitability with the index of 0.80–1.00 was predominantly clustered in the central region, while moderate suitability zones with the index of 0.50–0.80 were mainly found in its northern and southern regions. Unsuitable zones with the index of 0.00–0.50 were mainly confined to the northern and southern extremities of the province. Under future climate scenarios, oilseed rape planting suitability is projected to improve significantly, with highly suitable zones expanding, particularly into the central and parts of the northern Jiangsu. Moderately suitable zones also will be extended, including potential areas such as the parts of Lianyungang and Wuxi. Unsuitable zones will be reduced, with only limited areas like southern Wuxi retaining lower suitability. Future temperature increases in Lianyungang are expected to be in favor of oilseed rape production. However, excessive precipitation in the southern region will require enhanced drainage measures. Improved temperature and precipitation conditions in Xuzhou are anticipated to boost the climatic suitability. Overall, oilseed rape planting climatic factors in the central and northern regions are projected to improve, enabling production expansion, while the southern region will face the challenge of excessive precipitation in Jiangsu Province.

Keywords: climate change; *Brassica napus* L.; suitability index

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1. Introduction

In recent years, the continuous improvement of living standards in China has driven a rapid growth in the demand for vegetable oils [1]. As one of China's major oilseed crops, edible oilseed rape (*Brassica napus* L.) plays a pivotal role in safeguarding national food and oil security, with a cultivation area of 13.5 million hectares and an annual oil output of 4.5 to 5 million tons [2]. Among China's major production regions, Jiangsu Province—located in the middle and lower reaches of the Yangtze River—stands out as a core oilseed rape producer, accounting for approximately 9% of the national cultivation area while contributing 13% of the total national output, and its annual yield consistently ranks among the top four nationwide [3,4].

The IPCC AR6 indicates that the global average temperature has risen by approximately 1 °C compared to that before the Industrial Revolution and is projected to increase by 1.5 °C or more in the coming 20 years [5]. Shifts in temperature, precipitation, and solar radiation have modified agricultural climate resources, in turn affecting crop distribution, cropping systems, planting structures, and suitability, while triggering cascading effects on yield and quality [6–8]. Under the background of climate change, the agro-climatic resources, such as temperature, precipitation, and solar radiation, have largely changed in Jiangsu Province [8]. Consequently, in the context of global climate change, widespread attention has been paid to the regional climatic resource, climatic suitability, and the future trends for oilseed rape planting [9].

Previous studies investigated the climatic suitability for oilseed rape using some methods, including the fuzzy mathematics method, the weighted index method, the spatial analysis method, and the cluster analysis method in some provinces of China [10,11]. For instance, the fuzzy mathematics method was employed to construct the climatic suitability model for oilseed rape at different growth stages, considering the physiological characteristics of oilseed rape in Anhui Province [12]. The precipitation suitability model was established for the oilseed rape flowering period and analyzed its changing trend, based on the physiological water-demand characteristics in Zhejiang Province [13]. The climate suitability model was used to estimate the suitability index of oilseed rape and explored how oilseed rape production responded to climate change in Sichuan Province [14]. Internationally, MaxEnt has been applied to project habitat suitability for Chilgoza pine under future climates [15] and adapted to predict 2050 cocoa climatic suitability by Läderach et al. [16], while Alsafadi et al. [17] used AHP-based weighted indices to assess wheat suitability in Southern Syria. Yebeyen et al. [18] also utilized SDM to identify suitable habitats for Ethiopian highland bamboo. However, three critical gaps exist: (1) Regional gap: Jiangsu lacks systematic suitability research, with existing studies only addressing meteorological disasters or nitrogen impacts on yield [3,19,20]; (2) Temporal gap: Domestic studies rely on static models, lacking decadal-scale dynamic analysis under warming; (3) Future gap: Few studies combine historical trends with climate scenarios (SSP2-4.5) to predict suitability, a key oversight for Jiangsu's long-term planting planning.

To fill these gaps, this study used daily meteorological data (1969–2018) from 13 major meteorological stations in Jiangsu Province, combined with linear trend analysis and the Mann–Kendall test, to quantify temporal trends in key climatic factors (temperature, precipitation, sunlight) affecting oilseed rape. We then constructed suitability functions for these factors and a comprehensive suitability model, integrating multi-site data and topographic factors at 10-year intervals. Using the Inverse Distance Weighting (IDW) method in ArcGIS, we clarified the spatial distribution and temporal evolution of oilseed rape climatic suitability across Jiangsu. To address future trends, we adopted model data under the SSP2-4.5 scenario (given the milder land use and aerosol pathways under the

SSP2-4.5 scenario—core to DAMIP and DCPP [8]—this study used this model data) to predict spatiotemporal changes in suitability.

2. Data and Methods

2.1. Overview of the Study Area

Jiangsu Province is located in the lower reaches of the Yangtze River, Eastern China (latitude 30°45′ N to 35°20′ N; longitude 116°18′ E to 121°57′ E). It covers a total area of approximately 107,200 km^2 and is characterized by a temperate continental macrobioclimate of the steppe variant [21]. The average annual temperature ranges from 13 °C to 16 °C, and the average annual precipitation is between 800 mm and 1200 mm in the province.

2.2. Data Source

(1) Surface meteorological data: The National Climate Center of China provides the daily surface climatic data, including the mean temperature, sunlight hours, and precipitation from 1969 to 2018 in Jiangsu Province (Figure 1). For data quality control, linear interpolation was used to fill missing data with durations ≤ 3 days; for missing data exceeding 3 days, values were replaced with the mean from neighboring observation stations (selected by geographical proximity and similar observational conditions). The reliability of these filling methods was validated via cross-validation.

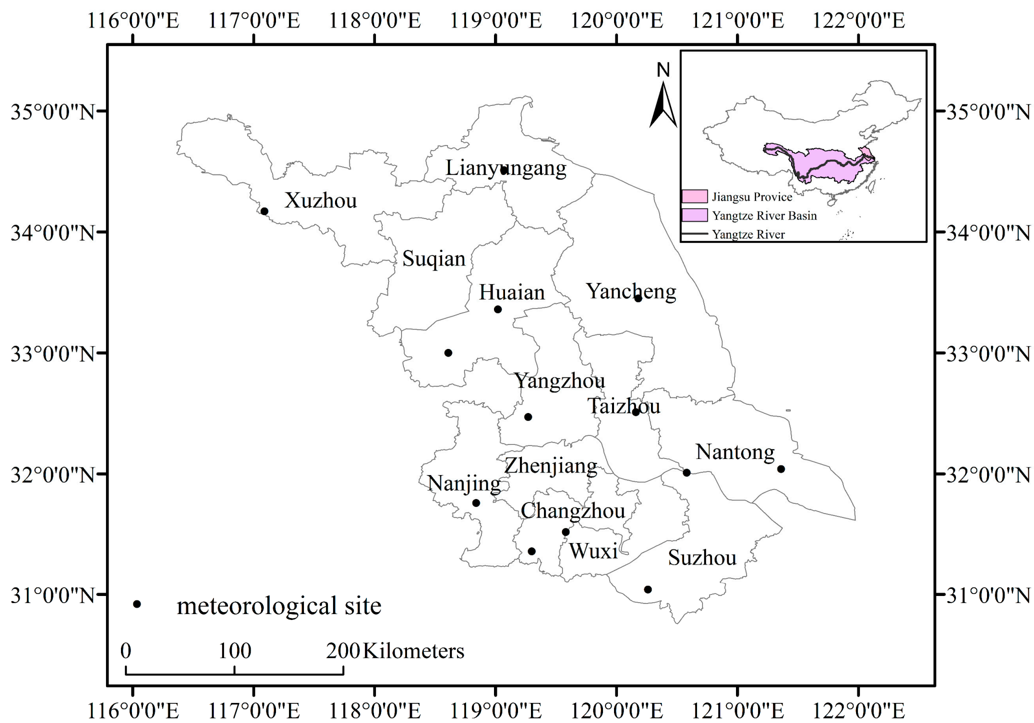

Figure 1. Spatial distribution of meteorological stations in Jiangsu Province.

(2) Future climate scenario data: The future scenario meteorological data from 2024 to 2050 in the province are from the simulated meteorological data (temperature and precipitation) under the SSP2-4.5 scenario in the CMIP6 scenario. The data were downloaded from https://aims2.llnl.gov/search/cmip6/ (accessed on 15 June 2024).

(3) DEM data: The digital elevation model data (30 m × 30 m) for the province were collected from https://www.gscloud.cn/.

(4) The 1:250,000 administrative region vector map of the province includes the provincial boundary and the boundaries of 13 cities and counties. The data were collected from https://www.resdc.cn/.

2.3. Methodology

2.3.1. Framework Flowchart

To enhance the clarity of the overall framework and technical workflow of this study and to facilitate readers' intuitive understanding of the logical connections between successive steps as well as their respective input–output relationships, a technical flowchart has been included (Figure 2).

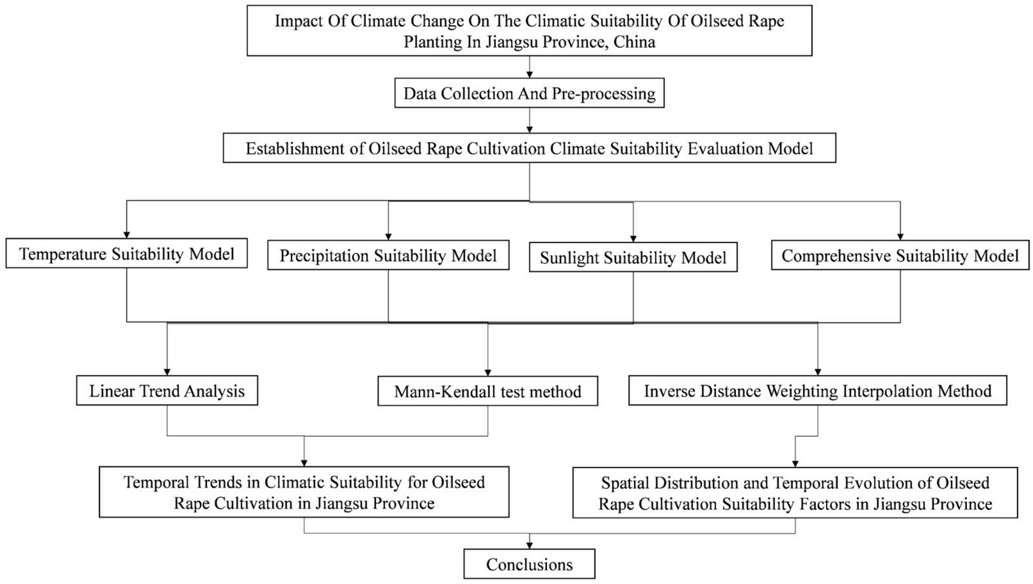

Figure 2. Flowchart of the technical route of this study.

2.3.2. Univariate Linear Trend Analysis

A statistical method was used to analyze time-series data (data gaps caused by non-human factors such as equipment failure are handled by meteorological data interpolation [22]). In this method, time was taken as the independent variable and meteorological elements as the dependent variable. A simple linear regression equation was established to describe the changing trend of meteorological elements over time [23].

Univariate regression can directly and clearly reflect the independent temporal changes in a single variable, and its results are more intuitive—the regression slope directly indicates the trend rate, making it easier to understand and interpret the evolution patterns of different climate factors.

2.3.3. Anomaly Analysis

This method was used to calculate the difference between meteorological data over a specific period and its long-term average.

2.3.4. Mann–Kendall Test Method (M–K Test)

The M–K test method is a non-parametric statistical method for detecting the trend and mutation in time-series data. In this study, the method was applied to conduct a time-series analysis of the meteorological data in Jiangsu Province to reveal the trend and mutation characteristics of each meteorological element in the province [24,25].

Furthermore, this method employs both forward and inverse statistics ($UB_k = -UF_k$) to identify trends and abrupt change points in climatic variables [26].

2.3.5. Inverse Distance Weighting Interpolation Method

The Inverse Distance Weighting (IDW) interpolation method is a commonly used spatial interpolation approach for estimating the value of an unknown point. It relies on the distance relationship between the values of known points and the unknown point. This method determines the output raster value by applying inverse distance weighting to the sample points. The farther an input point is from the output raster, the less influence it has on the output raster. Points closer in space tend to have more similar attributes [27].

IDW was selected for meteorological interpolation for three core reasons: no predefined data distribution (avoiding biases with the study area's topography-driven non-stationary temperature/precipitation), alignment with macro-scale crop climate suitability analysis, and easily interpretable outputs integrable with regional agricultural planning.

2.3.6. Spatial Modeling of Meteorological Data

Research indicates that climate is closely associated with geographical factors (such as longitude, latitude, altitude, aspect, and slope) [28]. Therefore, this study uses the multiple linear regression method to build a spatial analysis model. The model incorporates geographical factors and is based on the daily meteorological data of temperature, precipitation, sunlight, etc., in Jiangsu Province over the past 50 years (1969–2018) and in the future (2024–2050) under the SSP2-4.5 scenario. This study uses the 'Raster Calculator' tool in ArcGIS to input the regression equation with calibration coefficients obtained from fitting meteorological station data into the tool. Its form is expressed as follows:

$$Y = f(\phi, \lambda, h, \beta, \theta) + e \tag{1}$$

where in the formula, Y is the climate zoning factor, ϕ is the latitude (°), λ is the longitude (°), h is the altitude (m), β is the aspect (°), θ is the slope (°), and other geographical factors. e is the residual, known as the geographical residual.

2.3.7. Climate Suitability Model

(1) Temperature suitability model

Air temperature is a key factor that affects the growth, development, and yield formation of oilseed rape [29]. As winter oilseed rape has temperature requirements during the growth periods, a non-linear beta function is adopted in the temperature suitability model to match the three cardinal temperatures of each growth period [30]. The temperature suitability model is expressed as follows [31,32]:

$$S_t = \frac{(t - t_1)(t_2 - t)^b}{(t_0 - t_1)(t_2 - t_0)^b} \tag{2}$$

$$b = \frac{t_2 - t_0}{t_0 - t_1} \tag{3}$$

where S_t represents the temperature suitability of oilseed rape, t is the actual temperature (°C) during the growth period, and t_0, t_1, and t_2 denote the optimum, lower-limit, and upper-limit temperatures (°C) for oilseed rape growth, respectively (Table 1).

Table 1. Reproductive period of oilseed rape in Jiangsu Province: three base points of temperature division.

Growth Stage	Period	Three Base Point Temperature T (°C)		
		t_0	t_1	t_2
Seedling	September 15–November 30	15	12	25
Overwintering	December 1–February 15	2	−3	8
Bud and shoot	February 16–March 15	8	1	10
Flowering	March 16–April 30	16	10	20
Maturity	May 1–May 31	20	15	24

(2) Sunlight suitability model

Oilseed rape is a long-day crop, and light directly affects its photosynthetic efficiency. Sunlight significantly impacted oilseed rape growth and yield [17,33]. In this paper, the sunlight suitability model is divided using an exponential function with the natural number e as the base. The model is described as follows [32]:

$$S_S = \begin{cases} e^{-(S_0 - S)/b} & S_0 > S \\ e^{-(S - S_0)/b} & S_0 \leq S \end{cases} \tag{4}$$

where in the formula, S_s represents the light suitability for oilseed rape, S is the actual sunshine hours, S_0 is the possible sunshine hours when the sunshine percentage is 60%, b is an empirical constant (fitted through crop growth data), and in this study, b is set to 5.1. The model is expressed as follows:

$$\sin\frac{a}{2} = \sqrt{\frac{\sin\left(45^\circ - \frac{\Phi - \delta - \gamma}{2}\right)\sin\left(45^\circ + \frac{\Phi - \delta - \gamma}{2}\right)}{\cos\Phi \times \cos\delta}} \tag{5}$$

$$S_0 = \frac{2a}{15} \times 60\% \tag{6}$$

where in the formula, Φ denotes the latitude of the corresponding region in Jiangsu Province, δ is the declination, γ is the astronomical refraction, and a is the hour angle.

(3) Precipitation suitability model

Precipitation is an important climatic factor influencing oilseed rape growth and yield [34,35]. The precipitation suitability model for oilseed rape is as follows [32]:

$$S_r = \begin{cases} R/R_0 & R_0 > R \\ R_0/R & R_0 \leq R \end{cases} \tag{7}$$

where in this formula, S_r represents the precipitation suitability for oilseed rape, while R denotes the actual precipitation. Based on previous research findings and the actual production conditions of oilseed rape in Jiangsu, the physiological water requirement R_0 during the oilseed rape growing period in Jiangsu is determined to be 400 mm.

(4) Comprehensive climate suitability model

The geometric mean method was employed to develop the comprehensive climate suitability model for oilseed rape [32]:

$$S = \sqrt[3]{S_t \times S_s \times S_r} \tag{8}$$

where in this formula, S stands for the comprehensive suitability for oilseed rape, and S_t, S_s, and S_r represent the temperature, sunshine, and precipitation suitability for oilseed rape, respectively.

To validate the suitability models, this study leveraged historical rapeseed yield and climate data in Jiangsu spanning from 1969 to 2018. By establishing correlations between the model-calculated historical suitability values and the corresponding historical yields, a significant positive correlation was confirmed, which demonstrates that the models can effectively capture the actual cultivation suitability of rapeseed in this region.

3. Results

3.1. Spatiotemporal Variability of Climatic Suitability for Oilseed Rape in Jiangsu During the Past Five Decades

3.1.1. Temperature Suitability

Figure 3a indicated that, from 1969 to 2018, the temperature suitability for oilseed rape during the growing periods in Jiangsu Province consistently ranged from 0.60 to 1.00. The minimum temperature suitability of 0.61 was observed in 1980, whereas the peak of 0.96 occurred in 2017. A clear upward trend in temperature suitability was identified over the study period, with a climate tendency rate of 0.02 per decade.

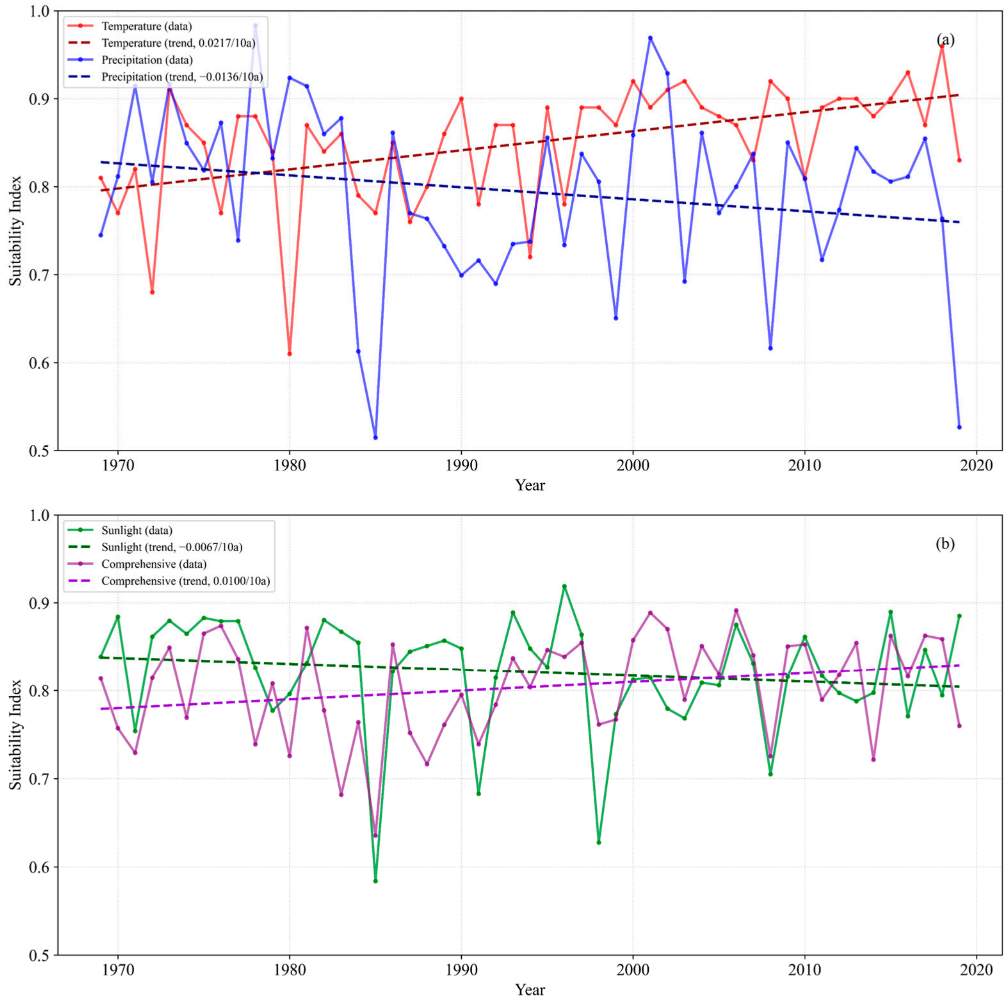

Figure 3. Temporal change in average suitability index for oilseed rape in Jiangsu Province: (**a**) temperature and precipitation suitability; (**b**) sunlight and comprehensive suitability.

The Mann–Kendall (M-K) test was applied to analyze the trends of temperature suitability for oilseed rape across the entire growing period over the past 50 years (Figure 4a). The results revealed that the UF curve of temperature suitability remained consistently above zero since 1998, indicating a sustained upward trend from 1998 to 2018. In 2008, the UF curve exceeded the upper confidence boundary, demonstrating a significant increase in temperature suitability after 2008. Furthermore, the intersection of the UF and UB curves occurred in 1998 within the confidence interval, suggesting an abrupt shift in temperature suitability during the year. This transition marked the beginning of a significant rise in thermal suitability for oilseed rape cultivation in Jiangsu Province.

Figure 4. Mann–Kendall test for suitability index for oilseed rape during the reproductive period in Jiangsu Province (the red curve represents the UF curve, and the blue curve represents the UB curve.): (**a**) temperature suitability; (**b**) precipitation suitability; (**c**) sunlight suitability; (**d**) comprehensive suitability.

Using a linear regression model incorporating meteorological and geographical factors from corresponding years, provincial temperature distribution data were generated through computational modeling. Based on the oilseed rape growth suitability model requirements, temperature suitability distributions for oilseed rape were observed across five decades: 1969–1978, 1979–1988, 1989–1998, 1999–2008, and 2009–2018.

The analysis indicated that the overall temperature suitability for oilseed rape across the province exhibited a gradual increasing trend over the study period, with a distinct spatial pattern of "higher suitability in the central region and lower suitability in the northern and southern regions" (Figure 5). Against the backdrop of climate warming, the core long-term trend was the northward expansion of the optimal suitability zone (>0.80), which was originally concentrated in the central region (e.g., Nanjing, Nantong, Taizhou, Yangzhou, and Huai'an). This expansion persisted for most of the study period, except for a notable phase shift during 2009–2018: compared with the 1999–2008 period, the temperature suitability across the province decreased significantly, and the area of the high-suitability zone (>0.80) was substantially reduced. Nevertheless, the central core region still maintained a relatively high level of temperature suitability.

In terms of spatial variations, the central region consistently remained the high-suitability hotspot for oilseed rape (with suitability > 0.80 in most periods), whereas Lianyungang and Suzhou showed prominent characteristics of suitability instability and low overall values. Specifically, the suitability in Lianyungang and Suzhou was generally <0.40 during 1969–1978; although it improved to approximately 0.60 in 1989–1998 and entered the range of 0.40–0.80 in 1999–2008 (driven by the overall increase in provincial suitability), their suitability levels remained consistently lower than that of the central region and never formed a stable high-suitability state.

The 50-year average temperature suitability (Figure 5f) further confirmed that Huai'an, Yancheng, Yangzhou, Taizhou, Nanjing, and Nantong exhibited the most stable suitability (with >0.80 in most periods and areas), representing the ideal thermal conditions for oilseed rape cultivation. In contrast, Lianyungang and Suzhou displayed large fluctuations in suitability and generally low values, highlighting the need for adaptive agricultural practices to mitigate potential reductions in oilseed rape yield and quality caused by temperature stress.

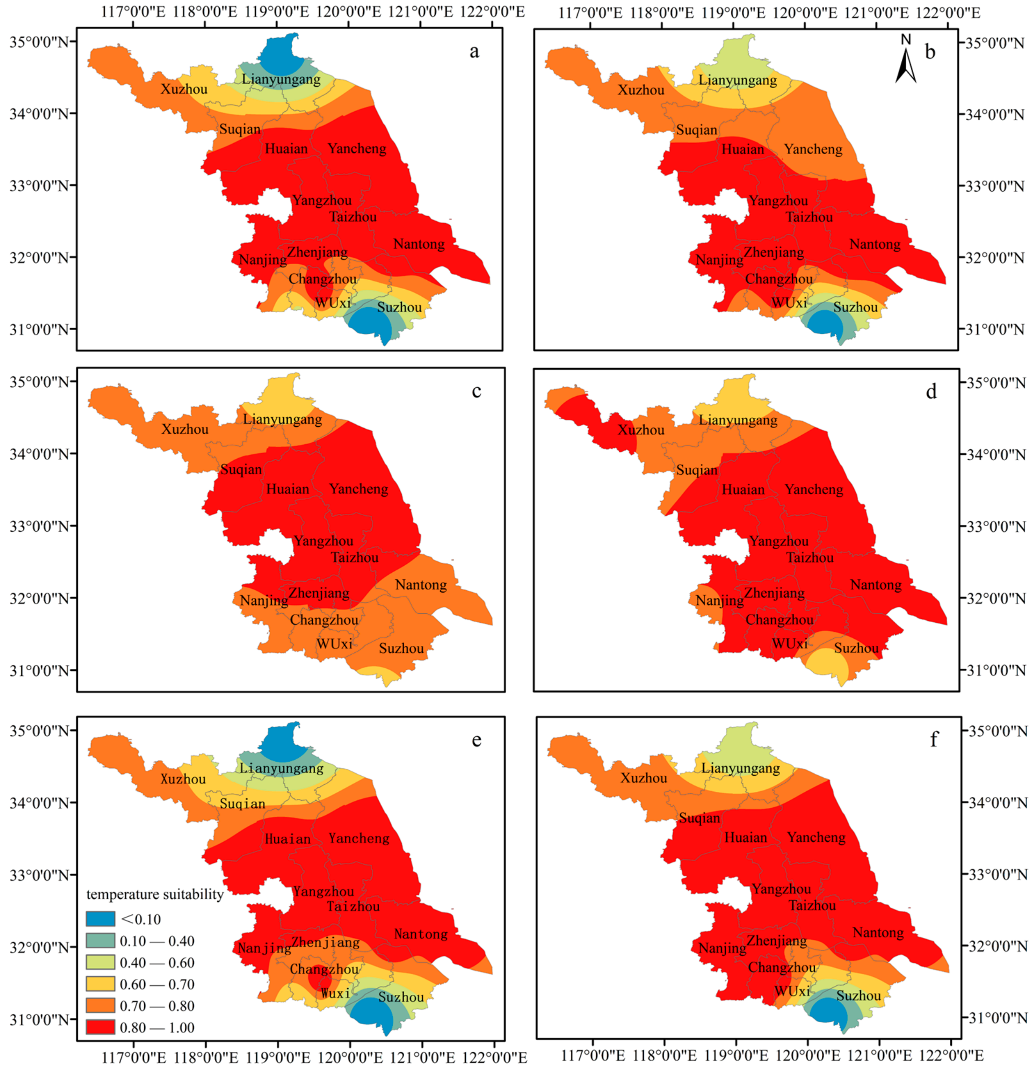

Figure 5. Distribution of temperature suitability for oilseed rape in Jiangsu Province: (**a**) 1969–1978; (**b**) 1979–1988; (**c**) 1989–1998; (**d**) 1999–2008; (**e**) 2009–2018; (**f**) 1969–2018.

3.1.2. Precipitation Suitability

Over the 50-year study period (1969–2018), the precipitation suitability index for oilseed rape across its entire growth period ranged from 0.50 to 1.00 in Jiangsu Province (Figure 3b). Temporal analysis indicated a statistically significant decreasing trend with a climate tendency rate of −0.01 per decade: the provincial average precipitation suitability reached a maximum of 0.98 in 1978 and a minimum of 0.51 in 1985.

M–K trend test results further confirmed this declining pattern (Figure 4b): the UF remained consistently negative from 1984 to 2018, reflecting a persistent downward trend in precipitation suitability during this period; in some years, the UF values exceeded the critical confidence thresholds, verifying the statistical significance of the decline at those intervals. Additionally, the intersection of the UF and UB curves occurred in 1982 within the confidence boundaries, identifying 1982 as a significant abrupt change point for precipitation suitability.

Over the 1969–2018 study period, spatial heterogeneity in precipitation suitability outweighed temporal variations, and the spatial pattern remained dominated by a radial distribution—suitability decreased from the central belt toward the northern and southern peripheries, with distinct differences in stability across regions (Figure 6). The central belt (Huai'an–Yancheng–Taizhou–Yangzhou) maintained stably high precipitation suitability (>0.80 in 82% of the study years) throughout the period: it served as the core high-suitability zone even in the initial decade (1969–1978), expanded slightly to incorporate Taizhou in 1979–1988, and remained the persistent optimal region in the 50-year average (Figure 6f). In contrast, the northern regions (Xuzhou–Lianyungang–Suqian) exhibited high interannual variability—though their suitability improved statistically (e.g., the Xuzhou–Lianyungang agricultural zone saw a substantial expansion of high-suitability areas (0.80–0.90) in 1999–2008), they still had the lowest mean suitability (0.50–0.65) and largest fluctuations among all regions. The southern regions (Suzhou–Changzhou) maintained relatively low suitability (0.40–0.70) with mild variability, while the eastern transition zone (Changzhou–Wuxi–Taizhou–Nantong) showed stable intermediate suitability (0.60–0.80) consistently. Across the study period, approximately 65% of Jiangsu's oilseed rape cultivation area experienced statistically significant improvements in precipitation suitability. Given the spatial differences in suitability and stability, site-specific water management strategies are recommended: northern regions (with low mean suitability and high variability) should prioritize irrigation to mitigate water scarcity risks, while southern regions (with persistent low suitability and potential waterlogging in local areas) would benefit from enhanced drainage measures.

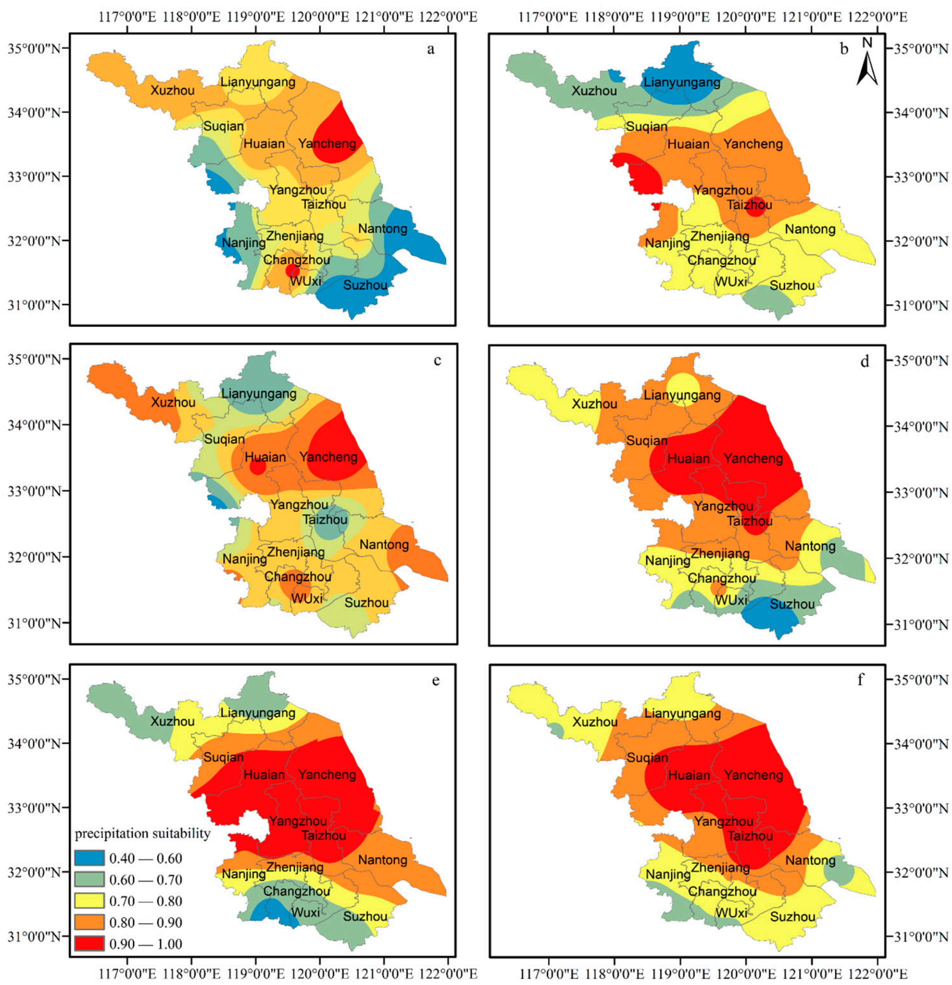

Figure 6. Distribution of precipitation suitability for oilseed rape in Jiangsu Province: (**a**) 1969–1978; (**b**) 1979–1988; (**c**) 1989–1998; (**d**) 1999–2008; (**e**) 2009–2018; (**f**) 1969–2018.

3.1.3. Sunlight Suitability

The results indicated that sunlight suitability for oilseed rape varied between 0.50 and 1.00 over the past 50 years (Figure 3b). A statistically significant decreasing trend ($p < 0.05$) was identified, with the climate tendency rate of −0.01 per decade. The analysis revealed that 1985 marked the least favorable year for solar radiation conditions, with sunlight suitability being 0.58, while 1996 exhibited optimal sunlight conditions for oilseed rape growth, with sunlight suitability being 0.92.

The results demonstrate that UF statistics maintained consistently negative values since 1979, revealing a persistent decline in sunlight suitability through 2018 (Figure 4c). However, the absence of UF values exceeding the critical confidence thresholds indicated that the decreasing trend did not reach statistical significance. Notably, the intersection point between UF and UB curves occurred in 1983 within the confidence boundaries, marking a significant transition point in the sunlight suitability regime for oilseed rape cultivation.

Across the 1969–2018 study period, sunlight suitability for oilseed rape in Jiangsu Province was characterized by a persistent and decisive north–south gradient—suitability was consistently higher in the central and southern regions than in the northern region, and this gradient remained the key factor shaping oilseed rape growth conditions (Figure 7). Spatially, the southwest and central regions (e.g., Yangzhou, Taizhou, Nanjing, Changzhou) maintained relatively high solar radiation suitability: Yangzhou and Taizhou, in particular, exhibited both high suitability (mostly >0.75, with occasional peaks > 0.85) and strong stability throughout the 50 years, making them the most suitable areas for oilseed rape cultivation in terms of solar conditions. In contrast, the northern region (primarily Lianyungang and parts of Xuzhou and Suqian) consistently had the lowest suitability (often <0.50) and greater variability, with only minor interdecadal fluctuations (e.g., a temporary decline in Lianyungang during 1979–1988 and widespread low values < 0.50 in 1999–2008). While interdecadal changes in suitability were observed (e.g., a brief expansion of high-suitability areas > 0.85 in 1979–1988 and 2009–2018, and a temporary decline in 1989–2008), these temporal variations did not alter the fundamental north–south gradient. The 50-year average (Figure 7f) further confirmed this pattern: most regions had a suitability index above 0.75, except for parts of Lianyungang and Xuzhou, where the index remained below 0.50.

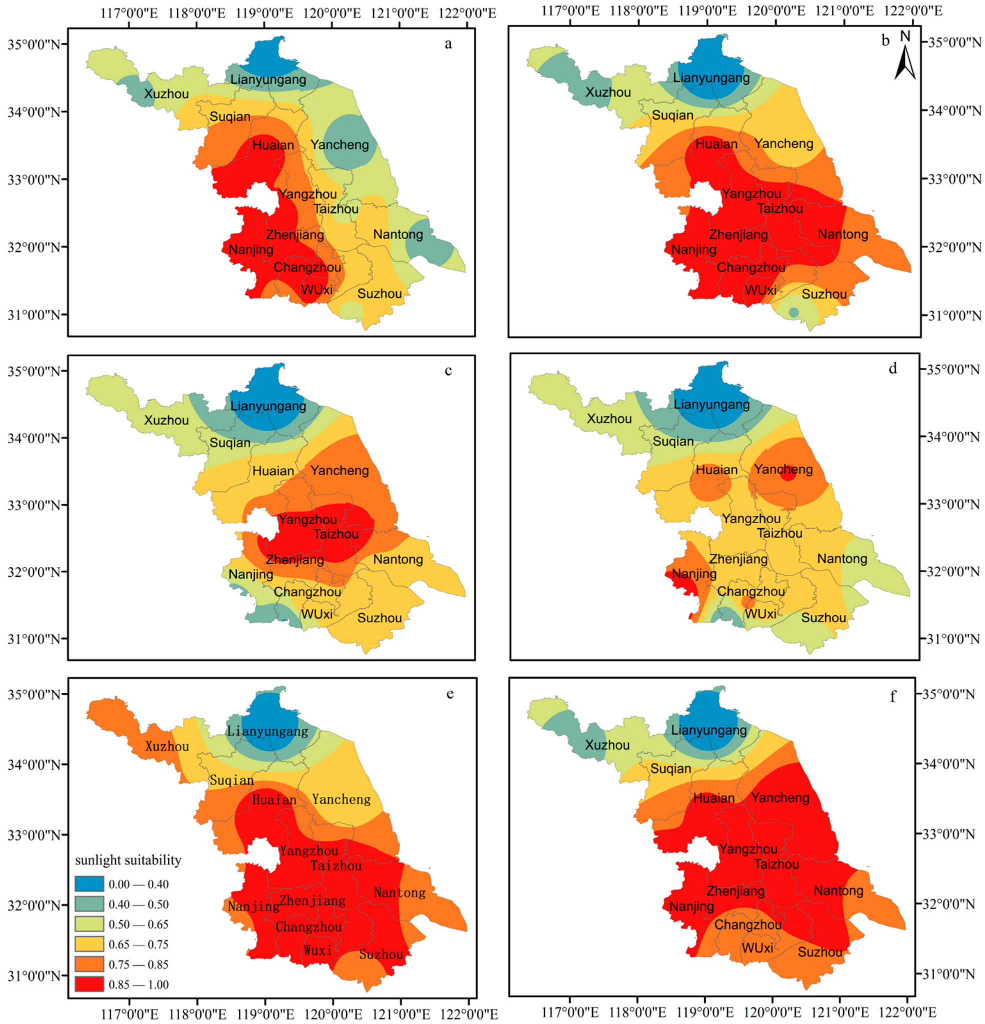

Figure 7. Distribution of sunlight suitability for oilseed rape in Jiangsu Province: (**a**) 1969–1978; (**b**) 1979–1988; (**c**) 1989–1998; (**d**) 1999–2008; (**e**) 2009–2018; (**f**) 1969–2018.

3.1.4. Comprehensive Suitability

Based on the suitability analysis of temperature, precipitation, and sunlight during the oilseed rape growth period in Jiangsu Province over the past 50 years, spatiotemporal patterns of comprehensive suitability were derived through computational modeling and spatial interpolation. The results showed that the comprehensive suitability index for oilseed rape ranged between 0.60 and 0.90 during the study period, with the lowest value of 0.64 occurring in 1985 and the highest value of 0.89 in 2006. A gradual increasing trend in comprehensive suitability was found across Jiangsu Province, with the climate tendency rate of 0.01 per decade (Figure 3b).

The M–K trend test was used to analyze the comprehensive suitability for oilseed rape over the past 50 years (1969–2018). The analysis revealed that the UF statistics have maintained consistently positive values since 1995, indicating the persistent upward trend in comprehensive suitability through 2018. Notably, the intersection point between UF and UB curves occurred in 1995 within the confidence boundaries, marking the statistically significant ($p < 0.05$) transition in the comprehensive suitability regime for oilseed rape cultivation during the critical year (Figure 4d).

The comprehensive climatic suitability for oilseed rape was evaluated using the geometric mean method, based on the temperature, precipitation, and sunlight suitability distribution across six study periods (1969–1978, 1979–1988, 1989–1998, 1999–2008, 2009–2018, and 1969–2018).

Over the 1969–2018 study period, the comprehensive suitability for oilseed rape in Jiangsu Province exhibited a persistently stable spatial pattern, with high suitability concentrated in the central belt—this belt (encompassing Yangzhou, Taizhou, and parts of Nanjing, Nantong, and Huai'an) served as the consistent core production zone for oilseed rape, while northern regions (e.g., Lianyungang) and parts of Suzhou maintained relatively low suitability. The central belt, particularly Yangzhou and Taizhou, demonstrated exceptional stability in comprehensive suitability: these two regions maintained a suitability index above 0.85 for the entire 50 years, and the broader central belt (including Nanjing, Yancheng, and parts of Huai'an and Nantong) consistently achieved suitability ≥ 0.75. Although inter-decadal improvements in suitability were observed (e.g., gradual expansion of areas with suitability > 0.75 from 1979 to 2008 and further growth of high-suitability areas > 0.85 in 2009–2018), these changes did not alter the central belt's dominant role as the core production zone. In contrast, non-core regions showed distinct characteristics: Lianyungang and its surrounding areas had the lowest comprehensive suitability (often <0.50 and even declining to <0.40 in 2009–2018) with significant interannual fluctuations, making them unsuitable for large-scale oilseed rape planting from a climatic perspective. Parts of Suzhou also maintained low suitability, while the 50-year average (Figure 8f) confirmed that most regions outside Lianyungang and parts of Suzhou had suitability ≥ 0.50, further highlighting the central belt's superiority.

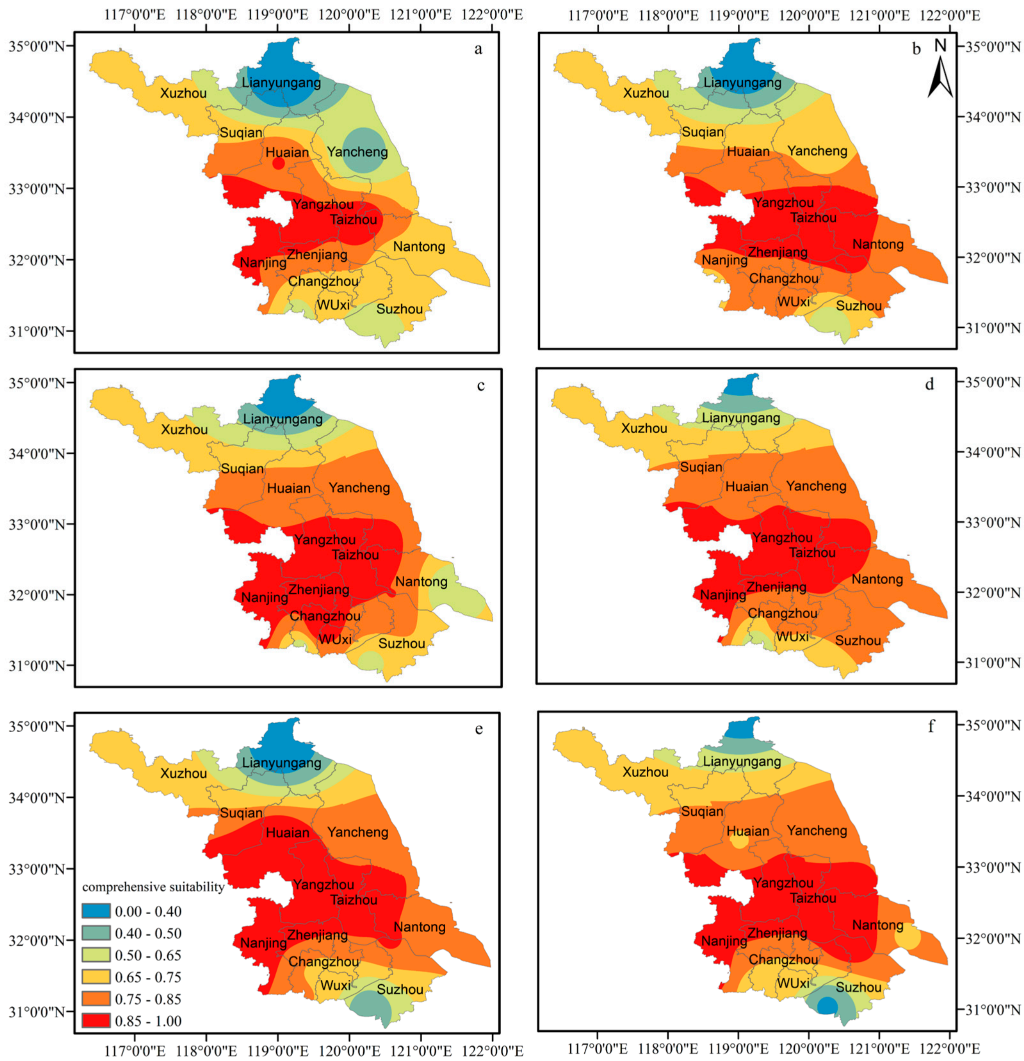

Figure 8. Distribution of comprehensive suitability for oilseed rape in Jiangsu Province: (**a**) 1969–1978; (**b**) 1979–1988; (**c**) 1989–1998; (**d**) 1999–2008; (**e**) 2009–2018; (**f**) 1969–2018.

3.2. Projected Changes in Climatic Suitability for Oilseed Rape Planting Under Climate Scenarios in Jiangsu Province

3.2.1. Climate Suitability Projection for Oilseed Rape Under Future Climate Conditions

A comparison of the temperature suitability anomaly characteristics between Figure 9a (1969–2018) and Figure 9b (2024–2050) reveals that under the current climatic conditions, the temperature suitability anomaly values primarily fluctuate within the range of −0.20 to 0.10. Despite the occurrence of phased alternations between positive and negative anomalies, the overall variation amplitude remains relatively moderate. In the future projection period, however, the fluctuation range of temperature suitability anomalies can extend to approximately −0.30. Although the intensity of negative anomalies increases, the frequency of their occurrence shows a decreasing trend. This discrepancy indicates that the magnitude of changes in temperature suitability will increase in the future, with a corresponding increase in climate variability. Meanwhile, the direction of change tends to incline toward temperature conditions conducive to oilseed rape growth; that is, the tendency of negative deviations (i.e., reduced suitability) is mitigated.

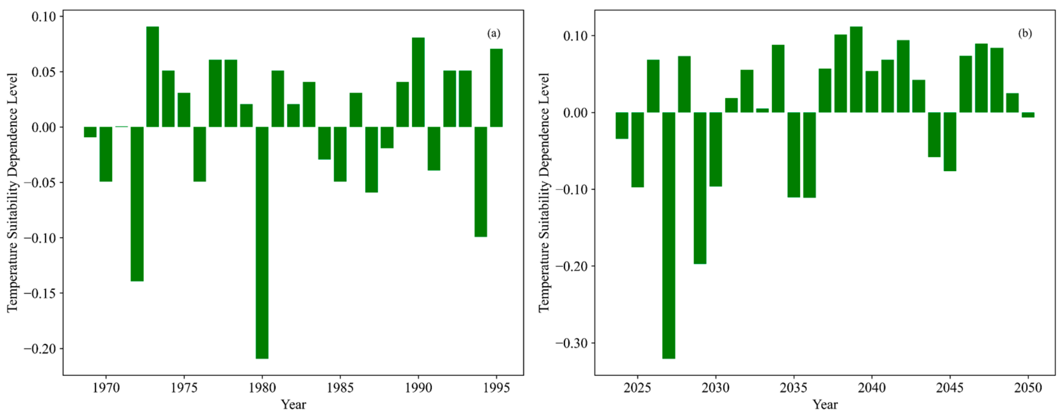

Figure 9. Anomaly of temperature suitability for oilseed rape in Jiangsu: (**a**) last 50 years; (**b**) SSP2 4.5 scenario.

Based on the climatic and geographical factors in Jiangsu Province, the regression model was established and integrated with the spatial analysis module of ArcGIS to compute a single meteorological raster map. Subsequently, the suitability spatial distribution was generated using the climate evaluation mode for oilseed rape.

Regarding the temperature suitability for oilseed rape, the results indicate that over the past 50 years (Figure 10a), the temperature suitability generally exhibited the spatial pattern of higher values in the southwestern region and lower values in the northeastern region. The most suitable zones for oilseed rape growth, with the temperature suitability exceeding 0.90 during the entire growth period, were primarily concentrated in Zhenjiang, Nanjing, and parts of Wuxi in southwestern Jiangsu. Moderately suitable zones, with the suitability being above 0.80, included Yangzhou, Nantong, Taizhou, and their surrounding areas. In contrast, the lowest suitability was observed in Lianyungang and parts of Suzhou, with the values being around 0.40. Under future climate scenarios (Figure 10b), the temperature suitability for oilseed rape will continue to follow the spatial distribution characterized by higher suitability in southwestern Jiangsu. However, compared to the past 50 years, the zones with the suitability exceeding 0.90 will expand significantly. Notably, the zones such as Taizhou, Nantong, and parts of Yangzhou will experience the increase in temperature suitability to above 0.90. Concurrently, due to the relatively substantial rise in temperature, the suitability in Lianyungang will improve from 0.40 to 0.80–0.90.

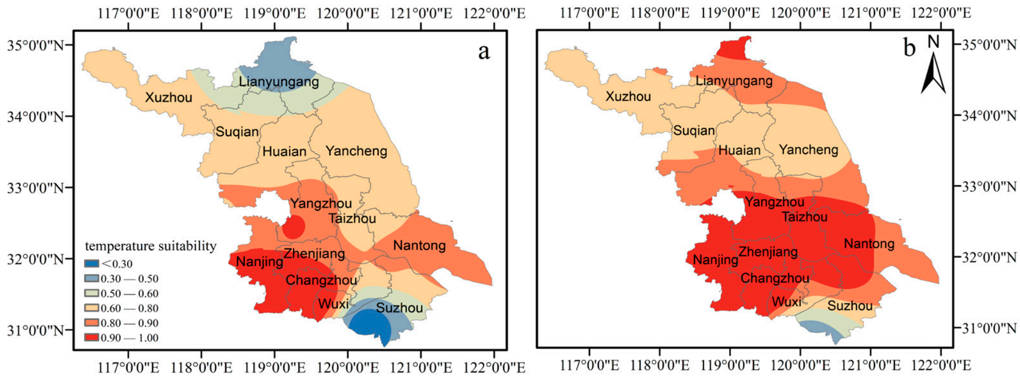

Figure 10. Spatial distribution of temperature suitability for oilseed rape in Jiangsu: (**a**) last 50 years; (**b**) SSP2 4.5 scenario.

A comparison of the precipitation suitability anomalies in Figure 11a (1969–2018) and Figure 11b (2024–2050) indicates that under the current climate conditions (Figure 11a), the precipitation suitability anomaly fluctuates within a narrow range of approximately −0.10 to 0.08. There is no evident long-term unidirectional trend, with only alternating positive and negative anomalies observed. In contrast, during the future projection period (Figure 11b), the fluctuation range of precipitation suitability anomalies widens significantly, spanning from −0.20 to around 0.20. This suggests that the magnitude of changes in precipitation suitability will increase substantially in the future, resulting in heightened climate variability. Furthermore, although positive and negative anomalies will continue to coexist in the future, there is a tendency toward more extreme anomalies, with the potential for stronger positive deviations (i.e., higher precipitation suitability) and negative deviations (i.e., lower precipitation suitability). This reflects greater uncertainty in precipitation conditions influencing the growth of oilseed rape.

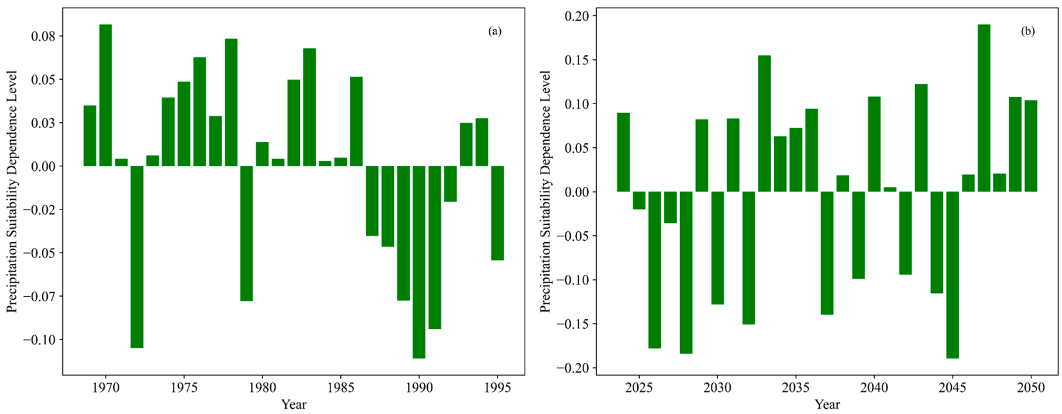

Figure 11. Anomaly of precipitation suitability for oilseed rape in Jiangsu: (**a**) last 50 years; (**b**) SSP2 4.5 scenario.

The precipitation suitability for oilseed rape demonstrated the distinct spatial distribution over the past 50 years, with higher values in the central region and lower values in peripheral areas (Figure 12a). Across the province, the precipitation suitability index ranged from 0.50 to 1.00, with the most favorable condition (the suitability > 0.90) concentrated in the zones of Suqian, Yancheng, and Huai'an. Moderately suitable zones, exhibiting values between 0.80 and 0.90, included Yangzhou and Taizhou, whereas relatively low suitability was observed in Suzhou, Changzhou, Lianyungang, and Xuzhou. Projections based on future climate data analysis (Figure 12b) indicate that the central-high, peripheral-low precipitation suitability pattern will persist, albeit with notable spatial adjustments. Compared to the historical conditions, the zones exceeding 0.90 suitability will contract and shift northward, particularly with decreasing suitability in Yancheng and improving conditions in Xuzhou. The southern region of Jiangsu will experience a marked decline, with the precipitation suitability in Suzhou, Changzhou, and parts of Wuxi plummeting to 0.10–0.50. In contrast, Yangzhou and Taizhou will maintain stable suitability levels within the 0.80–0.90 range.

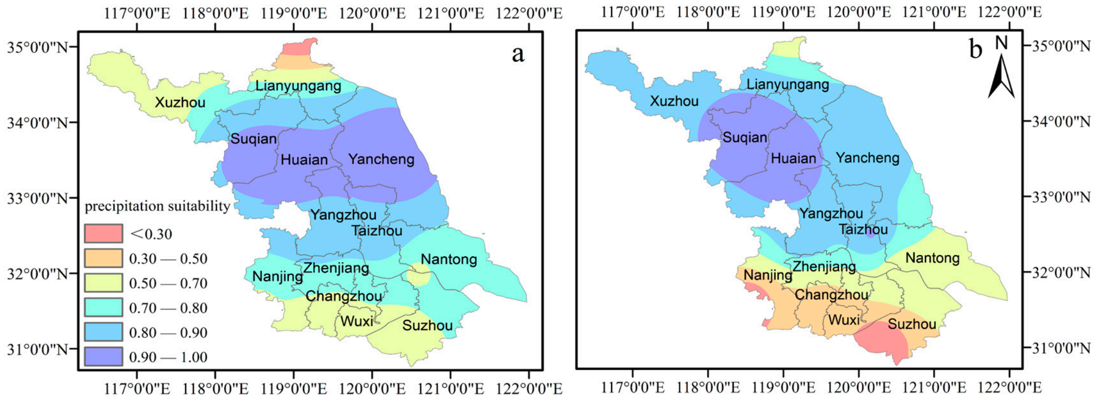

Figure 12. Spatial distribution of precipitation suitability for oilseed rape in Jiangsu: (**a**) last 50 years; (**b**) SSP2 4.5 scenario.

3.2.2. Evaluation of Future Comprehensive Suitability for Oilseed Rape in Jiangsu and the Potential Variation

A comparison of composite suitability levels between the historical period (1969–2018; Figure 13a) and the future period (2024–2050; Figure 13b) reveals that the magnitude of fluctuations in composite suitability during the future period is statistically significantly greater than that during the historical period. Specifically, positive peaks in the later stage of the future period are more pronounced, while negative extremes are more intense. This indicates that fluctuations in composite suitability driven by future climate change will be more drastic, and there is a tendency toward more extreme scenarios (either more suitable or less suitable).

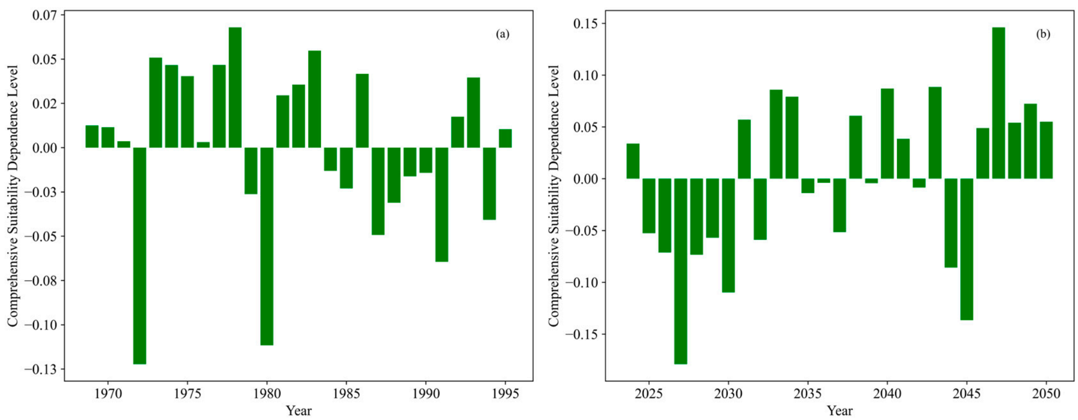

Figure 13. Anomaly of comprehensive suitability for oilseed rape in Jiangsu: (**a**) last 50 years; (**b**) SSP2 4.5 scenario.

In view of the absence of sunlight duration data in future climate datasets, the analysis of oilseed rape climate suitability zones in Jiangsu Province under the SSP2-4.5 scenario is primarily based on temperature and precipitation suitability. Via computational modeling and spatial interpolation methods, the spatiotemporal distribution patterns of comprehensive suitability were derived. Results show that the comprehensive suitability for oilseed rape cultivation in Jiangsu Province will improve significantly in the future, with a marked expansion of areas where suitability exceeds 0.90 (Figure 14). Regions such as Yancheng, Suqian, Xuzhou, and Lianyungang will exhibit increased suitability for oilseed rape cultivation. Conversely, the comprehensive suitability in regions including Changzhou, Nanjing, and Suzhou will decrease, with their suitability indices ranging from 0.50 to 0.70.

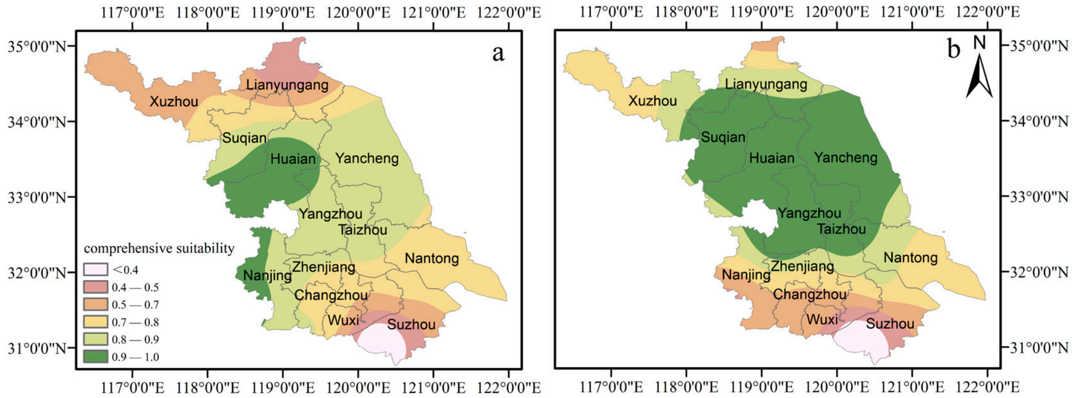

Figure 14. Spatial distribution of comprehensive suitability for oilseed rape in Jiangsu: (**a**) last 50 years; (**b**) SSP2 4.5 scenario.

4. Discussion

Over the past five decades, oilseed rape cultivation suitability in Jiangsu Province has exhibited divergent trends: temperature suitability increased at a rate of 0.02 per decade, while precipitation suitability decreased by 0.01 per decade. This pattern reflects the region's specific response to global climate change, with the upward trend in temperature suitability consistent with findings from Nordic studies, where rising temperatures have enhanced rapeseed cultivation suitability [36], while the decline in precipitation suitability may be attributed to the marked strengthening of the Northern Hemisphere summer monsoon, leading to significantly increased global monsoon precipitation intensity [37]. Notably, Lianyungang and Suzhou show marked variability in temperature suitability, underscoring the urgency of implementing frost mitigation strategies to mitigate potential yield losses. Such measures include the cultivation of cold-tolerant varieties [38], pre-frost irrigation, and lime application—all of which have been shown to reduce rapeseed's vulnerability to frost damage [39]. In terms of precipitation suitability, Huai'an, Yancheng, and Suqian maintained relatively suitable conditions for rapeseed cultivation. By contrast, precipitation suitability in parts of Lianyungang, Xuzhou, and Suzhou remained consistently below the provincial average, necessitating reliable irrigation support. Generally, precipitation suitability was low across both northern and southern Jiangsu, but for distinct reasons: in northern regions, insufficient rainfall failed to meet rapeseed's basic physiological water requirements, increasing the risk of drought stress—an observation aligned with projections of drought-induced adverse impacts on rapeseed production in southern Europe [36], highlighting the need for vigilance against drought-related reductions in rapeseed biological yield [40]; in southern regions, excessive rainfall (exceeding rapeseed's optimal physiological water demand) elevated waterlogging risks, which may cause flower and fruit abscission and subsequent yield decline [41]. This aligns with global findings: in southern Europe, spring precipitation is a critical driver of rapeseed growth, with excessive spring rainfall and high humidity significantly reducing yields [42]; similarly, in the southeastern Pampas of Argentina, the seasonal distribution of precipitation during the crop growth cycle is a key determinant of rapeseed yield [43]. The sunlight suitability of oilseed rape showed a slightly decreasing trend, with the decrease being 0.01 per decade. The sunlight suitability in the Yangzhou and Taizhou areas was relatively high and stable, while that in Lianyungang and Suzhou was relatively low, less than 0.50. For the latter regions, the selection of low-light-tolerant oilseed rape varieties is recommended to safeguard the stability of oilseed rape production [44]. Taking into account factors such as temperature, precipitation, and sunlight, the overall suitability of oilseed rape has been relatively high in the past 50 years. However, southern Jiangsu had been negatively affected by precipitation, which largely restricted the growth of oilseed rape. The northern region was mainly negatively affected by factors such as temperature and sunlight. Overall, the conditions for oilseed rape cultivation in Yangzhou, Taizhou, and their surrounding areas were relatively favorable and stable, while the climate suitability in Lianyungang and some areas of Xuzhou was relatively low and showed an unstable trend.

The uncertainty of climate change effects on oilseed rape production would increase over time [36]. In the United Kingdom, temperature variation in late autumn and early winter is associated with yield instability in oilseed rape harvests [45]. Under the future climate scenario (SSP2-4.5), during the period from 2024 to 2050, based on the temperature suitability prediction, the temperature suitability in Zhenjiang, Nanjing, and some areas of Wuxi will remain at a relatively high level (0.95). The temperature suitability will increase from 0.85 to 0.95 in Taizhou and some areas of Yangzhou and Nantong. Lianyungang will transform from the unsuitable area to the sub-suitable one. In general, temperature changes are likely to alleviate the severity of late-spring frosts in Jiangsu Province, thereby reducing the risk of cold damage to oilseed rape crops [46]. This trend is expected to exert a positive influence on oilseed rape cultivation across the province, with a particularly notable effect in the southern region. In the future, as the temperature suitability in Lianyungang increases, the suitable area for oilseed rape cultivation will be moderately expanded. From 2024 to 2050, the area of high value with precipitation suitability greater than 0.90 decreased, especially in Huai'an. The reason is that the precipitation in the area slightly increased, exceeding the optimal physiological water requirement for oilseed rape (400 mm). Meanwhile, the extent of areas with precipitation suitability below 0.50 has increased significantly, predominantly concentrated in Suzhou, Changzhou, Wuxi, and adjacent regions. In these areas, excessive precipitation will further exceed the water requirements of oilseed rape during its growth period. Moreover, elevated precipitation may trigger a cascading reduction in sunlight, thereby impairing oilseed rape photosynthesis and photomorphogenesis [47,48]. In addition, the suitability of precipitation in the Nantong and Zhenjiang areas will also slightly decline. In the face of these changes, future oilseed rape production needs to strengthen field water management, especially during the flowering period, which is the most sensitive critical stage to flooding. Efficient drainage measures must be taken to ensure that oilseed rape growth is not affected by excessive water [49]. The suitability of precipitation in Xuzhou will improve, and the precipitation conditions will be more favorable for oilseed rape cultivation. In regard to the factors of precipitation and temperature, the future temperature in the Xuzhou area will rise and the precipitation will be appropriate, which will improve the comprehensive climate suitability of oilseed rape. Based on the agricultural conditions in Xuzhou, it is suggested to moderately expand the oilseed rape planting in the future and to fully utilize the favorable aspects brought by climate change. The comprehensive climate suitability in the Suqian, Huai'an, Yangzhou, and Taizhou areas will rise above 0.90, which is suitable for further expanding oilseed rape production. However, in the southern region, due to excessive precipitation, the comprehensive climate suitability for oilseed rape cultivation will decline. Therefore, it is recommended to strengthen drainage management and to ensure the safety of oilseed rape production. Under future climate scenarios, the comprehensive suitability of oilseed rape will significantly increase in the central and northern regions of the province, which is mainly due to the increasing temperature near to the optimal growth temperature of oilseed rape and the appropriate precipitation. Therefore, Jiangsu can fully utilize the characteristics of climate change, in combination with cultivar introduction, to moderately expand the planting of oilseed rape.

Several limitations should be noted in this study: it only considered climatic and geographical factors for oilseed rape suitability zoning (excluding edaphic variables like soil types and socio-economic factors such as field management), used climate data ending in 2018 (missing recent extreme events), faced localized uncertainties from limited monitoring station density in data interpolation, and relied solely on the SSP2-4.5 scenario for future projections (failing to account for uncertainties from other pathways). Future research should integrate microclimatic variations, meteorological disaster risks, edaphic properties, and socio-economic factors into a comprehensive model and incorporate post-2018 data to update trends and explore multiple climate scenarios—ultimately providing stronger scientific support for sustainable oilseed rape production in Jiangsu.

5. Conclusions

Over the past five decades, central Jiangsu (encompassing Huai'an, Yancheng, Yangzhou, and Taizhou) has remained the most stable core region for oilseed rape cultivation, maintaining consistently high suitability (index > 0.80) with no major fluctuations. In contrast, northern and southern Jiangsu faced opposite limitations: northern areas (e.g., Lianyungang, parts of Xuzhou) were constrained by low suitability (0.00–0.50) mainly due to water deficit, while southern areas (e.g., Suzhou, parts of Wuxi) struggled with water excess, resulting in their classification as unsuitable or sub-suitable zones (0.00–0.80).

Under the SSP2-4.5 future climate scenario (2024–2050), oilseed rape climate suitability is projected to improve significantly in central and northern Jiangsu: the core suitable zone in central regions will further stabilize with comprehensive suitability > 0.90, and northern areas (e.g., Suqian, parts of Xuzhou, and potential areas in Lianyungang) will shift from sub-suitable/unsuitable to suitable/sub-suitable, expanding the overall cultivable area. However, southern Jiangsu will continue to face risks from excessive precipitation, with only localized unsuitable zones (e.g., southern Wuxi) remaining but requiring targeted measures—such as enhanced drainage infrastructure and adoption of waterlogging-tolerant varieties—to mitigate yield losses.

To ensure the sustainability of oilseed rape production in Jiangsu, future research should prioritize two directions: first, integrating soil properties (e.g., texture, water-holding capacity) and field management practices (e.g., irrigation/drainage regimes) into suitability assessments to refine zoning accuracy; second, exploring alternative climate scenarios (e.g., SSP1-1.9, SSP5-8.5) to account for uncertainties in future climate change, thereby providing more robust support for long-term agricultural planning.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available because the data are too large.

Conflicts of Interest: The authors declare no conflicts of interest.

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