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Evolution of Land Use Suitability and Adaptation Strategies of the Agro-Pastoral Transitional Zone in Northern China Under Multiple Climate Change Scenarios

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Abstract

The Agro-Pastoral Transitional Zone in northern China is a typical ecologically fragile area highly sensitive to climate change. Understanding how future climate change will affect the suitability of agricultural and pastoral land use in this region is a critical scientific issue for both climate change research and regional sustainable development. This study integrates multi-scenario climate projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6) with a land use suitability evaluation framework. Three Shared Socioeconomic Pathways (SSPs) are employed, driven by three Integrated Assessment Models (IAMs): IMAGE (SSP1-2.6, low emission), MESSAGE (SSP2-4.5, moderate emission), and REMIND-MAGPIE (SSP5-8.5, high emission). Future climate variables (annual precipitation and accumulated temperature $\geq 10^\circ\text{C}$) are statistically downscaled to 1 km resolution for the years 2030, 2050, and 2100. Using a restrictive factor evaluation method that incorporates climatic, topographic, and edaphic indicators, we assess the evolution of land use suitability for both agriculture and livestock farming under each scenario. The results reveal that under moderate- and high-emission scenarios, thermal conditions gradually improve across the study area, particularly in the central and eastern parts, leading to enhanced natural suitability for agricultural and pastoral production. However, precipitation shows no consistent trend of increase or decrease. The moderate emission scenario (SSP2-4.5) yields the most balanced improvement in suitability, with the proportion of unsuitable agricultural land decreasing from 84.5% in 2030 to 37.4% in 2100, and unsuitable pastoral land decreasing from 53.1% to 13.6%. In contrast, the low-emission scenario (SSP1-2.6) results in a sharp contraction of suitable areas by 2100 due to concurrent warming and drying. These findings suggest that climate warming may benefit mid-to-high-latitude agro-pastoral transition zones under moderate emission pathways, but the benefits are spatially heterogeneous and contingent on precipitation stability. This study provides a scientific basis for regional land use planning and climate adaptation strategies.



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Keywords: the Agro-Pastoral Transitional Zone in northern China; land use suitability; adaptation strategies; multiple climate change scenarios; CMIP6

1. Introduction

Mitigating and adapting to global climate change represents one of the most pressing challenges confronting human society [1]. The social–ecological effects of climate change,

however, are profoundly heterogeneous across different regions of the Earth [2]. Consequently, understanding the responses of social–ecological systems in key geographical zones to climate change has emerged as a frontier topic in contemporary geographical research [3,4].

The Agro-Pastoral Transitional Zone in northern China (hereafter APTZ) is a transitional belt between semi-humid and semi-arid regions [5]. It functions as a coupled development zone integrating grassland animal husbandry with arable land agriculture, serves as an important ecological security barrier for central and eastern China, and acts as a vital water source conservation area in the north. The APTZ possesses a unique ecosystem and socio-economic system distinct from purely pastoral or agricultural areas. On one hand, as a typical ecologically fragile and climate-sensitive zone, the APTZ is highly susceptible to ecological degradation under external disturbances [6]. On the other hand, its land use is tightly constrained by climatic factors and exhibits pronounced marginal characteristics, with marked fluctuations in response to interannual and decadal climate variability [7]. Critically, future global climate change remains subject to substantial uncertainty, originating from multiple sources including divergent emission scenarios, structural differences among Global Climate Models (GCMs), and internal climate variability [1]. As an important ecological barrier, food production area, and forage supply base, the APTZ will be differentially affected by climate change across its sub-regions. Investigating this scientific issue therefore constitutes a central theme in climate change and regional geography research [8–10].

Research on climate change impacts and land suitability evaluation has traditionally belonged to separate disciplinary domains. The former focuses on climate change pattern recognition, species distribution and crop yield modeling, hydrology, carbon cycling, and climate change trend simulation, aiming to characterize the basic features and plausible trajectories of future climate [11–15]. At the impact level, attention has been directed toward vegetation dynamics, hydrological processes, soil properties, and human welfare [16–18]. The latter concentrates on comprehensive suitability assessment for target land uses, with extensive applications in land consolidation, crop growth modeling, and potential evaluation [19–21].

Recent studies have begun to bridge these two fields, but efforts remain largely confined to specific natural geographic units such as the Qinghai–Tibet Plateau [22–25]. Two major challenges persist. First, there is a lack of a coherent and comprehensive evaluation index system that seamlessly integrates climate change outputs with land suitability indicators; inconsistencies in indicator selection and data types between climate models and land evaluation frameworks hinder robust coupling [26,27]. Second, the inherent uncertainty of global climate change necessitates comparable land use suitability assessments across multiple scenarios, which represents a nascent methodological frontier [28]. Furthermore, from an application perspective, it is imperative to extend such analyses to a broader array of global ecologically fragile areas, identify climate change-sensitive zones, and formulate targeted governance measures for mitigation and adaptation [29,30].

In summary, there is an urgent need to develop a research pathway that systematically couples climate change projections with land use suitability evaluation [31,32]. Such a pathway should first establish a robust climate change baseline through multi-scenario simulations to address the uncertainty inherent in future projections [33]. Second, it should strengthen the alignment and complementarity between land suitability indicators and climate variables, accommodating the demands of short-term, medium-term, and long-term temporal scales at the regional level [34,35]. Ultimately, land suitability assessment must progressively embrace new scenarios informed by climate change projections, while climate change research should reinforce its linkages with traditional land evaluation frameworks.

To address these gaps, the present study integrates traditional land use suitability evaluation with multi-scenario climate change projections derived from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Specifically, we employ three Shared Socioeconomic Pathways (SSP1-2.6, SSP2-4.5, and SSP5-8.5), each driven by a distinct Integrated Assessment Model (IMAGE, MESSAGE, and REMIND-MAGPIE, respectively), and downscale the climate outputs from three GCMs (BCC-CSM2-MR, CanESM5, and IPSL-CM6A-LR) to a 1 km resolution. Using a restrictive factor evaluation method that incorporates climatic, topographic, and edaphic indicators, we assess the evolution of agricultural and pastoral land use suitability in the APTZ under low-, moderate-, and high-emission scenarios for the years 2030, 2050, and 2100.

Based on previous theoretical and empirical studies, we propose the following research hypotheses: (1) Future climate change will shift the optimal zones of agricultural and pastoral land use northward and eastward within the APTZ; (2) The magnitude and direction of suitability change will vary significantly across emission scenarios, with the moderate emission scenario (SSP2-4.5) yielding the most balanced outcomes; (3) The western part of the study area, constrained by limited precipitation, will experience persistent or worsening unsuitability regardless of warming trends. These hypotheses are tested in Sections 3 and 4.

The results of this study are expected to directly inform regional agricultural and animal husbandry development planning and climate resilience construction, while expanding the application scenarios of climate change simulation outputs and enriching the methodological repertoire and regional research dimensions of land use suitability evaluation.

2. Materials and Methods

2.1. Study Area

The Agro-Pastoral Transitional Zone in northern China (APTZ) is a 793,800 km² ecologically fragile belt stretching from 105° E to 127° E and 35° N to 50° N, spanning nine provincial-level regions (Figure 1). It forms a critical transitional interface between the semi-humid agricultural plains in the east/south and the semi-arid pastoral steppes in the west/north, serving as an important ecological security barrier for central and eastern China.

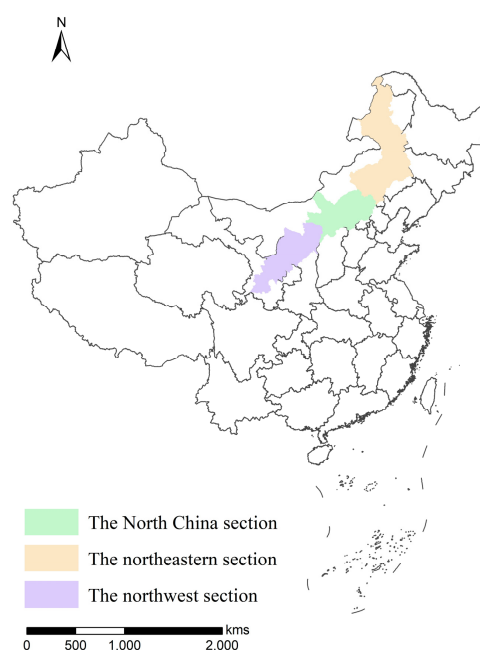


Figure 1. Regional map of the Agro-Pastoral Transitional Zone in Northern China.

Climatically, the APTZ is defined by three marginal thresholds: annual precipitation of 250–450 mm, a dryness index of 1.0–2.0, and precipitation variability of 15–30%. These boundaries represent the absolute limits for rain-fed agriculture, making the region exceptionally sensitive to minor shifts in temperature and precipitation. The region is topographically diverse, transitioning from the Mongolian Plateau (>1000 m) in the west to the North China Plain (<200 m) in the east, with the Yanshan and Yinshan mountains creating complex local climate gradients.

Following prior studies, the APTZ is divided into three sub-regions based on longitudinal differentiation: the Northeast Section (dominated by the Greater Khingan Range with low accumulated temperatures), the North China Section (a highly competitive mosaic of cropland and grassland), and the Northwest Section (arid steppe with limited agricultural potential). This spatial heterogeneity underpins the differentiated responses of land use suitability to climate change analyzed in this study.

What makes the APTZ scientifically unique is its dual marginality: it is simultaneously constrained by both thermal and moisture deficits, meaning that any climate change—whether warming or drying—directly reshapes the boundary between agriculture and animal husbandry. This characteristic positions the APTZ as an ideal natural laboratory for investigating the impacts of future climate scenarios on land use suitability.

2.2. Data Sources

This study is conducted based on a multi-source data system, involving various data such as climate, land use, soil, terrain, etc. (Table 1). Here, some data sources will be clarified. In the data preprocessing stage, the raster data is resampled to a spatial resolution of 1 km to support comprehensive analysis. Vector data is screened for geometric topology errors and stored as a whole to support comprehensive spatial analysis. Some meteorological station data research uses Kriging interpolation for spatial interpolation processing. The data used in the research institute are all open source data with no confidentiality requirements. Their sources can be traced and downloaded, and they have standardization and scientificity, making them highly applicable to this study.

Table 1. Research basic data connotation and source.

Data Name	Data Content	Precision	Data Sources	Data Purpose
Global land cover/use data	Global land cover/use database for the years 2000, 2005, 2010, 2015, and 2020	Spatial resolution 30 m raster data	https://storage.googleapis.com/earthenginepartners-hansen/GLCLU2000-2020/v2/download.html (accessed on 8 January 2025)	Identification of agro-pastoral ecotone and analysis of land use evolution characteristics
Multi-scenario climate data	Global annual average temperature and precipitation spatial distribution database, China land annual precipitation frequency distribution parameter dataset, China meteorological element average status spatial interpolation dataset (annual precipitation, annual evaporation, annual average temperature) from 1960 to 2020, global coupled model comparison project (CMIP6) data (BCC-CSM2-MR, CanESM5, IPSL-CM6A-LR)	Spatial resolution 1 km raster data	https://giovanni.gsfc.nasa.gov/gpm.nasa.gov/data/imerg/precipitation-climatology/ (accessed on 5 December 2024) https://www.resdc.cn/DOI/DOI.aspx?DOIID=39 (accessed on 10 December 2024) https://pcmdi.llnl.gov/CMIP6/ (accessed on 18 December 2024)	Supporting the identification of the world's agro-pastoral ecotone and the simulation analysis of global climate scenarios

Table 1. Cont.

Data Name	Data Content	Precision	Data Sources	Data Purpose
Terrain data	Spatial distribution data of altitude in China (DEM)	Spatial resolution 90 m raster data	https://www.resdc.cn/data.aspx?DATAID=284 (accessed on 10 December 2024)	Supporting the evaluation of land use suitability
Soil data	China soil texture distribution database, soil organic matter content database, soil layer thickness database	Spatial resolution 1 km raster data	https://www.resdc.cn/data.aspx?DATAID=260 (accessed on 20 December 2024)	Research on supporting regional-scale land suitability evaluation
Administrative divisions and policy reports	Data from various provinces, cities, and county-level administrative regions in China	2015 Vector data	https://www.resdc.cn/ https://www.stats.gov.cn https://www.mnr.gov.cn (accessed on 27 December 2024)	Assist in delineating the spatial scope of the agricultural pastoral transition zone and conducting spatial statistics

2.3. Methods

2.3.1. Multi-Scenario Climate Change Prediction Model

Future climate projections in this study are derived from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) framework. Within CMIP6, climate change scenarios are defined by Shared Socioeconomic Pathways (SSPs) that describe alternative societal development trajectories. The emission pathways underlying these SSPs are generated by Integrated Assessment Models (IAMs), which integrate energy, economy, land use, and climate systems [36,37]. Importantly, IAMs do not directly produce gridded climate variables (e.g., temperature, precipitation); instead, they provide the radiative forcing trajectories that drive Global Climate Models (GCMs), which in turn simulate the spatial climate fields.

To capture a range of plausible futures, we adopt three representative SSP scenarios, each linked to a specific IAM (Figure 2):

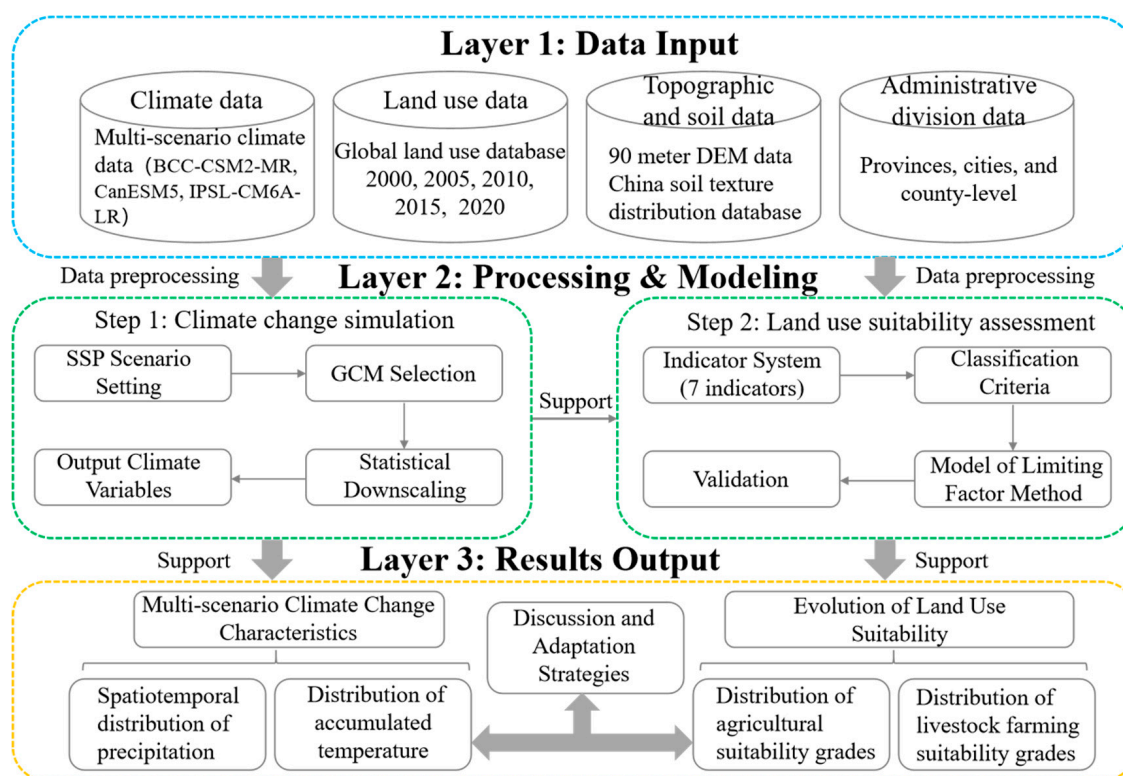


Figure 2. Methodological framework.

Low-emission scenario (SSP1-2.6): Aligned with the IMAGE 3.0 IAM. This scenario represents a sustainable development pathway, with radiative forcing stabilized at 2.6 W/m^2 by 2100 and a global mean temperature rise of $1.8 \text{ }^\circ\text{C}$. Fossil fuel use is largely replaced by renewables, population growth is low, and international cooperation on climate mitigation is strong.

Moderate-emission scenario (SSP2-4.5): Aligned with the MESSAGEix-GLOBIOM IAM. This middle-of-the-road scenario assumes moderate population growth, gradual technological change, and partial decarbonization. Radiative forcing reaches 4.5 W/m^2 by 2100, with a temperature rise of $3.6 \text{ }^\circ\text{C}$. Fossil fuel use declines slowly, and international cooperation is limited.

High-emission scenario (SSP5-8.5): Aligned with the REMIND-MAGPIE IAM. This scenario represents a fossil-fuel-intensive development path, with radiative forcing rising to 8.5 W/m^2 by 2100 and a temperature increase of $4.4 \text{ }^\circ\text{C}$. Economic growth is high, but reliance on conventional energy persists, and environmental regulations are weak.

For each SSP, the corresponding IAM-derived emission trajectory is used to force a set of GCMs participating in CMIP6. In this study, we select three widely used GCMs that have demonstrated reliable performance over East Asia:

BCC-CSM2-MR (Beijing Climate Center, China Meteorological Administration): a medium-resolution (100 km) model with a well-calibrated representation of the East Asian monsoon.

CanESM5 (Canadian Center for Climate Modeling and Analysis): a coarser-resolution (250 km) model known for its high climate sensitivity and realistic simulation of precipitation variability.

IPSL-CM6A-LR (Institut Pierre Simon Laplace, France): a low-resolution (250 km) model that captures the broad-scale features of the mid-latitude westerlies and associated moisture transport.

These three GCMs provide daily to monthly fields of surface air temperature and precipitation under each SSP scenario. The raw GCM outputs are originally at their native resolutions (100–250 km). To match the 1 km spatial resolution required for the land suitability evaluation, a statistical downscaling procedure is applied. Specifically, we employ the delta-change method. For each climate variable (precipitation and accumulated temperature $\geq 10 \text{ }^\circ\text{C}$), the future change signal (anomaly) is computed as the difference (for temperature) or ratio (for precipitation) between the future period (e.g., 2030, 2050, 2100) and the baseline period (1961–2020) at the GCM grid scale. These anomalies are then bilinearly interpolated to a 1 km grid and superimposed onto the high-resolution baseline climate surfaces (1 km) obtained from the Resource and Environment Science and Data Center (RESDC, <https://www.resdc.cn>). The baseline surfaces themselves are derived from station observations interpolated via kriging. This approach preserves the spatial detail of the observed climatology while imposing the large-scale climate change signals simulated by the GCMs.

The downscaled climate variables—annual precipitation and accumulated temperature $\geq 10 \text{ }^\circ\text{C}$ —are produced for three future time slices: 2030 (near-term), 2050 (mid-term), and 2100 (long-term), under each of the three emission scenarios. These serve as the climatic inputs to the land use suitability assessment described in Section 2.3.2.

2.3.2. Land Use Suitability Assessment Method

Land use suitability assessment evaluates the appropriateness of land for a specific use under given biophysical and management conditions [38–42]. In this study, we apply a limiting factor method to determine the suitability of each grid cell for rain-fed agriculture

and livestock farming. The method identifies the most restrictive indicator among a set of selected criteria, and the overall suitability class is assigned based on that limiting factor.

(1) Indicator System

Seven indicators are selected to represent climatic, topographic, and edaphic conditions: annual precipitation, accumulated temperature $\geq 10^\circ\text{C}$, slope, altitude, soil texture (silt content), soil organic matter content, and effective soil thickness. Each indicator is classified into five suitability levels (1 = completely suitable, 2 = highly suitable, 3 = moderately suitable, 4 = basically suitable, 5 = unsuitable) according to the thresholds defined in Table 2. Separate threshold sets are applied for agriculture and livestock farming, reflecting their differing biophysical requirements.

(2) Mathematical Formulation

Let S denote the overall suitability class for a given grid cell. The limiting factor method is expressed as:

$$S = \min\{s_1, s_2, \dots, s_n\}$$

where s_n is the suitability score for the n -th indicator ($n = 7$). The minoperator selects the worst (highest numerical) score among all indicators. Each s_n is determined by a piecewise function based on the thresholds in Table 2. For example, for agricultural suitability, the score for annual precipitation $P(\text{mm})$ is:

$$s_{\text{precip}}(P) = \begin{cases} 1, & P \geq 600 \\ 2, & 500 \leq P < 600 \\ 3, & 400 \leq P < 500 \\ 4, & 350 \leq P < 400 \\ 5, & P < 350 \end{cases}$$

Analogous functions are defined for accumulated temperature, slope, altitude, and soil properties using the thresholds in Table 2. The same logic applies to livestock farming with adjusted thresholds. The final suitability class for each cell is the minimum score across all indicators (Table 3).

(3) Implementation and Validation

The assessment was performed on a 1 km grid covering the entire APTZ. Climate inputs for the baseline period (1961–2020) and future scenarios (2030, 2050, 2100) were obtained from the downscaled CMIP6 outputs (Section 2.3.1). Topographic and soil data were resampled to the same resolution.

To validate the framework, we compared the baseline suitability classification with actual land use from the Global land cover/use database. Grid cells where predicted suitability (suitable vs. unsuitable) matched actual land use (cropland for agriculture, grassland/forest for livestock) were counted as correct. The overall accuracy reached 78.5%, indicating reasonable reliability for scenario-based projections. Uncertainty sources are discussed in Section 4.3.

Table 2. Evaluation system for land use suitability of the Agro-Pastoral Transitional Zone in Northern China.

Type of Suitability	Grade	Climatic Conditions		Topographic Conditions		Soil Conditions		
		Annual Average Precipitation (mm)	Accumulated Temperature $\geq 10\text{ }^{\circ}\text{C}$ ($^{\circ}\text{C}$)	Slope ($^{\circ}$)	Altitude (m)	Soil Texture (Silt Content, %)	Soil Organic matter Content (g/kg)	Effective Soil Layer Thickness (cm)
Agriculture	1	≥ 600	≥ 3000	≤ 2	≤ 200	60–65	≥ 30	≥ 100
	2	500–600	2800–3000	2–6	200–500	50–60, 65–70	20–30	50–100
	3	400–500	2500–2800	6–15	500–1000	40–50, 70–75	10–20	30–50
	4	350–400	2000–2500	15–25	1000–2500	<40, 75–80	6–10	20–30
	5	<350	<2000	>25	>2500	≥ 80	<6	<20
Livestock farming	1	≥ 500	≥ 2500	1–3	≤ 200	60–70	≥ 25	≥ 80
	2	400–500	2200–2500	≤ 1 , 3–6	200–800	50–60, 70–75	15–25	50–80
	3	300–400	2000–2200	6–15	800–1200	40–50, 75–80	10–15	30–50
	4	200–300	1500–2000	15–25	1200–3000	<40, 80–90	2–10	15–30
	5	<200	<1500	>25	>3000	≥ 90	<2	<15

Table 3. Connotation of suitability level for agricultural and pastoral land use of the Agro-Pastoral Transitional Zone in Northern China.

Suitability Type	Suitability Level	Suitability Characteristics
Agricultural land use	1	Completely suitable. The land is flat, the soil layer is deep and fertile, and the water and heat are extremely good. It can be stably used for rain-fed crop planting and cultivation without the need for special land protection measures.
	2	Highly suitable. The land is generally flat, with thick and fertile soil layers, excellent water and heat conditions, and can be stably used for rain-fed crop planting and cultivation without the need for special land protection measures.
	3	Moderate suitability. Individual natural factors have a certain degree of constraint. The land is relatively flat, the soil layer thickness is average, the fertility is average, and the water and heat conditions are average. It can be used for rain-fed crop planting and cultivation, but certain land protection measures need to be taken.
	4	Basically suitable. There are one or more limiting factors, such as a certain slope of the land, relatively thin soil layers or lack of nutrients, insufficient water and heat conditions, which can be limited for rain-fed crop planting and cultivation, and poor stability. Strict land protection measures are required for land use.
	5	Not suitable. There are one or more serious limiting factors that prevent the planting and cultivation of rain-fed crops. Avoid damaging natural vegetation.

Table 3. Cont.

Suitability Type	Suitability Level	Suitability Characteristics
Livestock farming land use	1	Completely suitable. The land is flat, the soil layer is deep and fertile, the water and heat are extremely good, and it can be stably used for natural grass growth. It has a large livestock carrying capacity and does not require special land protection measures.
	2	Highly suitable. The land is generally flat, with thick and fertile soil layers, excellent water and heat conditions, and can be stably used for natural grass growth and grazing. It has a large carrying capacity and does not require special land protection measures.
	3	Moderate suitability. Individual natural factors have a certain degree of constraint. The land is relatively flat, the soil layer thickness is average, the fertility is average, and the water and heat conditions are average. It can be used for natural grass growth and grazing, and the carrying capacity is average. Therefore, certain land protection measures need to be taken.
	4	Basically suitable. There are one or more limiting factors, such as a certain slope of the land, relatively thin soil layers or lack of nutrients, insufficient water and heat conditions, limited use for natural grass growth and grazing, limited carrying capacity, and poor stability. Strict land protection measures need to be taken.
	5	Not suitable. There are one or more serious limiting factors that prevent the growth of natural grass. Avoid damaging natural vegetation.

3. Results

3.1. Analysis of Multi-Scenario Climate Change in the Agro-Pastoral Transitional Zone in Northern China

3.1.1. Annual Precipitation

Under the low-emission scenario (SSP1-2.6), the mean annual precipitation across the APTZ is projected to be 322.16 mm, 433.33 mm, and 287.49 mm for 2030, 2050, and 2100, respectively, exhibiting an initial increase followed by a decline, with an overall decreasing tendency. Spatially, precipitation increases in the northeast and north China sections from 2030 to 2050, accompanied by a westward expansion of the 400 mm isohyet. However, from 2050 to 2100, the 400 mm isohyet retreats significantly eastward, signaling pronounced aridification in the northwest and north China sections (Figure 3).

Under the moderate-emission scenario (SSP2-4.5), the projected mean precipitation is 386.39 mm (2030), 515.42 mm (2050), and 446.44 mm (2100), again following an initial increase and subsequent decrease, but with an overall increasing trend. Spatially, the northeast and north China sections experience regional precipitation increases from 2030 to 2050, with the 400 mm isohyet expanding westward. Notably, precipitation increases are observed in the Greater Khingan Range (northeast section) and the Yanshan area (north China section). From 2050 to 2100, the 400 mm isohyet contracts slightly eastward and stabilizes along the Yinshan–Yanshan line in the central-north China section, indicating sustained wetting in the northeast and north China sections (Figure 3).

Under the high-emission scenario (SSP5-8.5), the projected mean precipitation is 491.74 mm (2030), 337.10 mm (2050), and 422.32 mm (2100), exhibiting a decreasing-then-increasing pattern with an overall declining tendency. Spatially, wetting dominates the northeastern and eastern APTZ in 2030, while the 400 mm isohyet remains stable in the central north China section. By 2050, aridification emerges in the southern northeast section and northern north China section, whereas wetting appears in the southern north China section and the southern boundary of the northwest section. The 400 mm and other isohyets display a multi-stage distribution, dividing wetting areas into northern and southern zones. By 2100, wetting re-emerges in the northern part of the northeast section, with the 400 mm isohyet forming a continuous band along the western foothills of the Greater Khingan Range, Yanshan Mountains, and Yinshan Mountains (Figure 3).

Overall, the low- and moderate-emission scenarios exhibit broadly similar precipitation trends, while the high-emission scenario produces the largest inter-period variability. Across all scenarios, the spatial pattern of precipitation consistently follows an east–west gradient, with higher values in the east and lower values in the west. Precipitation changes in the northern and northwestern sections are relatively modest, whereas the northeastern section displays pronounced dry–wet alternations between its northern and southern sub-regions (Figure 3).

3.1.2. Accumulated Temperature ($\geq 10\text{ }^{\circ}\text{C}$)

Under the low-emission scenario (SSP1-2.6), the mean accumulated temperature $\geq 10\text{ }^{\circ}\text{C}$ across the APTZ is projected to be 2374.23 $^{\circ}\text{C}$, 2575.00 $^{\circ}\text{C}$, and 2494.56 $^{\circ}\text{C}$ for 2030, 2050, and 2100, respectively, exhibiting an initial increase followed by a slight decline, with an overall increasing tendency. Spatially, the 2000 $^{\circ}\text{C}$ isoline shifts northward from 2030 to 2050, then expands slightly southward in the southern part of the northeast section between 2050 and 2100. Meanwhile, accumulated temperature in the northwest section remains stable above 3000 $^{\circ}\text{C}$ throughout the projection period (Figure 4).

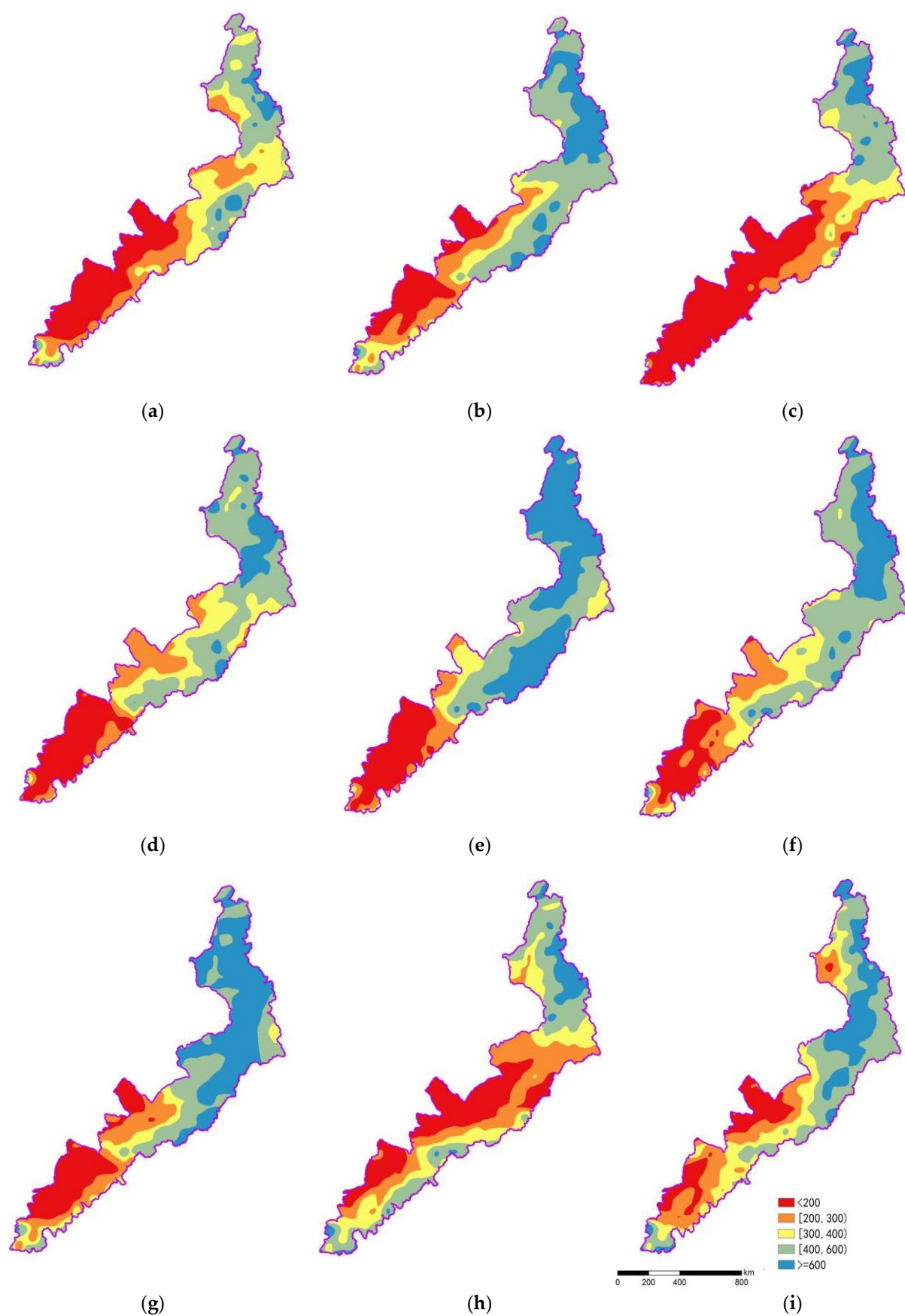


Figure 3. Low-emission scenario in the Agro-Pastoral Transitional Zone in Northern China ((a) 2030; (b) 2050; (c) 2100), moderate-emission scenario ((d) 2030; (e) 2050; (f) 2100), high-emission scenario ((g) 2030; (h) 2050; (i) 2100) distribution map of annual precipitation forecast (mm).

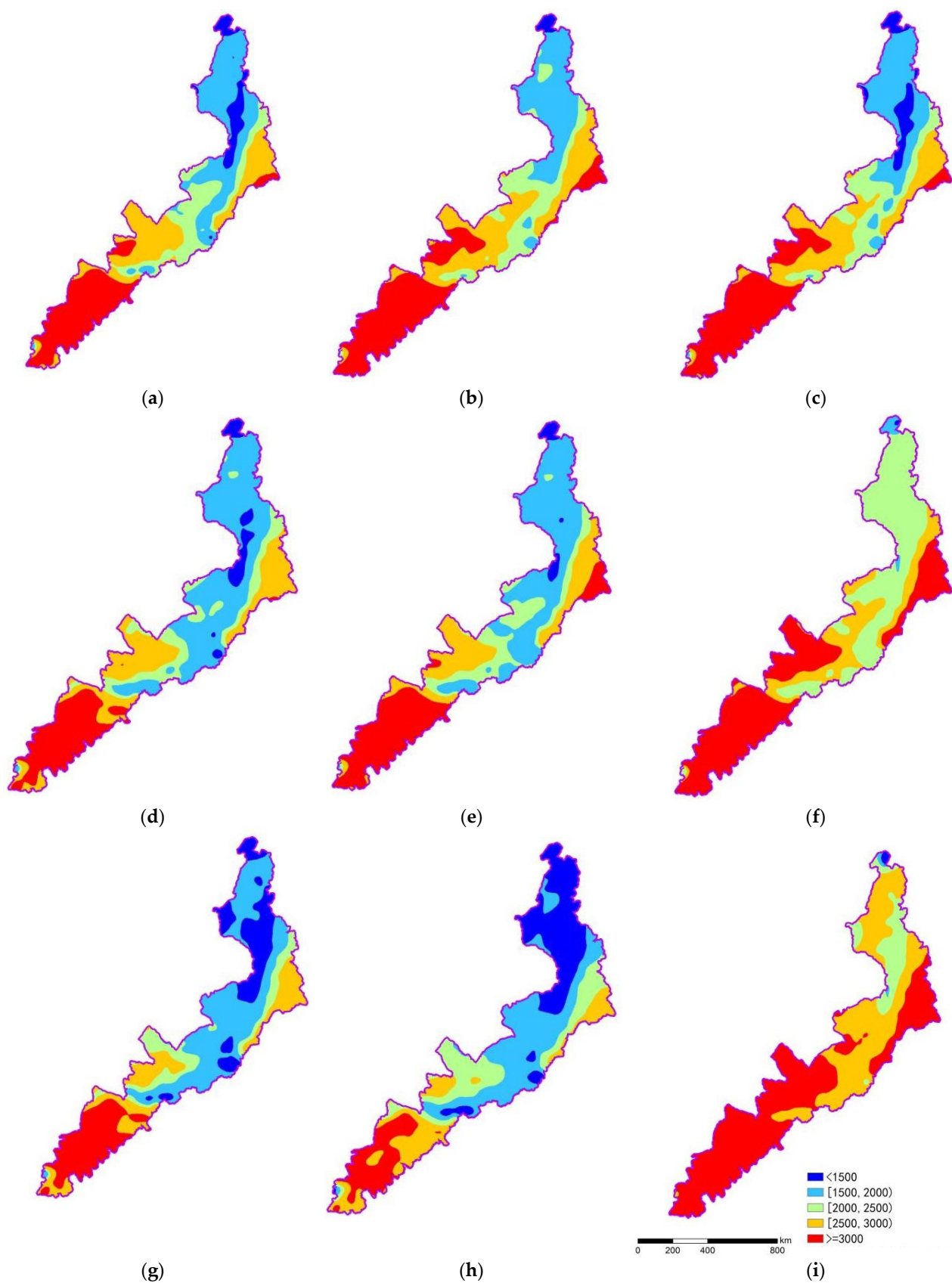


Figure 4. Low-emission scenario in the Agro-Pastoral Transitional Zone in Northern China ((a) 2030; (b) 2050; (c) 2100), moderate-emission scenario ((d) 2030; (e) 2050; (f) 2100), high-emission scenario ((g) 2030; (h) 2050; (i) 2100) forecast distribution map of accumulated temperature greater than or equal to 10 °C.

Under the moderate-emission scenario (SSP2-4.5), the projected mean accumulated temperature is 2273.10 °C (2030), 2376.96 °C (2050), and 2948.46 °C (2100), showing a continuous and significant increasing trend. Spatially, the 2000 °C isoline contracts progressively in the southern northeast section and eastern north China section from 2030 to 2050, with most of the northeast section falling below 2000 °C. However, between 2050 and 2100, the 2000 °C isoline retreats markedly northward, and areas with accumulated temperature exceeding 2000 °C expand substantially in the western north China section and along the eastern foothills of the Greater Khingan Range (Figure 4).

Under the high-emission scenario (SSP5-8.5), the projected mean accumulated temperature is 2130.00 °C (2030), 2081.38 °C (2050), and 3047.42 °C (2100), exhibiting a decreasing-then-increasing pattern with a pronounced overall increase. Spatially, the 2000 °C isoline remains stable along the Yanshan–Yinshan line from 2030 to 2050, while areas with accumulated temperature below 1500 °C expand in the northeast section and areas above 3000 °C contract in the northwest section. From 2050 to 2100, the 2000 °C isoline shifts northward to the northernmost Hulunbuir region. With the exception of the Greater Khingan Range, Yanshan, and Yinshan areas, most of the APTZ experiences accumulated temperatures exceeding 3000 °C by 2100 (Figure 4).

Overall, accumulated temperature across the APTZ exhibits a consistent south–high, north–low spatial pattern. Changes under the low-emission scenario are relatively modest, whereas the moderate- and high-emission scenarios produce more pronounced shifts. The southern part of the northeast section and the eastern part of the north China section emerge as key zones of thermal transition, experiencing the most substantial cold–warm alternations across scenarios.

Integrating the dual factors of precipitation and accumulated temperature, distinct scenario-dependent climate regimes emerge. Under the low-emission scenario (SSP1-2.6) by 2100, the simultaneous increase in accumulated temperature and decline in precipitation is projected to create a drying-and-warming process conducive to drought risk. The moderate-emission scenario (SSP2-4.5) consistently exhibits a warming-and-humidifying regime. The high-emission scenario (SSP5-8.5) is projected to induce a drying-and-cooling phase in the north China region by 2050, transitioning to a warming-and-humidifying regime by 2100.

3.2. Analysis of Land Suitability Evolution in the Agro-Pastoral Transitional Zone in Northern China Under Multiple Climate Change Scenarios

Based on the restrictive factor evaluation method, the evolution of agricultural and pastoral land suitability under three SSP scenarios for 2030, 2050, and 2100 is presented below. Detailed proportional distributions are provided in Tables 4 and 5.

3.2.1. Agricultural Land Suitability

Under the low-emission scenario (SSP1-2.6), the proportion of unsuitable agricultural land follows a decreasing-then-increasing trajectory across the three time slices, reaching its maximum (92.72%) in 2100. Spatially, suitable agricultural areas are initially concentrated in the central-eastern APTZ near the southern boundary. By 2050, these areas expand moderately, but by 2100 they contract sharply, becoming confined to the eastern APTZ east of the Greater Khingan Range. The remainder of the study area is classified as unsuitable.

Under the moderate-emission scenario (SSP2-4.5), the proportion of unsuitable agricultural land decreases continuously from 84.53% in 2030 to 37.42% in 2100, while moderately suitable land increases substantially (from 3.26% to 29.49%). Spatially, suitable agricultural areas expand markedly in the central and eastern APTZ by 2050 and 2100. Improved thermal conditions significantly enhance suitability in the northeastern Greater Khingan Range and Hulunbuir Plateau regions. The western APTZ remains persistently unsuitable throughout.

Table 4. Proportion of agricultural suitability evaluation at different levels in the Agro-Pastoral Transitional Zone in northern China.

Agricultural Suitability Evaluation	Low-Emission Scenario				
	Completely Suitable	Highly Suitable	Moderate Suitability	Basically Suitable	Unsuitable
2030	0.00%	0.01%	1.73%	9.78%	88.49%
2050	0.00%	0.00%	6.59%	28.80%	64.60%
2100	0.00%	0.00%	2.39%	4.90%	92.72%

Agricultural Suitability Evaluation	Moderate-Emission Scenario				
	Completely Suitable	Highly Suitable	Moderate Suitability	Basically Suitable	Unsuitable
2030	0.00%	0.00%	3.26%	12.21%	84.53%
2050	0.00%	0.00%	4.99%	21.88%	73.13%
2100	0.00%	0.20%	29.49%	32.89%	37.42%

Agricultural Suitability Evaluation	High-Emission Scenario				
	Completely Suitable	Highly Suitable	Moderate Suitability	Basically Suitable	Unsuitable
2030	0.00%	0.00%	1.59%	9.59%	88.81%
2050	0.00%	0.00%	3.86%	20.65%	75.49%
2100	0.00%	0.24%	25.38%	28.03%	46.35%

Table 5. Proportion of animal husbandry suitability evaluation at different levels in the Agro-Pastoral Transitional Zone in northern China.

Animal Husbandry Suitability Evaluation	Low-Emission Scenario				
	Completely Suitable	Highly Suitable	Moderate Suitability	Basically Suitable	Unsuitable
2030	0.00%	0.80%	12.31%	33.78%	53.12%
2050	0.00%	1.96%	19.41%	44.22%	34.41%
2100	0.00%	1.28%	5.14%	28.51%	65.07%

Animal Husbandry Suitability Evaluation	Moderate-Emission Scenario				
	Completely Suitable	Highly Suitable	Moderate Suitability	Basically Suitable	Unsuitable
2030	0.00%	1.42%	12.05%	33.41%	53.11%
2050	0.00%	1.66%	9.60%	41.93%	46.81%
2100	0.00%	3.44%	36.12%	46.86%	13.58%

Animal Husbandry Suitability Evaluation	High-Emission Scenario				
	Completely Suitable	Highly Suitable	Moderate Suitability	Basically Suitable	Unsuitable
2030	0.00%	1.09%	6.76%	30.58%	61.57%
2050	0.00%	1.78%	15.17%	48.32%	34.72%
2100	0.00%	3.23%	33.18%	50.55%	13.04%

Under the high-emission scenario (SSP5-8.5), the unsuitable proportion also declines continuously, from 88.81% in 2030 to 46.35% in 2100, with notable increases in moderately and basically suitable categories. From 2030 to 2050, agricultural suitable areas expand mainly in the southern part of the central and western APTZ, as well as parts of the northeast. By 2100, suitable areas in the west contract significantly, while large-scale expansion occurs in the central and eastern regions.

Overall, the moderate-emission scenario yields the highest proportion of suitable agricultural land in the near term (2030) and long term (2100), while the low-emission scenario performs best in the medium term (2050) due to temporary precipitation increases. Spatially, the south-central APTZ, the eastern Greater Khingan Range, and the Horqin region exhibit the strongest fluctuations in agricultural suitability, identifying them as the most climate-sensitive zones for agricultural land use (Figures 5 and 6).

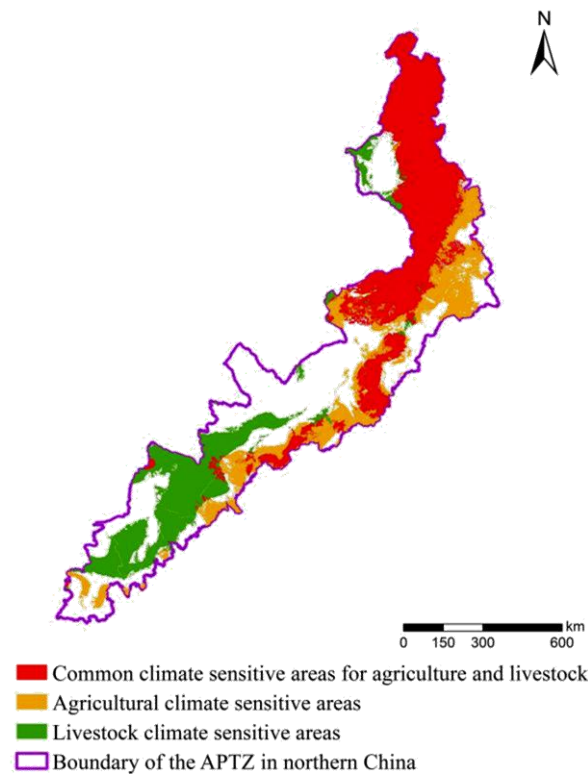


Figure 5. Distribution of climate-sensitive areas for agricultural and pastoral land use in the future climate change scenario in the Agro-Pastoral Transitional Zone in northern China.

3.2.2. Livestock Farming Land Suitability

Under the low-emission scenario (SSP1-2.6), the proportion of unsuitable pastoral land follows a decreasing-then-increasing pattern, peaking at 65.07% in 2100. Spatially, large contiguous suitable areas are concentrated in the southern and central APTZ, as well as the eastern foothills of the Greater Khingan Range. By 2050, suitable areas expand slightly in the central and western regions, while the east experiences an improvement in suitability level. By 2100, basic suitable areas in the central and western APTZ shrink markedly, and suitability levels in the east decline significantly.

Under the moderate-emission scenario (SSP2-4.5), the unsuitable proportion decreases continuously from 53.11% in 2030 to 13.58% in 2100, with substantial increases in moderately and basically suitable categories. Spatially, pastoral suitable areas exhibit a clear pattern of “expanding northward and extending westward” from 2030 to 2100. By 2100, with the exception of the western APTZ, the entire study area becomes suitable for livestock farming. Suitability levels in the southern and eastern APTZ continue to improve, reaching the largest spatial extent across all scenarios.

Under the high-emission scenario (SSP5-8.5), the unsuitable proportion also declines continuously, from 61.57% in 2030 to 13.04% in 2100. The northward and westward expansion of suitable areas is more rapid and extensive than under the moderate-emission scenario, with unsuitable areas retreating to the northern and central parts of the APTZ.

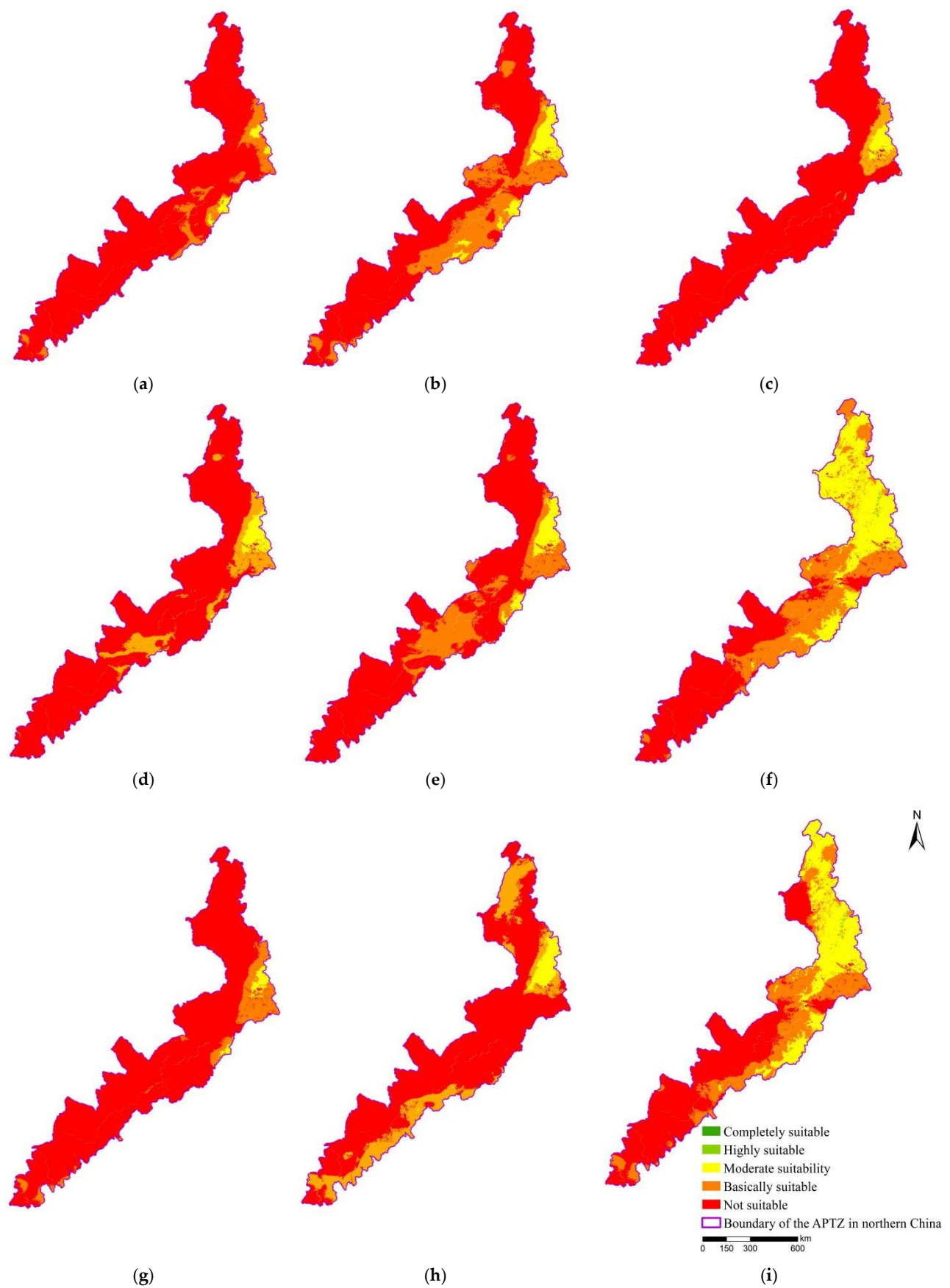


Figure 6. Low-emission scenario in the Agro-Pastoral Transitional Zone of northern China ((a) 2030; (b) 2050; (c) 2100), moderate-emission scenario ((d) 2030; (e) 2050; (f) 2100), high-emission scenario ((g) 2030; (h) 2050; (i) 2100) distribution map of agricultural suitability assessment grades.

Overall, the moderate-emission scenario yields the highest proportion of suitable pastoral land in the near term (2030), the low-emission scenario performs best in the medium term (2050), and the high-emission scenario achieves the largest suitable proportion in the long term (2100). However, the moderate-emission scenario offers superior suitability quality (higher proportions of moderately and highly suitable classes). Spatially, the southwestern region, central hinterland, and eastern Greater Khingan Range exhibit the strongest fluctuations in pastoral suitability, marking them as the most climate-sensitive zones for livestock farming (Figures 5 and 7).

3.2.3. Integrated Assessment and Adaptation Implications

Integrating the suitability assessments for both agriculture and livestock farming reveals a clear spatial hierarchy. Climate-sensitive zones for agricultural land use are generally located south of those for pastoral land use. Notably, the agricultural climate-sensitive areas coincide with long-term stable pastoral suitable areas. This creates a zone of intense competition and mosaic distribution between agriculture and pastoralism in the central-southern APTZ and the eastern Horqin region—areas where fluctuating agricultural land use at the margin overlaps with naturally stable pastoral land use.

Given that the APTZ is situated in a mid-latitude arid and semi-arid region, global warming under moderate- and high-emission scenarios is projected to improve thermal conditions in the central and eastern APTZ, thereby enhancing the natural suitability for both agriculture and livestock farming. However, in the western APTZ, climatic constraints—particularly precipitation deficits—are expected to intensify, preventing long-term stable improvement in land use suitability.

From a global climate governance perspective, the Paris Agreement aims to limit global warming to well below 2 °C, preferably 1.5 °C, above pre-industrial levels by 2100—a target comparable to the low-emission scenario (SSP1-2.6) in this study. Under this scenario, our results indicate a large-scale contraction of suitable agricultural and pastoral land in the APTZ by 2100, with reduced precipitation as the primary driver. During the transitional decades (2030 and 2050), the moderate-emission pathway (SSP2-4.5) may offer a more pragmatic reference for climate governance in this region.

Based on these findings, targeted adaptation strategies are recommended for different climate-sensitive zones (Figure 5):

Agricultural climate-sensitive zones (central-eastern APTZ): Optimize land use in conjunction with terrain zoning. In valley areas, strengthen irrigation and drainage infrastructure to enhance resilience against climatic extremes. In mountainous and hilly areas, prioritize rain-fed agriculture supplemented by irrigation, and construct rainwater harvesting facilities to buffer against precipitation variability.

Pastoral climate-sensitive zones (western APTZ): Expand artificial grassland construction and develop localized grassland irrigation and water storage systems to stabilize carrying capacity under drought conditions.

Dual-sensitive zones (central-southern APTZ and Horqin region): Strictly control arable land expansion, designate ecological protection areas, and construct ecological barrier belts to enhance sandstorm-interception and water-source-conservation functions.

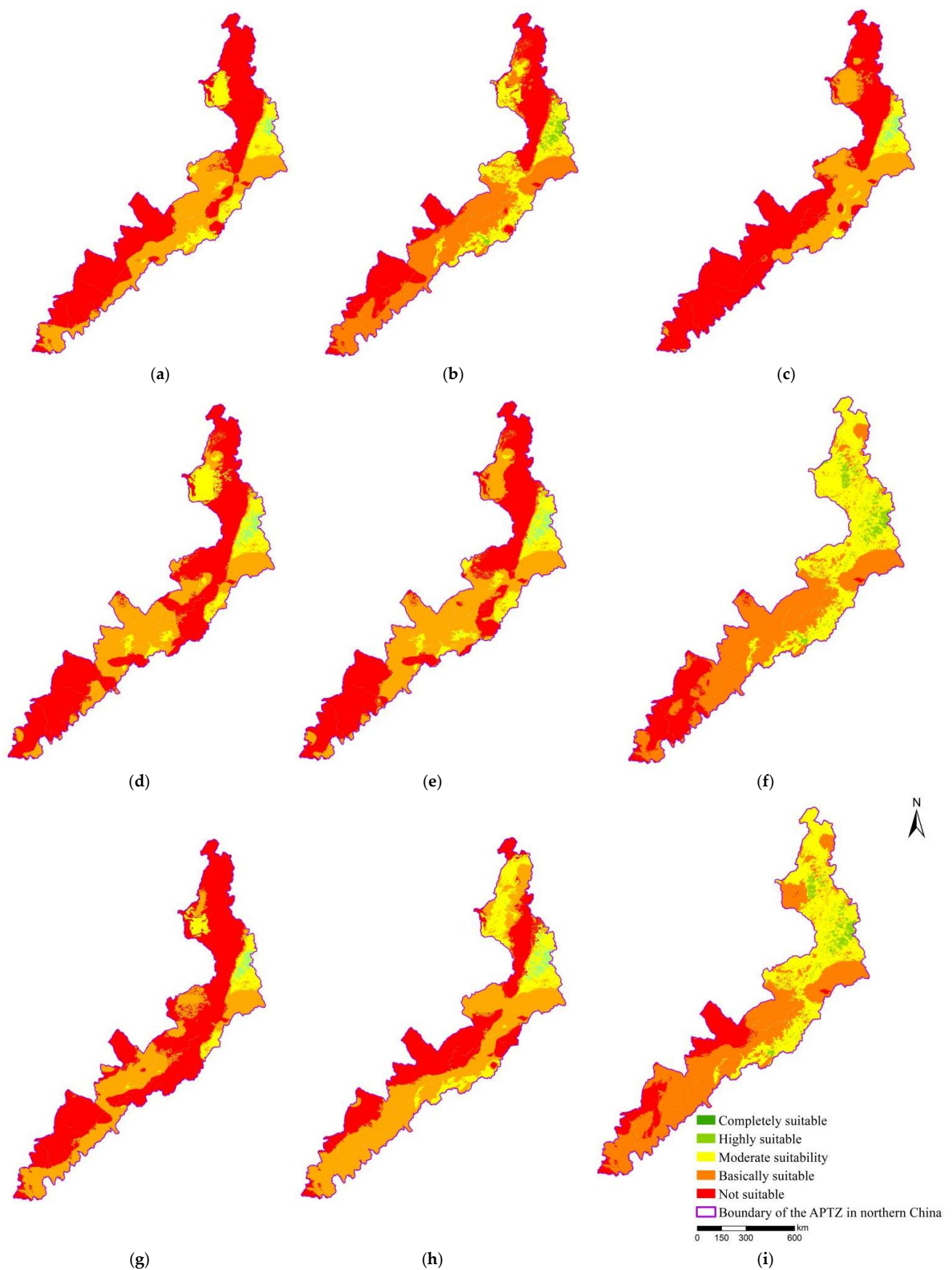


Figure 7. Low-emission scenario in the Agro-Pastoral Transitional Zone of northern China ((a) 2030; (b) 2050; (c) 2100), moderate-emission scenario ((d) 2030; (e) 2050; (f) 2100), high-emission scenario ((g) 2030; (h) 2050; (i) 2100) distribution map of suitability evaluation levels for animal husbandry.

4. Discussion

The Agro-Pastoral Transitional Zone in northern China (APTZ) occupies a climatically marginal position at the tail of the East Asian summer monsoon, where both thermal and moisture conditions hover near the critical thresholds for rain-fed agriculture and natural grassland productivity. Our multi-scenario analysis reveals that future climate change will induce spatially heterogeneous and scenario-dependent shifts in land use suitability, with the moderate emission scenario (SSP2-4.5) offering the most balanced improvement across both agricultural and pastoral land use types. This finding carries important implications for regional adaptation planning and contributes to the broader debate on the differential impacts of climate change across global ecotones.

4.1. Comparison with Previous Studies

Our results corroborate and extend findings from several recent international studies. Investigations on analogous mid-latitude transition zones, such as the Mongolian Plateau [43,44], have reported a northward expansion of suitable agricultural areas under moderate warming, driven primarily by improved thermal conditions—a pattern consistent with our observations in the central and eastern APTZ. Similarly, research focusing on mid-latitude agro-pastoral zones in North America indicates enhanced biomass productivity under moderate emission scenarios (SSP2-4.5), while emphasizing that precipitation variability remains a dominant constraint [45]. This echoes our finding that the western APTZ, despite benefiting from warming, fails to achieve suitability improvements due to persistent aridity.

However, our results diverge from studies conducted in lower-latitude or more arid ecotones. For instance, investigations in the Sahel region of West Africa have documented widespread declines in agricultural suitability under all emission scenarios, primarily attributable to intensified droughts and heat stress [46]. This contrast underscores a latitude-dependent asymmetry of climate change impacts: mid-to-high-latitude transition zones may experience net gains in suitability under moderate warming, whereas tropical and subtropical margins face disproportionate losses. Our study thus provides empirical evidence supporting the emerging consensus that climate change is not uniformly detrimental but produces both winners and losers at the global scale.

Compared to earlier research on high-altitude ecotones such as the Qinghai–Tibet Plateau, the APTZ exhibits a more pronounced improvement in pastoral suitability under high-emission scenarios [47]. This difference is likely attributable to the APTZ's lower elevation and its stronger coupling with the East Asian monsoon system, which amplifies the moisture response to warming. Nevertheless, a noteworthy finding of our study is that the low-emission scenario (SSP1-2.6) leads to a sharp contraction of suitable areas by 2100. This counterintuitive result arises from the simultaneous occurrence of modest warming and precipitation decline under this scenario in the specific GCM outputs employed, which may reflect internal climate variability rather than a robust forced signal. Future studies employing multi-GCM ensembles will be necessary to disentangle forced responses from stochastic noise and to confirm whether this pattern is reproducible across different model structures.

4.2. Implications for Adaptation Strategies

The spatially differentiated responses identified in this study call for tailored adaptation measures. The central and eastern APTZ, where agricultural suitability improves markedly under moderate and high emissions, should prioritize investments in irrigation infrastructure and drought-resistant crop varieties to capitalize on extended growing seasons while hedging against precipitation instability. In contrast, the western APTZ, where

aridity persistently constrains suitability, may require a fundamental reorientation toward low-intensity pastoralism and ecological restoration rather than agricultural expansion. The dual climate-sensitive zones identified in the central-southern APTZ and the eastern Horqin region—where agriculture and animal husbandry compete for land—demand integrated land-use planning that balances food security with ecological protection. Establishing ecological corridors and promoting agro-pastoral integration (e.g., rotational grazing combined with fodder cropping) could enhance resilience in these hotspots.

Importantly, our analysis suggests that the moderate emission scenario (SSP2-4.5) aligns most closely with both improved suitability and realistic global climate governance trajectories, as reflected in current Nationally Determined Contributions (NDCs) under the Paris Agreement. While the low-emission scenario (SSP1-2.6) is environmentally preferable globally, its localized adverse effects in the APTZ—driven by precipitation decline—highlight the need for region-specific assessments when evaluating global climate targets.

4.3. Uncertainties and Limitations

Several uncertainties and limitations must be acknowledged. First, our use of a single GCM per SSP scenario (BCC-CSM2-MR for SSP1-2.6, CanESM5 for SSP2-4.5, IPSL-CM6A-LR for SSP5-8.5) limits the quantification of structural uncertainty arising from GCM formulation. GCMs exhibit substantial spread in precipitation projections for mid-latitude Asia, particularly under high-emission scenarios [48,49]. A multi-model ensemble approach would provide probabilistic suitability projections and confidence intervals, which we recommend for future work.

Second, the statistical downscaling method (delta-change) assumes that the spatial pattern of climate anomalies remains stationary over time. This assumption may be violated under strong warming, especially for precipitation, where changes in storm tracks and convective regimes could alter fine-scale patterns. Dynamical downscaling or hybrid methods could reduce this bias.

Third, the suitability evaluation adopts a limiting-factor approach that treats all indicators (climatic, topographic, edaphic) as equally constraining. In reality, climatic factors—particularly precipitation—likely exert stronger constraints than soil properties in this water-limited region. Weighted or hierarchical evaluation schemes could better reflect the relative importance of different factors.

Fourth, our analysis does not account for human adaptation responses, such as technological change, crop switching, or migration. Land use decisions are shaped not only by natural suitability but also by market forces, policy interventions, and institutional arrangements. Integrating agent-based or land-use change models (e.g., CLUE-S, FLUS) with climate projections would enable more realistic scenario simulations.

Finally, the validation of our suitability framework against historical land use data yielded an overall accuracy of 78.5% (see Section 2.3.2), which is acceptable but leaves room for improvement. Future research should incorporate higher-resolution soil and terrain data and refine threshold values based on field experiments.

4.4. Future Research Directions

To advance the understanding of climate–land use interactions in ecotonal regions, we propose the following priorities:

Multi-GCM ensemble projections: Employing 10–20 GCMs from CMIP6 under each SSP would allow uncertainty quantification and the identification of robust versus uncertain suitability changes.

Dynamic monitoring framework: Establishing a long-term observation network that compares predicted suitability trajectories with satellite-derived land use/cover data at 5-year intervals would enable early detection of deviations and adaptive management.

Socioeconomic coupling: Incorporating demographic, economic, and policy scenarios into land use simulations would bridge the gap between biophysical suitability and actual land use outcomes.

Cross-regional comparative studies: Extending the analytical framework to other global agro-pastoral transition zones (e.g., the Sahel, Central Asia) would test the generality of our findings and contribute to a global synthesis of climate change impacts on marginal lands.

5. Conclusions

This study assessed the evolution of land use suitability for agriculture and livestock farming in the Agro-Pastoral Transitional Zone in northern China (APTZ) under three CMIP6-based climate scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) for the years 2030, 2050, and 2100. The key findings are summarized as follows.

Climate change projections. Under all scenarios, the APTZ is projected to experience a general increase in accumulated temperature ≥ 10 °C, with the greatest warming occurring under SSP5-8.5 (mean increase of ~ 900 °C by 2100 relative to the baseline). Precipitation projections are more uncertain and scenario-dependent: SSP2-4.5 shows a modest overall increase (+13% by 2100), while SSP1-2.6 and SSP5-8.5 exhibit non-monotonic trends with a tendency toward drying in the western sub-regions. Spatially, the eastern APTZ consistently receives more precipitation than the west, and this east–west gradient is amplified under high emissions.

Land use suitability dynamics. The suitability of both agricultural and pastoral land use is projected to improve most substantially under the moderate emission scenario (SSP2-4.5). Under this scenario, the proportion of unsuitable agricultural land decreases from 84.5% in 2030 to 37.4% in 2100, while unsuitable pastoral land decreases from 53.1% to 13.6%. The high-emission scenario (SSP5-8.5) yields comparable improvements in pastoral suitability but slightly weaker agricultural gains. In contrast, the low-emission scenario (SSP1-2.6) leads to a sharp contraction of suitable areas by 2100, driven by concurrent warming and precipitation decline—a counterintuitive outcome that highlights the importance of region-specific assessments.

Spatial heterogeneity. The response to climate change is highly spatially differentiated. The central and eastern APTZ benefit from improved thermal conditions, particularly in the Greater Khingan Range and Horqin regions, where agricultural and pastoral suitability increases notably. Conversely, the western APTZ remains persistently unsuitable due to limited precipitation, and this constraint is unlikely to be alleviated under any scenario. The dual climate-sensitive zones—where agriculture and pastoralism overlap and compete—are concentrated in the central-southern APTZ and the eastern Horqin region, requiring integrated land-use planning.

Adaptation implications. Given the projected improvements under moderate emissions, adaptation strategies should prioritize: (i) strengthening irrigation and water-harvesting infrastructure in the central and eastern regions to buffer against precipitation variability; (ii) promoting ecological restoration and low-intensity pastoralism in the western arid zones; and (iii) establishing ecological corridors and agro-pastoral integration in the dual-sensitive zones. The moderate emission pathway (SSP2-4.5) aligns most closely with both enhanced suitability and realistic global climate governance trajectories.

Validation and uncertainties. The suitability evaluation framework was validated against historical land use patterns (baseline period 1961–2020), achieving an overall classi-

fication accuracy of 78.5%, indicating reasonable reliability for scenario-based projections. However, several sources of uncertainty warrant caution. First, the use of a single GCM per SSP scenario (BCC-CSM2-MR for SSP1-2.6, CanESM5 for SSP2-4.5, IPSL-CM6A-LR for SSP5-8.5) does not capture the full range of GCM structural uncertainty, which is particularly large for precipitation in mid-latitude Asia. Second, the statistical downscaling method (delta-change) assumes stationary spatial anomaly patterns, which may be violated under strong warming. Third, the limiting-factor evaluation method treats all indicators as equally constraining, whereas climatic factors likely dominate in this water-limited region. Fourth, human adaptation responses (e.g., technological change, crop switching) are not considered, potentially overestimating or underestimating realized suitability changes. Future studies should employ multi-GCM ensembles, dynamic downscaling, and coupled human–natural system models to reduce these uncertainties and provide more robust guidance for regional climate adaptation.

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