# STUDY ON THE ECOLOGICAL LAND EXPOSURE OF EXTREME TEMPERATURES IN SOUTHWEST CHINA

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**Abstract.** Under the influence of climate warming, the frequency and intensity of extreme weather events are increasing, posing a greater risk of exposing the ecological environment to extreme climatic conditions. Ecological land, as a land use type of paramount importance to both the natural environment and humanity, has not been examined regarding its exposure under extreme climatic conditions. Therefore, this study focuses on the ecologically significant Southwest China, characterized by frequent extreme temperature events. Based on CMIP6 climate data and land use data, and utilizing ArcGIS software, the exposure of ecological land to extreme temperature conditions is analyzed. The results indicate that, compared to historical periods, the area of ecological land exposed to extreme high temperatures is rapidly increasing, while the area exposed to extreme low temperatures is decreasing. Various types of ecological land show differences in area changes under extreme temperature exposure, and there is significant spatial heterogeneity in the changes in ecological land exposure, primarily due to the different spatial distributions of ecological land and extreme temperature indicators. The changes in exposure area of ecological land under extreme temperatures exhibit prominent topographical gradients. The findings of this study can provide crucial and clear information for the formulation of disaster prevention mitigation policies and land planning.
**Keywords:** *extreme climate, projections, impact, land use, mountainous areas*

## Introduction

The sixth IPCC report indicates that, influenced by both natural factors and various human activities, global climate warming has become an undeniable fact (IPCC, 2021; Soon et al., 2023). The rise in global temperatures has led to the instability of the climate system, increasing the frequency, intensity, and duration of extreme weather events (Wang et al., 2017; Gu et al., 2022; Zhao et al., 2023). Extreme climate events pose complex, multi-dimensional threats to natural resources and ecosystems, resulting in difficulties in natural resource supply, disruptions in ecological balance, and degradation of ecological functions (Solow, 2017; Islam, 2022; Runde et al., 2022; Mejía and Wetzel, 2023; Sun et al., 2023). Ecological land, represented by forests, grasslands, and water bodies, holds significant socio-economic and ecological value (Yang and He, 2022; Beregniak et al., 2023). However, with the increase in extreme climate events, extreme weather poses a severe threat to ecological land, potentially leading to ecological degradation, loss of biodiversity, and damage to ecosystem services (Smart et al., 2014; Calvo-Rodriguez et al., 2021; Yi et al., 2022). Therefore, it is imperative to study the exposure of ecological land to


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extreme climate events, forming an essential foundation for scientifically addressing global warming in land management.

The impacts of extreme climate on land are multifaceted, encompassing land-use conflicts, ecosystem services, soil quality, and land degradation. Extreme climate exacerbates land-use changes and soil erosion, triggering conflicts over land resources and land degradation, particularly prominent in areas affected by drought and water scarcity (Ye et al., 2012; Morán-Ordóñez et al., 2020). Simultaneously, extreme climate severely threatens various ecosystem services provided by land, such as water regulation, soil conservation, and carbon storage, profoundly affecting agricultural production and the health of natural ecosystems (Thompson et al., 2022; Arenas-Wong et al., 2023; Kicklighter et al., 2023). Furthermore, extreme climate may lead to changes in vegetation species, growth, and distribution, affecting the ecological balance and biodiversity of forests, grasslands, wetlands, and other land-use types (Barros et al., 2017; Williams et al., 2020; Litza et al., 2022). These impacts underscore the serious threat of extreme climate to land sustainability, emphasizing the urgency of adopting adaptive and mitigative measures to ensure sustainable land use (Booth et al., 2020; Quinlan et al., 2023). Previous research has found that extreme climate can affect both land use and cover directly by altering water balance and thermal conditions and indirectly by influencing ecological processes such as plant-soil ecosystems through changes in plant physiology, soil material cycling, and energy flow, thereby impacting various land-use types such as farmland, forests, and grasslands (De Boeck et al., 2016; Poudel and Shaw, 2017; Deb et al., 2018; Pipitpukdee et al., 2020; Egger et al., 2023). Although scholars have explored the effects of extreme climate on vegetation cover and net primary productivity at a macro scale (Fang et al., 2016; Shah et al., 2022; Liu et al., 2023), there is limited research on the exposure of ecological land to extreme climate events, which is crucial for the rational use and protection of land resources.

Against the backdrop of global warming, the southwestern region of China has experienced more frequent and intense extreme climate events due to factors such as excessive human activities and complex changes in the climate system (Gao et al., 2022; Wei et al., 2023). Among these events, extreme high and low temperatures are typical representatives of extreme climate events in this region (Li et al., 2022; Wang et al., 2023). Ecological land in the southwestern region of China plays a crucial role in ecological, economic, and social functions, serving as a key component for ecosystem health, sustainable socio-economic development, and biodiversity conservation (Niu et al., 2012; Jing et al., 2023; He et al., 2023). However, the intense and frequently extreme climate of the region profoundly affects the structure and function of ecological land, posing a serious threat to its utilization and protection (Luo et al., 2018; Liu et al., 2022a). Therefore, this study takes the southwestern region of China as an example to analyze the exposure conditions of ecological land under extreme high and low temperatures. The aim is to provide clear and valuable references for management authorities to optimize land use protection policies and alleviate the negative impacts of extreme climate on ecological land.

## Materials and Methods

### *Study area*

The southwestern region of China, encompassing Guizhou Province, Yunnan Province, Guangxi Zhuang Autonomous Region, Sichuan Province, and Chongqing Municipality, is situated between 91°21′ to 112°04′ E longitude and 20°54′ to 34°19′ N


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latitude, with a total area of 1.364 million $km^2$, accounting for 14.2% of China's total land area (*Figure 1*). The region features diverse and complex topography, including basins, plateaus, mountains, and hills, with significant elevation variations. The climate is predominantly subtropical, characterized by distinct wet and dry seasons, with dry and less rainy winters and humid, rainy summers. The annual average temperature ranges from 14°C to 24°C (Chen et al., 2020; Sun et al., 2023). Against the backdrop of climate change, the southwestern region experiences frequent extreme high temperatures, extreme low temperatures, and drought-flood disasters (Wang et al., 2023; Sun et al., 2023). The area boasts rich forest resources, with high forest coverage, serving as a concentrated distribution area for both natural and artificial forests in China. The diverse and abundant forested areas provide habitats for numerous flora and fauna, making it one of the most biodiverse regions in China (Zhang et al., 2023). Additionally, influenced by unique natural conditions and historical human activities, large expanses of mountain grasslands have formed in the region. These grasslands play a crucial role in the ecological safety of the southwestern mountainous areas and agricultural production (Xiao et al., 2020; He et al., 2023).

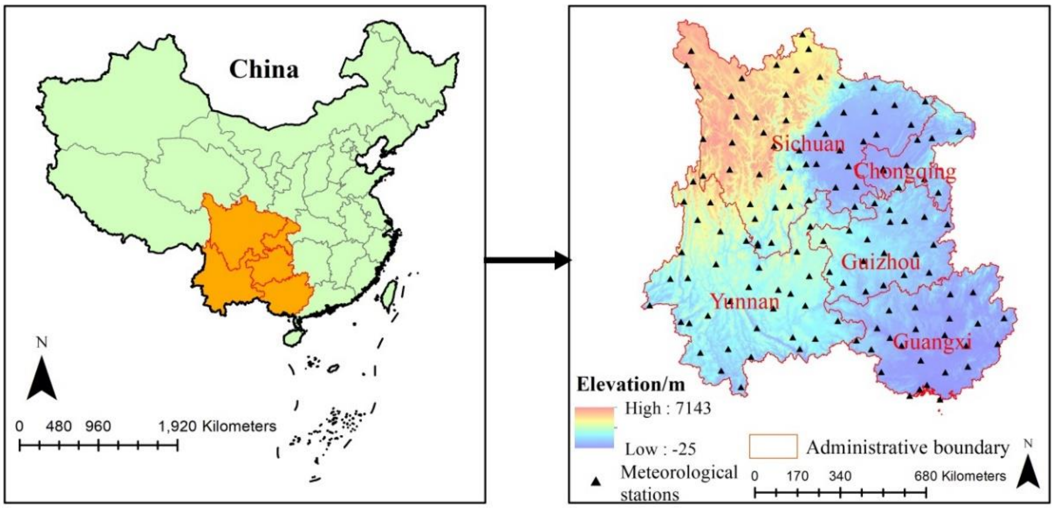


***Figure 1.** Geographical location and topography of the study area*

## *Data*

This study primarily utilized climate data, ecological land data, and elevation data. Historical climate data were obtained from daily observations of maximum and minimum temperatures from 137 meteorological stations in the southwest region of China for the years 1961-2020, provided by the China Meteorological Data Sharing Service Network (http://cdc.cma.gov.cn). The data quality is generally good, and missing parts were filled through interpolation. The data underwent strict quality control and met the requirements of this study.

Future climate data were sourced from 17 climate models under the CMIP6 (Coupled Model Intercomparison Project Phase 6) dataset, providing daily maximum and minimum temperature data for the years 2021-2100 under the SSP245 scenario. This dataset, with a spatial resolution of 0.25° × 0.25°, was produced by NASA using a daily variant of the monthly bias correction/spatial disaggregation method (Thrasher et al.,


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2022). Compared to SSP126, SSP370, and SSP585 scenarios, SSP2-4.5 represents a medium radiative forcing level, stabilizing at 4.5W/m$^2$ by 2100. This scenario aligns closely with carbon emission standards pursued by most countries for sustainable economic growth and is similar to the development situation in China (Golian et al., 2023; Haleem et al., 2023; Su et al., 2023; Dias et al., 2024). Therefore, SSP245 scenario data were chosen to analyze the exposure of ecological land under extreme temperature conditions.

Furthermore, existing research has identified uncertainties in the predictions of individual climate models, with better performance observed in the averages of multiple model simulations (Cai et al., 2021; Patel et al., 2023). Therefore, this study utilized a dataset from 17 climate models as a foundation, employing the method of equal-weighted arithmetic mean to calculate the average future climate data (2021-2100). This approach has been widely applied in climate model assessments (Gao et al., 2022; Liu et al., 2022). The 17 selected climate models for this study include: ACCESS-CM2, BCC-CSM2-MR, CanESM5, CMCC-ESM2, CNRM-CM6-1, EC-Earth3, FGOALS-g3, GFDL-ESM4, GISS-E2-1-G, INM-CM4-8, KACE-1-0-G, MIROC-ES2L, MPI-ESM1-2-HR, MRI-ESM2-0, NorESM2-LM, TaiESM1, and UKESM1-0-LL (https://portal.nccs.nasa.gov/datashare/nexgddp_cmip6/).

Ecological land data were derived from the 2020 Land Use Grid data with a 30-meter spatial resolution provided by the Chinese Academy of Sciences. This dataset, based on Landsat 8 OLI, GF-2, and other satellite remote sensing data, was generated using a fusion of remote sensing big data cloud computing and expert knowledge-assisted man-machine interactive interpretation methods. The accuracy of remote sensing interpretation exceeded 95% and met the study's requirements (Kuang et al., 2022; Yang et al., 2022; Wang and Yang, 2023). The land use types in this data were categorized into six: cropland, forestland, grassland, construction land, water bodies, and unused land. Among various land types, ecological land serves functions such as water conservation, soil protection, windbreak and sand fixation, climate regulation, environmental purification, and biodiversity protection. It is not only a crucial carrier for maintaining the safety pattern of regional ecosystems but also provides essential ecological services for human survival. While different land types exhibit certain ecological functions, their intensities vary. Therefore, we define ecological land as land use dominated by ecological functions. Based on the dominant functions of different land use types (e.g., cropland primarily for production, forestland mainly for ecological functions), this study selects forestland, grassland, water bodies, and unused land as the basis for ecological land data (*Figure 2*).

The elevation data were downloaded from the ASTER GDEM dataset (30 m resolution) available on the Geospatial Cloud Platform (https://www.gscloud.cn/sources). Slope data were obtained using the spatial analysis tools in ArcGIS software. Considering the topographical characteristics of the study area, elevation values were classified into four levels: <871 m, 872-1806 m, 1807-3182 m, and >3183 m.

### *Methods*

Referring to the research methods of Wang et al. (2017) and Xue et al. (2020), four indicators were used to characterize extreme temperature events: duration of extreme high temperature, duration of extreme low temperature, intensity of extreme high temperature, and intensity of extreme low temperature. This study uses a 9-day duration


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as the basis for calculating extreme high and low temperature durations. Days in a year that exceed the extreme high temperature threshold for 9 days or more are defined as duration of extreme high temperature, and similarly, days that fall below the extreme low temperature threshold for 9 days or more are defined as duration of extreme low temperature. Historical observed data from 1961-2020 for daily maximum and minimum temperatures are sorted in descending and ascending order respectively, and the 10th percentile is used as the thresholds for extreme high and low temperatures. Intensity of extreme high temperature is defined as the difference between the average of all daily maximum temperatures exceeding the high temperature threshold and the threshold itself. Similarly, intensity of extreme low temperature is defined as the difference between the average of all daily minimum temperatures below the low temperature threshold and the threshold (*Figure 3*).

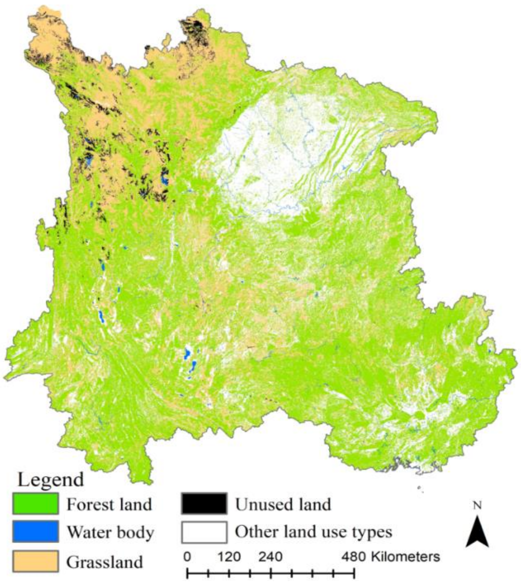


***Figure 2.*** *Distribution of ecological land*

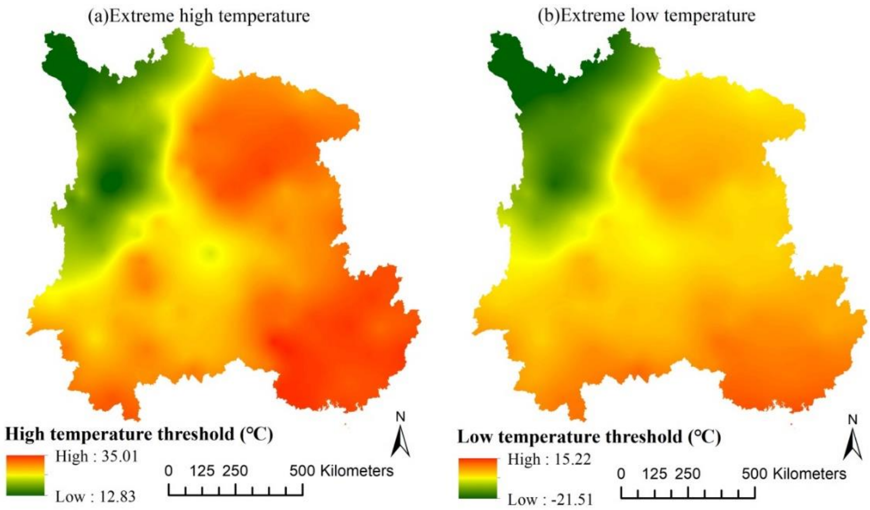


***Figure 3.*** *Spatial distribution of extreme temperature threshold*


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Based on these four indicators, extreme temperature indices are calculated for the historical period from 1995-2014 and future periods under the SSP245 scenario for each 20-year interval from 2021-2100. These indices are classified into 5 levels according to their numerical characteristics (*Table 1*).

***Table 1.*** *Classification of extreme temperature indicators*

| Indicators | I | II | III | IV | V |
|---|---|---|---|---|---|
| Duration of extreme high temperatures /d | <10 | 20~30 | 30~40 | 40~50 | 50 |
| Duration of extreme low temperatures /d | <2 | 2~4 | 4~6 | 6~8 | >8 |
| Intensity of extreme high temperatures | <2 | 2~2.2 | 2.2~2.4 | 2.4~2.6 | >2.6 |
| Intensity of extreme low temperatures | >-2 | -2~-2.3 | -2.3~-2.6 | -2.6~-2.9 | <-2.9 |

Note: The units for extreme high temperature intensity and extreme low temperature intensity are dimensionless

To analyze the exposure characteristics of ecological land under extreme climatic conditions at different time periods, the following steps were taken. Firstly, considering the temporal characteristics of CMIP6 climate prediction data and referring to previous literature (Lehtonen et al., 2016; Li et al., 2022), the period 1995-2014 was used as the baseline period, 2021-2040 as the near-term future, 2051-2070 as the mid-term future, and 2081-2100 as the long-term future. Secondly, using the spatial statistical module Kriging interpolation method in ArcGIS software, spatial interpolation was performed on the four extreme temperature indicators for different periods to obtain spatial patterns of extreme temperature indicators. Furthermore, based on the classification criteria of various extreme temperature indices in *Table 1*, classify each index and create extreme temperature distribution maps of different levels. Subsequently, the ecological land data and spatial distribution maps of extreme temperature indicators in different gradients for different periods were spatially overlaid using ArcGIS software to obtain the exposed area of ecological land under extreme temperatures for each period. Finally, using the baseline period as a reference, the study analyzed the changes in exposure of ecological land under extreme temperatures.

## Results

### *Exposure status of ecological land under extreme temperature impact*

As observed in *Figure 4a*, the area of ecological land exposed to levels I and III of extreme high-temperature duration dominated during the periods 1995-2014 and 2021-2040, respectively. However, the area of ecological land exposed to level V became overwhelmingly dominant in the years 2051-2070 and 2081-2100. From 1995-2014 to 2081-2100, the area of ecological land exposed to extreme high-temperature duration of levels I and II consistently decreased, while the area exposed to level V increased rapidly. It is noteworthy that the area of ecological land exposed to levels III and IV exhibited a characteristic of first increasing and then decreasing. According to *Figure 4b*, during 1995-2014, 2021-2040, and 2051-2070, ecological land was primarily exposed to extreme high-temperature intensity of level I. However, by the period 2081-2100, it was predominantly exposed to extreme high-temperature intensity of level III. Over time, the exposed area of ecological land to extreme high-temperature intensity of level I gradually decreased, while the area exposed to other levels increased.


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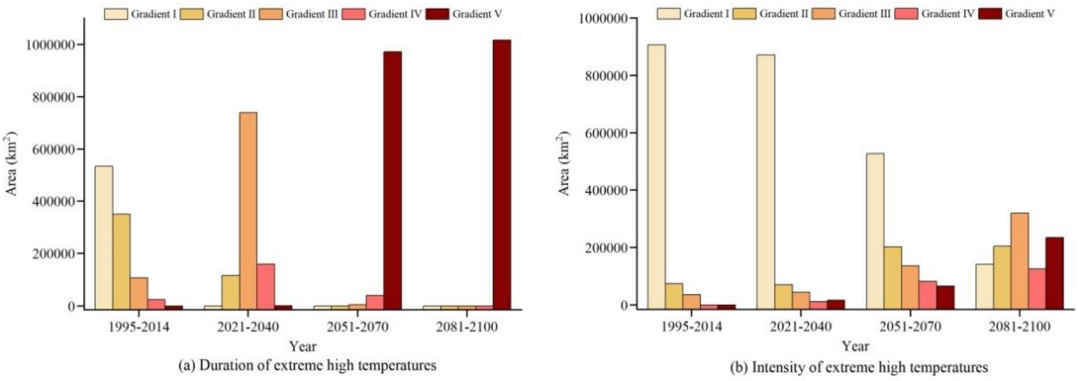


***Figure 4.*** *Changes in the area of ecological land exposed to extreme high temperatures*

*Figures 5a and 5b* illustrate the changes in the exposed area of ecological land to extreme low-temperature duration and intensity. During the period 1995-2014, ecological land was primarily exposed to level V of extreme low-temperature duration, while during 2021-2040, it was mainly exposed to levels III and IV. From 2051-2070 and 2081-2100, ecological land was predominantly exposed to level I of extreme low-temperature duration. From 1995-2014 to 2081-2100, the area of ecological land exposed to level V experienced a rapid decrease, while the area exposed to levels I and II increased rapidly. The area of ecological land exposed to levels III and IV increased initially and then decreased (*Figure 5a*). During the periods 1995-2014 and 2021-2040, ecological land was predominantly exposed to level V of extreme low-temperature intensity, while in 2051-2070 and 2081-2100, it was primarily exposed to level III of extreme low-temperature intensity. Over the historical to future periods, the area of ecological land exposed to extreme low-temperature intensity level V saw a significant reduction, while the areas exposed to levels I, II, and III experienced substantial increases. The area of ecological land exposed to extreme low-temperature intensity level IV exhibited an increase followed by a decrease (*Figure 5b*).

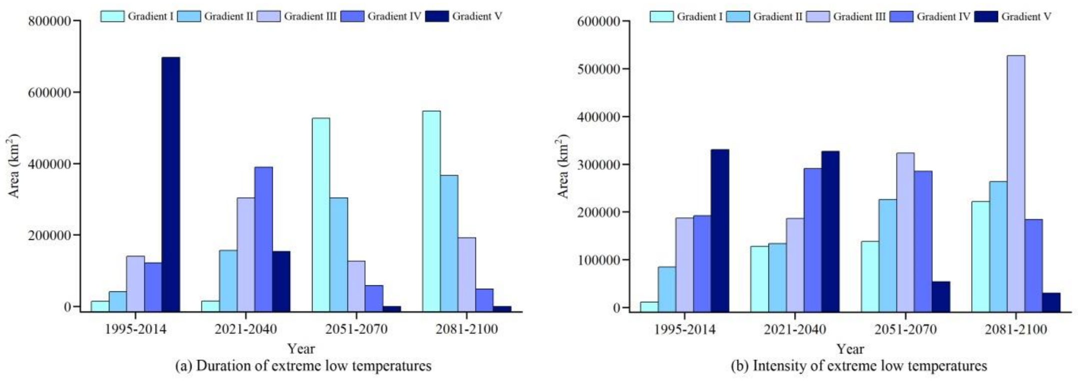


***Figure 5.*** *Changes in the area of ecological land exposed to extreme low temperatures*

## *Exposure status of various ecological land types under extreme temperature impact*

*Figure 6* illustrates the area changes of various ecological land types exposed to extreme high temperature duration. Except for water bodies, forestland, grassland and unused land were primarily exposed to level I of extreme high temperature duration


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during 1995-2014. During the period 2021-2040, all four ecological land types were predominantly exposed to level III of extreme high temperature duration, shifting to level V during 2051-2070 and 2081-2100. Over time, the areas of four ecological land types exposed to extreme high temperature duration at levels I and V decreased and increased, respectively. Except for unused land, the areas of forestland, grassland, and water bodies exposed to level II of extreme high temperature duration decreased. The areas of the four ecological land types exposed to levels III and IV of extreme high temperature duration increased initially and then decreased.

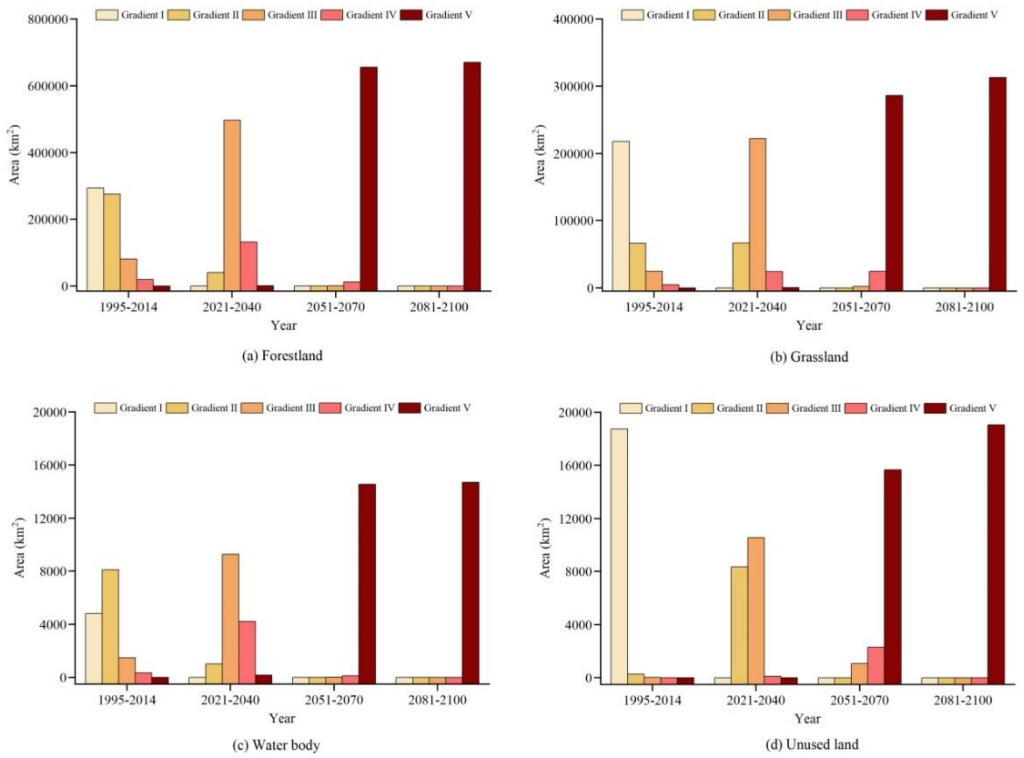


***Figure 6.*** *Changes in the area of various ecological land types exposed to extreme high-temperature duration*

The exposure statistics of various ecological land types to extreme high-temperature intensity provided by *Figure 7* indicate that, in the periods 1995-2014, 2021-2040, and 2051-2070, all types of ecological land were predominantly exposed to extreme high-temperature intensity level I, while in 2081-2100, they were mainly exposed to level III. From 1995-2014 to 2081-2100, the areas exposed to high-temperature intensity level I for various ecological land types decreased, while the areas exposed to levels IV and V increased. The areas of forestland and water bodies exposed to extreme high-temperature intensity level II continued to increase, while the exposure areas of grassland and unused land showed a characteristic of first increasing and then decreasing. Except for unused land, the areas of forestland, grassland, and water bodies exposed to extreme high-temperature intensity level III continued to increase.


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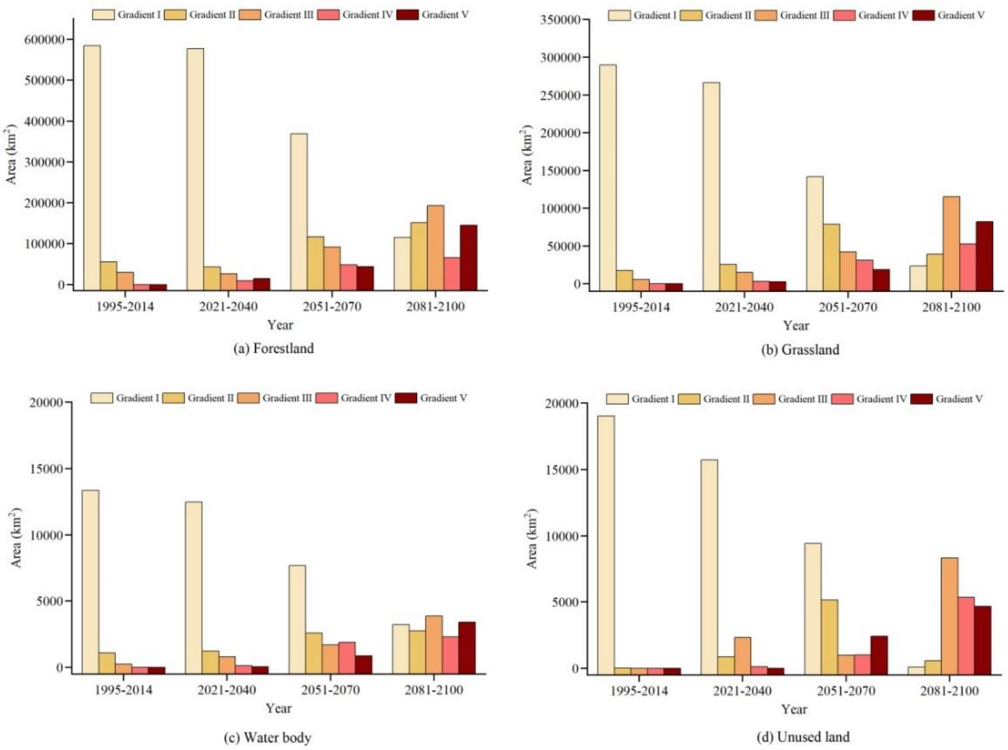


***Figure 7.*** *Changes in the area of various ecological land types exposed to extreme high-temperature intensity*

As shown in *Figure 8*, all four types of ecological land were predominantly exposed to level V of extreme low-temperature duration in the period 1995-2014, while in the years 2051-2070 and 2081-2100, they were mainly exposed to level I or II. Except for unused land, the other three types of ecological land in the period 2021-2040 were mainly exposed to levels III and IV of extreme low-temperature duration. From the historical period to the future period, the areas of ecological land exposed to level V and II of extreme low-temperature duration showed a significant decrease and increase, respectively. The areas of ecological land exposed to levels I, III, and IV of extreme low-temperature duration first increased and then decreased.

As observed in *Figure 9*, level V was the predominant exposure level for extreme low-temperature intensity for forestland and water bodies in the period 1995-2014, while grassland and unused land were mainly exposed to level I. In the period 2021-2040, forestland and water bodies were primarily exposed to levels III, IV, and V of extreme low-temperature intensity, while unused land was mainly exposed to level I. The differences in grassland area exposed to the five levels of extreme low-temperature intensity were not significant in the period 2021-2040. In the years 2051-2070, forestland and water bodies were mainly exposed to levels III and IV of extreme low-temperature intensity, while grassland was mainly exposed to levels II and III. Levels I and II were the predominant exposure levels for unused land in the period 2051-2070. Except for unused land, in the year 2081-2100, forestland, grassland, and water bodies were mainly exposed to level III. From the historical period to the future period, the areas of four ecological land types exposed to extreme low-temperature intensity levels I and V continued to decrease, while the areas exposed to levels II and III continued to

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increase. The areas exposed to extreme low-temperature intensity level IV for all four types of ecological land are expected to increase initially and then decrease.

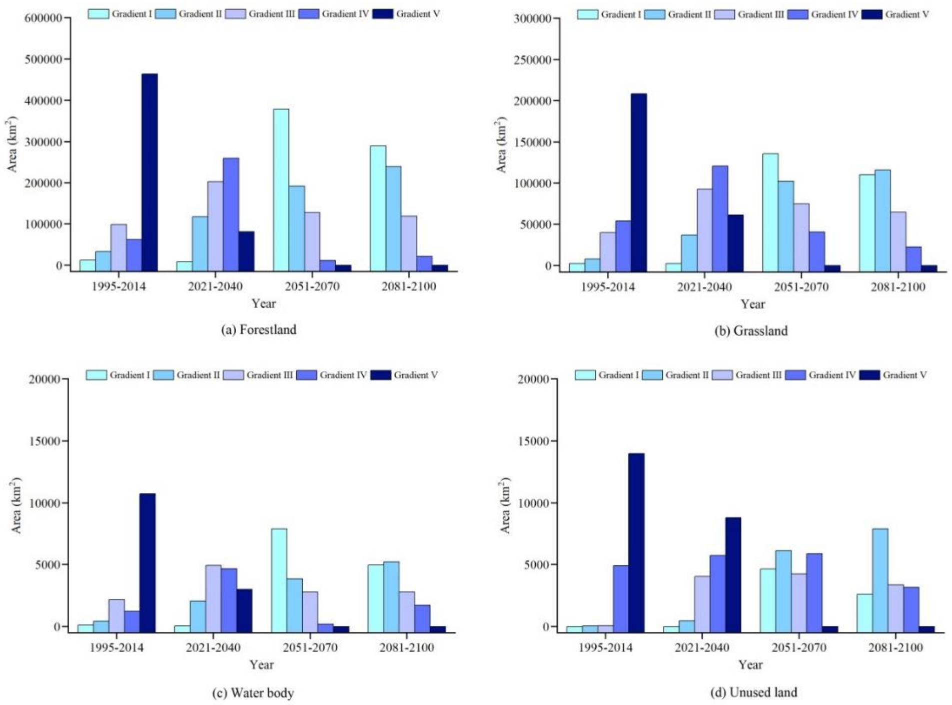


***Figure 8.*** *Changes in the area of various ecological land types exposed to extreme low-temperature duration*

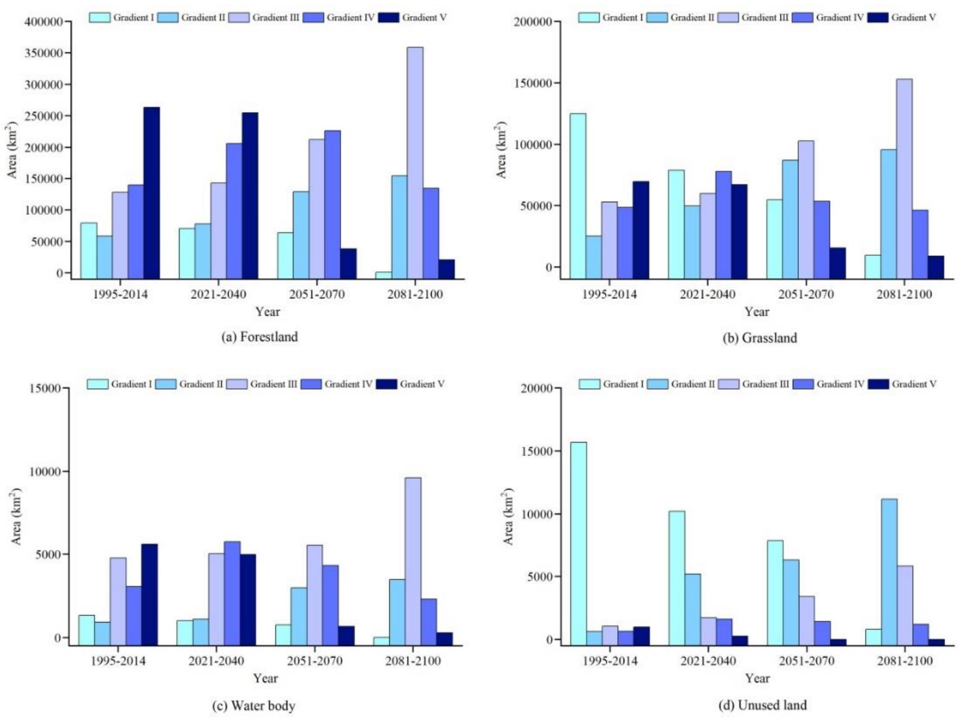


***Figure 9.*** *Changes in the area of various ecological land types exposed to extreme low-temperature intensity*


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***Spatial patterns of ecological land exposure to extreme temperatures***

*Figure 10* illustrates the spatial patterns of ecological land exposure to extreme high temperatures. In the period 1995-2014, the majority of ecological land in the study area was exposed to levels I and II of extreme high-temperature duration, with only sporadic areas in the southwest being exposed to levels III and IV (*Figure 10a*). By the period 2021-2040, most ecological land in the study area was exposed to levels III and IV of extreme high-temperature duration, and by the year 2081-2100, the vast majority of ecological land in the study area was exposed to level V (*Figures 10b*, *c*, *d*). This indicates a transition in the exposure of ecological land in the study area from predominantly experiencing levels I and II of extreme high-temperature duration in the historical period to levels III and IV, ultimately evolving into predominantly experiencing level V (*Figures 10a-d*). In the years 1995-2014 and 2021-2040, the majority of ecological land in the study area was mainly exposed to level I of extreme high-temperature intensity (*Figures 10e*, *f*). However, by the years 2051-2070 and 2081-2100, regions exposed to extreme high-temperature intensity levels III, IV, and V showed a rapid increase, particularly noticeable in the northeast and southwest regions (*Figures 10g*, *h*).

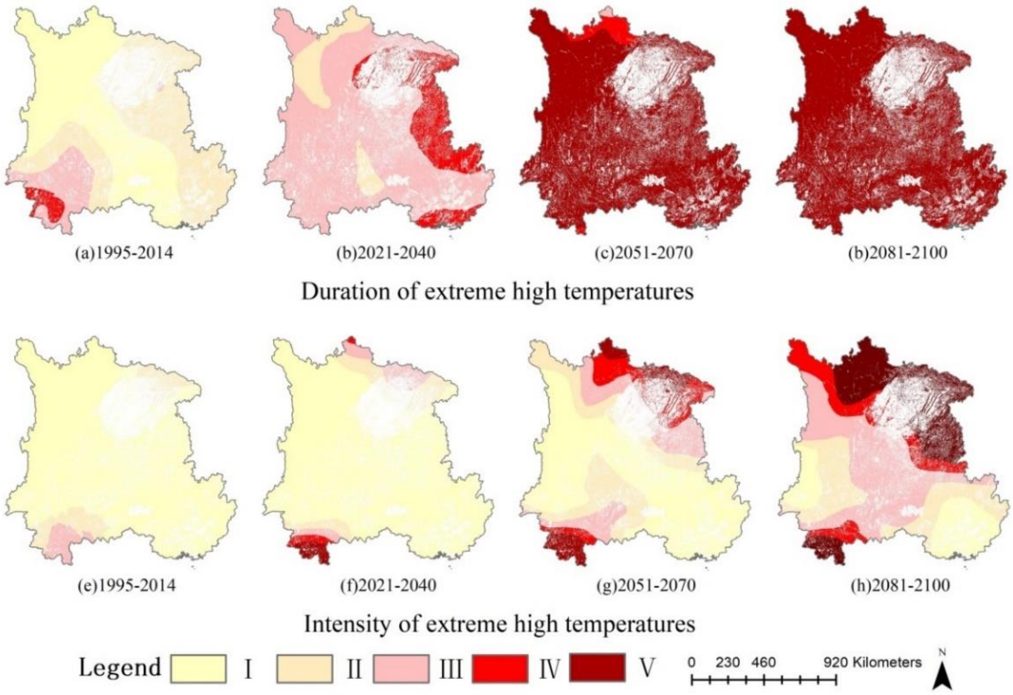


***Figure 10.** Spatial pattern of ecological land exposure to extreme high temperatures*

*Figure 11* depicts the spatial pattern of ecological land exposure to extreme low temperatures. Between 1995 and 2014, most areas of the study region showed ecological land exposure to level V of extreme low temperature duration. By the period 2021-2040, the spatial extent of ecological land exposed to levels II, III, and IV expanded. In the years 2051-2070 and 2081-2100, ecological land exposed to levels I and II of extreme low temperature duration is projected to dominate the study area, while the spatial extent exposed to levels III, IV, and V rapidly contracts (*Figure 11a-*


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*d*). Over the historical to future periods, the spatial extent of ecological land exposed to extreme low temperature intensity levels I and V is expected to decrease. Changes in ecological land exposed to level V intensity are particularly pronounced in the northwest and eastern regions, with substantial variations in level I exposure in the southern region. Simultaneously, the spatial extent of ecological land exposed to intensity levels II, III, and IV is projected to increase, especially evident in the central and southern parts of the region (*Figure 11e-h*).

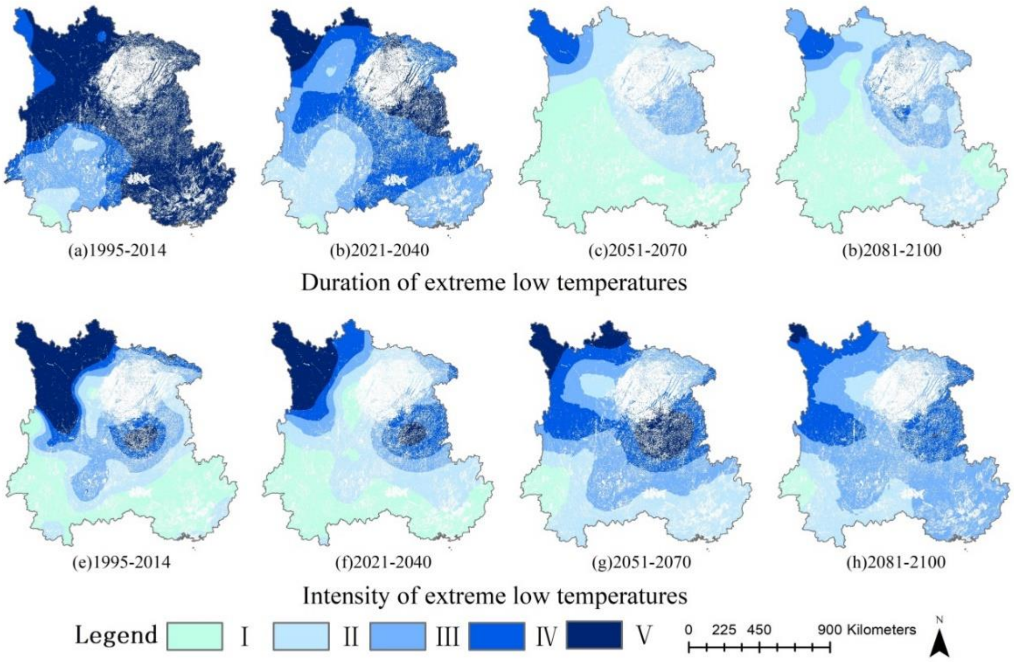


***Figure 11.*** *Spatial pattern of ecological land exposure to extreme low temperatures*

### *Characteristics of ecological land exposure to extreme temperatures along topographic gradients*

From *Figure 12(a)*, it can be observed that from historical to future periods, the ecological land area exposed to extreme high temperature duration of gradients I and V shows decreasing and increasing trends respectively across different elevation zones. Except for areas above 3183 m in altitude, the ecological land area exposed to extreme high temperature duration of gradient II shows a decreasing trend across other elevation zones. The ecological land areas exposed to extreme high temperature durations of gradients III and IV show an initial increase followed by a decrease across all four elevation zones. From *Figure 12(b)*, it can be seen that from 1995-2014 to 2081-2100, the ecological land area exposed to extreme high temperature intensity of gradient I shows a decreasing trend across all elevation zones, while gradients III, IV, and V show an increasing trend. Except for altitudes between 872-1806 m, the ecological land area exposed to gradient II shows a trend of initially increasing and then decreasing across other elevation zones.

According to the distribution characteristics of ecological land area exposed to extreme low temperature duration provided in *Figure 13(a)*, from 1995-2014 to 2081-2100, the ecological land area exposed to extreme low temperature duration of gradients


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I and II shows an increasing trend across all elevation zones, but decreases for gradient V. The ecological land area exposed to extreme low temperature duration of gradients III and IV generally shows an initial increase followed by a decrease across all four elevation zones. Similarly, from *Figure 13(b)*, it can be seen that from historical to future periods, the ecological land area exposed to extreme low temperature intensity of gradients I, II, and III shows an increasing trend across all elevation zones, but decreases for gradient V. The ecological land area exposed to extreme low temperature intensity of gradient IV shows a trend of initially increasing and then decreasing across all elevation zones.

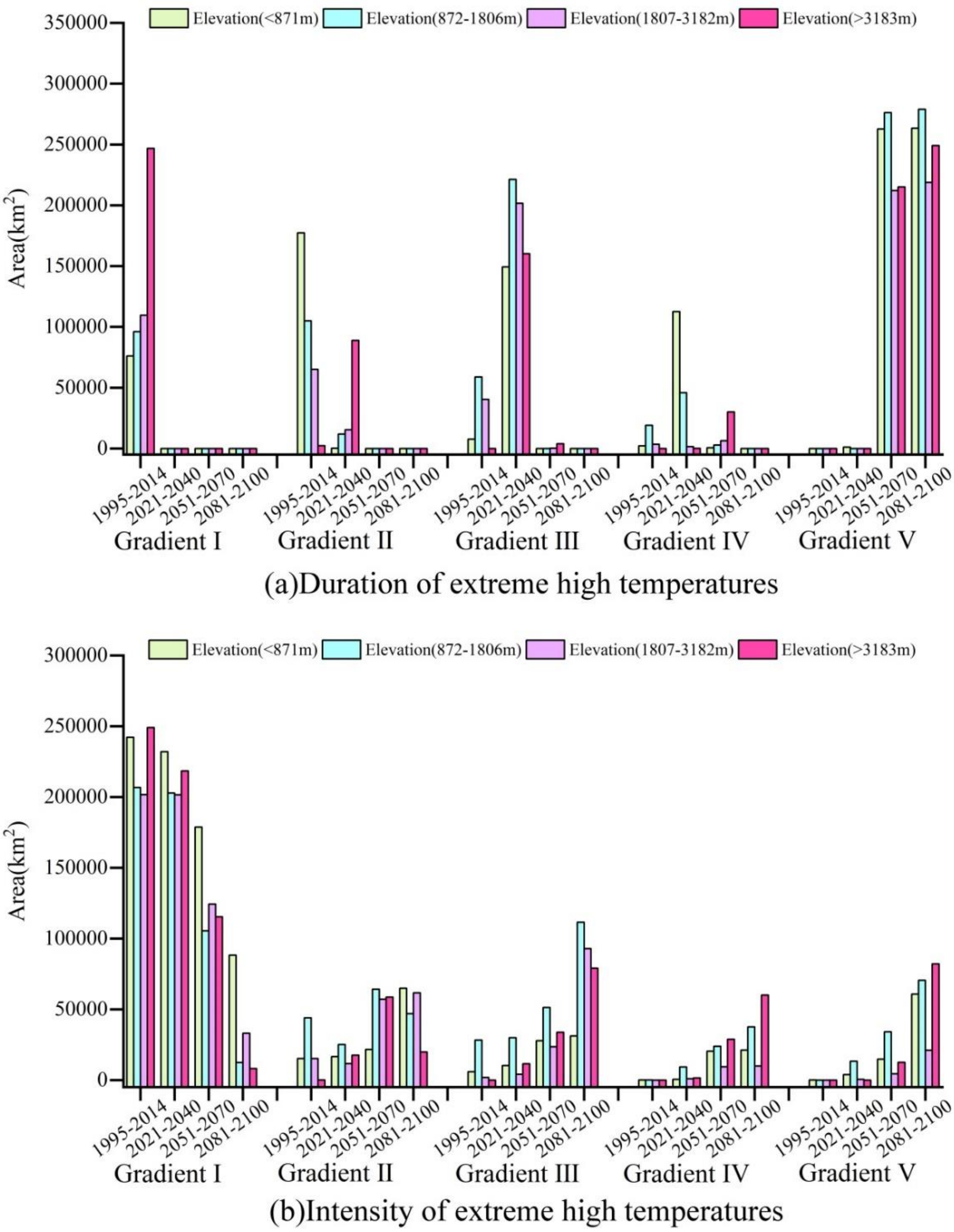


***Figure 12.*** *Variation in ecological land area exposed to extreme high temperatures along the topographic gradient*


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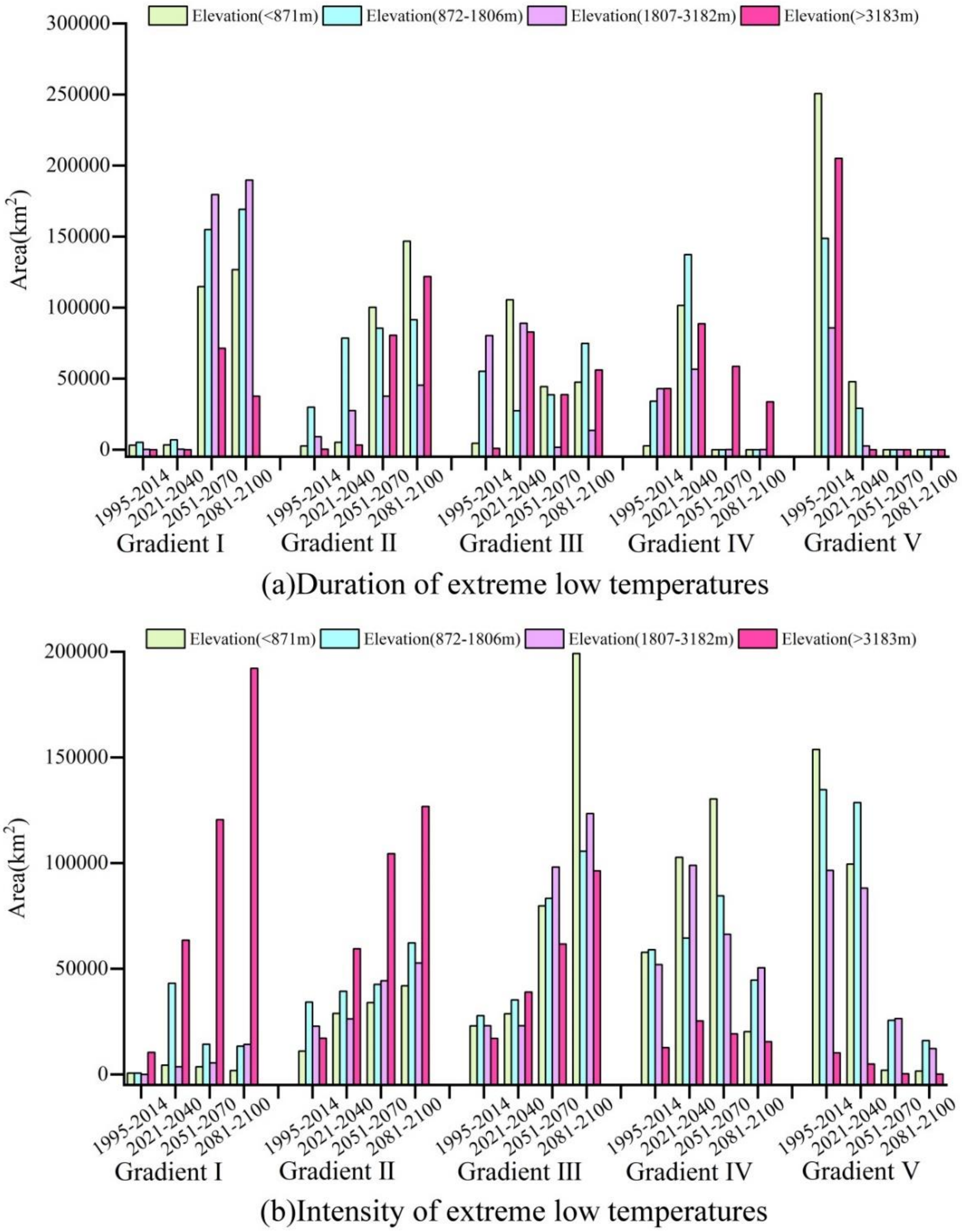


***Figure 13.*** *Variation in ecological land area exposed to extreme low temperatures along the topographic gradient*

## Discussion

### *Analysis of factors influencing the exposure of ecological land to extreme temperatures*

Before affecting global ocean circulation, global warming has intensified extreme high-temperature events and weakened extreme low-temperature events, consistent with findings from similar studies in the research area (*Table 2*). In light of this impact, the results of this study reveal that ecological land is more exposed to extreme high temperatures. This aligns with similar research findings on the exposure of populations,

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economies, and cultivated land to extreme high temperatures by Tuholske et al. (2021), Chen et al. (2020) and Wang et al. (2023). Simultaneously, this study observes a reduction in the area of ecological land exposed to extreme low temperatures, confirming the impact of global warming. This result is consistent with Yang et al.'s (2019) study on low-temperature exposure to the U.S. population. However, it is noteworthy that despite the decrease in the area exposed to highest-intensity low temperatures, areas exposed to higher and moderate intensity low temperatures still play a significant role (*Figure 4b*). This indicates that under the influence of climate warming, the intensity of extreme low temperatures will continue to have a prominent impact on the ecological environment. Furthermore, due to the evident spatial heterogeneity of extreme temperature events under climate warming, coupled with variations in the distribution of ecological land, there is a significant spatial disparity in the exposure of ecological land to extreme temperatures. For example, by 2100, all ecological lands in the study area will experience extreme high-temperature days lasting 9 days or more. However, concerning extreme high temperature intensity, ecological lands in the northeast and southwest of the study area are significantly exposed to stronger intensities, whereas exposure in other regions is relatively weaker. This indicates substantial heterogeneity in the increase of extreme high-temperature days and intensities across the study area. Moreover, due to spatial heterogeneity in extreme temperature index changes, different types of ecological lands are exposed to varying extreme temperature indices. Forests in the eastern and southern parts of the study area face more severe changes in extreme low temperature indices, whereas grasslands and unused lands in the northwest experience relatively smaller changes in extreme low temperature indices. More importantly, the complexity of the terrain enhances the spatial differences in extreme climate events and land use (Navarro et al., 2020; Luo et al., 2023), leading to a distinctive topographical gradient in the exposure of ecological land to extreme temperatures. This constitutes a crucial finding of the current study.

***Table 2.*** *Changes in the duration and intensity of extreme temperatures in the research area*

| Year | Duration of extreme high temperatures /d | Intensity of extreme high temperatures | Duration of extreme low temperatures /d | Intensity of extreme low temperatures |
|---|---|---|---|---|
| 1995-2014 | 11.89 | 1.54 | 9.23 | -2.45 |
| 2021-2040 | 26.14 | 1.66 | 6.24 | -2.39 |
| 2051-2070 | 56.76 | 2.06 | 2.54 | -2.28 |
| 2081-2100 | 82.19 | 2.36 | 2.25 | -2.09 |

## *Policy recommendations*

(1) Integrate disaster prevention and mitigation measures into ecological land planning. We recommend clearly delineating the scope of nature reserves to protect critical natural ecosystems, thereby mitigating the adverse impacts of extreme high and low temperatures. It is advised to formulate ecological restoration projects that enhance the stability of ecosystems through measures such as afforestation and wetland restoration, aiming to reduce the severity of meteorological disasters. Consideration should be given to the potential risks of meteorological disasters, and efforts should be


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made to minimize human activities' interference with ecological land in high-risk areas. Additionally, we advocate for the promotion of the construction of green infrastructure, such as green roofs, parks, and ecological corridors, to enhance the regional ecological resilience.

(2) Strengthen monitoring, forecasting, and early warning systems for extreme temperatures. Meteorological departments should strategically deploy monitoring and warning networks, intensifying monitoring efforts in areas with frequent extreme temperatures and temperature anomalies. Simultaneously, efforts should be made to enhance and expand the monitoring capabilities and physical modeling capabilities within the region, aiming to improve the reliability and stability of the regional monitoring system.

(3) Enhance disaster prevention and mitigation awareness among personnel in ecological management-related institutions and the general public. In regions prone to frequent extreme temperature events, it is suggested to appropriately strengthen the promotion of disaster prevention and mitigation knowledge and skills through training programs, thereby enhancing the region's capacity for disaster prevention, mitigation, and response.

### *Limitations*

The impacts of extreme temperature events on the ecological environment are not only related to their own intensity and duration but also influenced by human activities within the study area (Zabin et al., 2022; Mejía and Wetzel, 2023). The assessment of ecological land exposure under extreme temperatures in this study did not consider the influence of human activities on land use changes. Specifically, the calculated exposure area of ecological land to extreme temperatures in this paper is based on land data from the year 2020 and assumes no changes in land use, primarily due to the lack of high-precision and long-time-series land use prediction data both domestically and internationally. Therefore, the main limitation of this study is the absence of consideration for changes in land use under human interference. Although the selected SSP245 scenario closely aligns with the actual development situation in China, the study did not account for differences between various climate change scenarios. Exploring the exposure of land to extreme climates under different climate scenarios will be a crucial direction for future research.

## Conclusions

We conducted an analysis of the changes in exposure area and spatial characteristics of ecological land under extreme temperature conditions. The following conclusions were drawn: influenced by climate warming, the trend of changes (increase) in the exposure area of ecological land under extreme high temperatures is opposite to that under extreme low temperatures (decrease). The trend of changes in the exposure area of ecological land under extreme temperature duration is similar to that under extreme temperature intensity. There are certain differences in the area changes of different types of ecological land exposed to extreme temperatures, mainly reflected in the variations at different levels of extreme temperature indicators. In comparison to historical periods, the spatial pattern of ecological land exposed to extreme temperatures in future periods exhibits significant heterogeneity, primarily due to differences in the spatial distribution of ecological land and extreme temperature indicators. The area


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changes of ecological land exposed to extreme temperatures demonstrate distinct topographical gradients, and the exposure to extreme temperature duration and intensity also exhibits notable differences in the distribution of topographical gradients. Integrating disaster prevention and mitigation measures into ecological land planning, enhancing monitoring, forecasting, and early warning systems for extreme temperatures, and raising awareness of disaster prevention and mitigation are crucial measures to alleviate the exposure of ecological land. Future research will focus on incorporating the impact of human activities on land use changes and different climate change scenarios into the study of land exposure to extreme weather conditions.

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