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Original Research

Simulation and Attribution Analysis of Terrestrial Ecosystem Carbon Storage in the Yarlung Zangbo River and the Two Tributaries of the Qinghai-Tibet Plateau

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Abstract

Terrestrial ecosystem carbon stock (TECS) plays a vital role as a worldwide carbon sink, helping to mitigate global warming and lower atmospheric CO_2 levels. TECS serves as a reliable indicator for predicting global climate change. The patch generation land use simulation model incorporated human and socioeconomic factors and considered global sustainable development. Various shared-socioeconomic pathway-representative concentration pathway (SSP-RCP) scenarios were used to simulate and predict land use types in the Yarlung Zangbo River and Its Two Tributaries (YZRTT) basin on the Qinghai-Tibet Plateau (TQP). An integrated evaluation model of ecosystem services and trade-offs was employed to estimate the TECS of the YZRTT basin accurately during the same period. The potential factors influencing TECS were examined utilizing pairwise and single components in the geographical detector. In the SSP1-2.6 scenario, the TECS of the YZRTT basin will reach its highest point by 2050. This is mainly attributed to converting a significant portion of grassland into forest, resulting in the forest area reaching its maximum capacity. The expansion of cropland and constructed land area has been successfully restricted. The land area in the YZRTT basin would generally decline, except for the SSP5-8.5 scenario. Due to the rapid urbanization and growth of towns and cities, the existing developed land will be converted into cropland, artificial forests, and water bodies. The TECS of the YZRTT basin are projected to rise under various Shared Socioeconomic Pathway-Representative Concentration Pathway (SSP-RCP) scenarios. The relationship between the Digital Elevation Model (DEM) and TECS is negatively correlated, meaning that as DEM increases, TECS decreases. Settlements further away from the area tend to have higher TECS values. Anthropogenic influences significantly increase TECS in the YZRTT basin, eventually becoming the dominant factor. To enhance the TECS of the YZRTT basin, it is imperative for governments at all administrative levels

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within the basin to strategically plan the development of roads and other infrastructure while also imposing restrictions on the growth of constructed land.

Keywords: land use and cover change, land-use simulation, shared-socioeconomic pathway-representative concentration pathway scenarios, attribution analysis, terrestrial ecosystem carbon storage YZRTT basin

Introduction

The alteration of carbon stores in terrestrial ecosystems will directly influence global climate change. Terrestrial ecosystems actively participate in the cycling and exchange of carbon through vegetation, soil, microbes, and the atmosphere [1]. Global warming will result directly from the depletion of carbon stores in terrestrial ecosystems. Enhancing carbon storage in land-based ecosystems and reducing human-caused carbon emissions are viable strategies for mitigating the pace of global warming. Given the global variation in spatial patterns and causes of carbon stocks in terrestrial ecosystems, it is important to assess and predict carbon stocks in typical regions [2]. This will allow for an adequate evaluation of changes in terrestrial ecosystem carbon stocks and global climate change and response mechanisms.

Land use/land cover change (LUCC), alterations in environmental variables (such as temperature, precipitation, and slope/elevation), and the implementation of regional development policies (including the establishment of settlements, construction of roads, and mining activities) all contribute to modifications in the amount of TECS [3]. The conversion of forest or shrubs to grassland or cropland leads to a substantial decrease in carbon stores in the soil. Abnormal rises in rainfall and temperature on a local level expedite the speed at which soil erosion occurs in high-altitude areas, thus diminishing the ability of alpine soils to store carbon. High-altitude regions are frequently the primary locations where global climate change has the most substantial impact. Alterations in LUCC and climatic conditions would expedite the degradation of alpine vegetation and diminish TECS [4]. The ongoing urbanization, the rapid growth of communities, and the development of roads will result in LUCC. This will involve the transformation of natural forest and shrub areas into constructed land and converting wetlands into cropland and grassland. Human activities ultimately alter the initial LUCC and diminish the TECS. Hence, integrating the analysis of LUCC with environmental factors and regional development plans will enable a precise evaluation of the carbon stock in regional terrestrial ecosystems [5].

Currently, the most common approach for acquiring data for future land use type simulation and TECS simulation involves combining large-scale multi-temporal regional remote sensing imagery and typical-scale field surveys. This approach offers the benefits of quick data acquisition and accurate data calibration [6]. The majority of LUCC studies rely on remote sensing images to forecast forthcoming alterations in land use on a regional level. Various models and techniques, such as CLUE-S (land use conversion and its impacts at a small area scale) and IDRISI CA-Markov (automated metacellular machine-Markov chain), are employed [7]. However, IDRISI CA-Markov and CLUE-S need to consider the spatial distribution of current land use types across different land use categories [8]. The geographical neighborhood link between various existing land use types is used to analyze the trend of future changes. However, this method must provide a more accurate prediction of future land use kinds. The Patch Generation Land-Use Simulation (PLUS) is an enhanced model for the Future Land-use Simulation (FLUS). It uses the Random Forest algorithm to extensively analyze the factors that drive land expansion. This analysis allows PLUS to determine the contribution of each land class to the expansion process [9].

PLUS can simulate the changes at the patch level for each land class. The InVEST (Integrated Valuation of Ecosystem Services trade-offs) model is exact and has quantifiable qualities when simulating carbon stocks. The PLUS and InVEST models can be utilized to simulate and predict changes in TECS at the regional level [10].

Climate change is one of the most important global concerns, and the Fifth Assessment Report of the IPCC (AR5) concludes that humanity's yearly increase in greenhouse gas emissions has seriously affected the stability of natural ecosystems and human societies [11]. Over the past 100 years, global warming has increased the frequency of extreme weather and climate variability. According to the Green Paper on Climate Change, the Tibetan Plateau is one of the most sensitive regions to global climate change, with a significantly higher rate of warming than other neighboring regions. The study of future climate change is important for the sustainable development of the Tibetan Plateau region [12].

Earth system models are important for understanding history and predicting future climate change. The Sixth International Coupled Model Intercomparison Program (CMIP6) has carried out 23 sub-programs, including the Land Use Model Intercomparison Program (LUMIP), the Cooperative Regional Climate Downscaling Program (CORDEX), and the Scenario Model Intercomparison Program (Scenario MIP) [13]. Scenario MIP is one of the main sub-programs of CMIP6. Scenarios in CMIP6 are combined scenarios of different Shared Socioeconomic Pathways (SSPs) and RCPs, which incorporate the implications of future socioeconomic development, and the emission scenarios are divided into six IS92 scenarios, each of which consists of a set of chemical reactive gases (CREGs), aerosols, and greenhouse gases (GHGs). Emissions, concentrations, and land use/cover time routes influence the country's choice of different development strategy paths. The quantitative elements that make up the SSP cover seven main areas: population, lifestyle, economic development, environment and natural resources, human development, policy, science, and technology [14]. At the 2012 IPCC AR5 thematic meeting, five foundational SSPs (SSP1-SSP5) were identified as: sustainable development pathway SSP1, intermediate pathway SSP2, regionally competitive pathway SSP3, uneven pathway SSP4, and traditional fossil-fuel dominated pathway SSP5 [15, 16].

The YZRTT basin is renowned for its highly favorable ecological and natural conditions on the Tibetan Plateau. However, over the past three decades, the resources and environment in this basin have faced a significant increase in pressure. This can be attributed to the area's rapid economic and population growth. In the 1990s, the Tibet Autonomous Region initiated a 10-year extensive development project called "Yarlung Zangbo River and Its Two Tributaries". This project resulted in a continuous expansion of cropland in the basin and a relatively high population growth rate. Therefore, the carrying capacity of the basin resources and environment will reach its maximum in the future, and the conflict between protecting the ecological environment and achieving sustainable development will become increasingly noticeable [17]. The conflict between natural environmental conservation and sustainable development in the basin will become increasingly apparent. The combination of global warming and human-induced disturbances would intensify the alterations in the terrestrial environment [18]. In the framework of global sustainable development, predictions of regional-scale TECS and regional environmental monitoring are made by basin land use modeling under multiple shared-socioeconomic pathway-representative concentration pathway (SSP-RCP) scenarios [19]. An attribution study examined the factors that impact the regional TECS [20]. These predictions serve as a foundation for further analysis. The research findings can establish a theoretical foundation for the ecological security barrier in the YZRTT basin and serve as a guide for developing ecological civilization highlands in other areas of the Tibetan Plateau.

Materials and Methods

Study Site

The YZRTT basin is in the south-central part of the TQP, specifically at coordinates 87°10′-92°38′E and 28°18′-30°37′N. This basin serves as a significant area for plantation and agricultural animal husbandry in the Qinghai-Tibet region, as shown in Fig. 1. From 2000 to 2020, the GDP of the basin increased from RMB 5.256 billion to RMB 102.73 billion, and the population increased from 893,600 to 1,306,000 (Fig. 1c)). The Chengguan District of Lhasa experienced the highest population growth rate [21]. Tibet's population is projected to continue to grow steadily until 2050, with the YZRTT basin being one of the regions experiencing the most rapid population increase in Tibet [22]. The YZRTT basin experiences an arid and semi-arid climate due to its location in the temperate zone of the plateau. The average annual temperature ranges from 5-11°C, while the average annual precipitation is between 200-550 mm. The rainy season occurs from June to September, with the highest rainfall in July and August. The basin's terrain is characterized by high elevations in the north and south, as well as a flat central region. Vegetation in the basin is relatively sparse, with low forest coverage. The dominant vegetation types are grassland and shrubs. Over the past few decades, the YZRTT basin has experienced significant changes in land use and land cover due to the area's rapid population and economic growth [23]. These changes include the expansion of agricultural and constructed land, the conversion of wetlands and grasslands into agricultural land, and an increase in soil erosion. It is important to highlight that due to global warming, the size of wetlands and bodies of water is expanding while the size of glaciers is shrinking [24]. Additionally, some unused land is being converted into grassland or shrubland, while certain forested and shrub areas are being transformed into unused land.

Basic Data and Processing

Land-Use Harmonization 2 (LUH2) datasets for 2000-2020, as revised under the recommendations of the United Nations Intergovernmental Panel on Climate Change (IPCC), were used to predict and model future land use types in the One River and Two Rivers Basin for the period 2020-2050. Table 1 displays the drivers and basic data utilized by LUCC. The natural parameters considered in the study region include elevation, precipitation, dryness, temperature, and NDVI, which are the available data types. The anthropogenic factors we considered include night light intensity, GDP, population density, livestock density, the shortest distance to a habitation point (calculated using Euclidean distance from the study area), distance to waters (calculated using Euclidean distance from the study area), and distance to the road (calculated using Euclidean distance from the study area). The SSP-RCP scenario statistics were acquired using the most recent research findings from the IPCC [25].

Data Analysis Methods

PLUS, Models

The PLUS model was utilized to forecast and simulate the forthcoming land utilization in the YZRTT

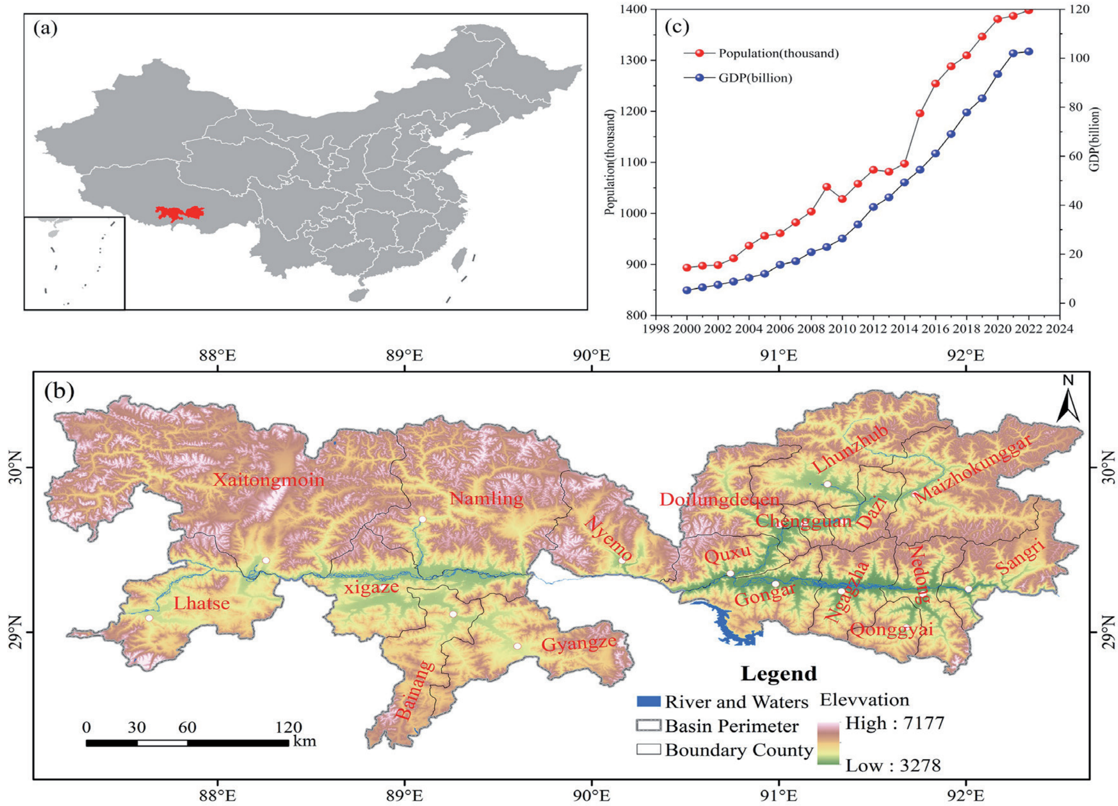

Fig. 1. General situation of the study site. a) Location of Yarlung Zangbo River and Its Two Tributaries of Tibet in China (YZRTT), b) administrative district of Yarlung Zangbo River and Its Two Tributaries (YZRTT), c) statistics of population and GDP of Yarlung Zangbo River and Its Two Tributaries (YZRTT).

Table 1. Sources of information and a description.

Data	Sources	Description	Access Date
Land Use and Land Cover (2000 to 2020)	IPCC https://luh.umd.edu/index.shtml/	Raster, 250 m × 250 m	20 May 2024
Digital Elevation Model (DEM)	Geospatial Data Cloud (China) (https://www.giscloud.cn/)	Raster, 30 m × 30 m	20 May 2024
Night-Time Lights	National Tibetan Plateau Data Center of China (https://www.tpdc.ac.cn)	Raster, 1 km × 1 km	20 May 2024
Aridity, Precipitation, and Temperature	Tibet Meteorological Bureau (http://xz.cma.gov.cn/)	Vector	20 May 2024
Gross Domestic Product (GDP)	Resource and Environment Science and Data Center of China (https://www.resdc.cn/)	Raster, 1 km × 1 km	20 May 2024
Population Density	World Pop Country Datasets (https://www.worldpop.org/)	Raster, 1 km × 1 km	20 May 2024
Livestock	World Food and Agriculture Organization (https://data.apps.fao.org/) Survey Data and Statistics	Raster, 1 km × 1 km	20 May 2024
NDVI	Resource and Environment Science and Data Center of China (https://www.resdc.cn/)	Raster, 1 km × 1 km	20 May 2024
Main Roads, Town, and Water	OpenStreetMap (http://www.openstreetmap.org/)	Vector	20 May 2024
Ecological Function Area	Tibet Natural Resources Bureau	Vector	20 May 2024
Carbon Density	Obtained from References (https://www.web of science.com/)	Calculated Average Carbon Density of Different Land-Use Types	

basin. The research process consisted of three distinct stages: 1. Determine the extent of land use in various categories within the YZRTT basin from 2000 to 2015, considering different development scenarios outlined in the SSP-RCP. Before analysis, the LUH2 dataset must be adjusted, and satellite images must be classified to represent land use accurately. Additionally, the overall land use extent should align with real-world measurements. This information will serve as the foundation for simulating LUCC. 2. Simulating LUCC requires ensuring that the overall land scale matches the actual land scale, and once this is achieved, the simulation preparation for LUCC is considered complete. 3. Using the PLUS model, we made predictions about the extent of various land types in 2000 and assessed the accuracy of the simulations. The PLUS model is commonly used to simulate LUCC at different scales. It consistently achieves high accuracy across different regional scales. The roulette wheel mechanism in the PLUS model effectively represents the competition between different land use types, making it a reliable model for studying LUCC. The roulette mechanism in the PLUS model reflects the competition between different land use types [26]. In contrast, the iterative mechanism adjusts the inertia coefficients to ensure consistency between existing and target land use types. The PLUS model accurately assesses land use types' prediction and simulation accuracy using kappa coefficients and FoM indexes. We predict and simulate the land use scale based on the development scenarios of the SSP-RCP. At a large scale, we properly replicate the land use in 2020 and project the land use change in the YZRTT basin. We use 17 driving factors from the PLUS model to drive the land use change, with ecological function zoning acting as a limiting factor.

Transfer Matrix of Land Use Types

The land use type transfer matrix clearly represents the number and types of land use transformations that occur over time and space in LUCC [27]. It effectively captures the process of land use type transformations. This study examines the changes in the quantity and distribution of different land use categories in the YZRTT basin. Eq. (1) explains the transfer matrix of land use types.

$$S = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \tag{1}$$

In the formula S, S_{ij}, and n represents the number i and area of the transformation of the j type from land use type to the type of land use type, respectively.

InVEST

The CASA (Carnegie-Ames-Stanford Approach) and InVEST models are prominent research models for evaluating TECS based on land use types. The CASA model primarily emphasizes the evaluation of ecosystem restoration and improvement effects, whereas the InVEST model primarily focuses on assessing ecosystem service values at medium and large scales. The carbon sequestration and storage module of the InVEST software allows us to determine the TECS in each area, considering various timeframes and spatial conditions [18]. This is achieved by integrating data on land use types, carbon density, and each land use type's specific carbon storage capacity within the region. The calculation is based on Eq. (2), which explains the relationship between the amount of carbon stored and the land use type.

$$C = C_{above} + C_{dead} + C_{below} + C_{soil} \tag{2}$$

In the formula: C, C_{above}, C_{dead}, C_{below}, and C_{soil} represent carbon density (t/ha), carbon density of above-ground biomass (t/ha), carbon density of dead biomass (t/ha), carbon density of below-ground biomass (t/ha), and carbon density in soil (t/ha), respectively.

Table 2. Different land use types' carbon densities in the Lhasa River Basin.

Land Use Type	Carbon Density (t/ha)			
	Above-ground Carbon Density (Cabove)	Underground Carbon Density (Cbelow)	Soil Organic Matter (Csoil)	Dead Organic Matter (Cdead)
Cropland	0.208	2.948	9.745	0
Forest	1.549	4.234	14.277	0
Shrub	0.61	0.677	16.53	0
Grassland	1.29	3.16	8.981	0
Waters	0.091	0	0	0
Constructed	0.11	0	0	0
Bare land	0.047	0	1.942	0

Geographical Detector

Geographical detectors have been extensively utilized in recent years to examine the connections between elements in ecologically significant neighborhoods. The geographical detector offers distinct advantages over typical linear models in assessing nonlinear data, correlating non-normally distributed data, and interpreting the weights of specific elements [28]. This study utilized pairs of factors and single factors in the geographical detector to investigate the potential variables that influence TECS. The Spearman correlation coefficient (ρ) was employed to ascertain the positive and negative correlations between the potential factors and TECS.

Results

LUCC Accuracy Calibration of PLUS Simulation

The mean area under the receiver operating characteristic curve (AUC) for various land use types in the YZRTT basin in Tibet is 0.912. This suggests that the PLUS model accurately simulates different LUCCs in the YZRTT basin. Furthermore, the model can be utilized to forecast land use types in the basin. The highest average AUC value for bare land was 0.927, while the lowest average for shrubs was 0.899. The mean values of Kappa and FoM in the YZRTT basin were 0.838 and 0.124, respectively. Based on the relevant research, a Kappa value of more than 0.8 and a Figure of Merit (FoM) value within the range of 0.1-0.3 is a fair distribution range. Hence, the range of AUC, Kappa, and FoM values demonstrates that the PLUS model's simulation accuracy is sufficient to simulate and predict various land use types in the YZRTT basin (Table 3).

Land Use Type Changes under Different SSP-RCP Scenarios in the YZRTT Basin in 2020-2050

Fig. 2 and Fig. 3 display the variations in land use types in the YZRTT basin across several SSP-RCP scenarios. In 2020, the terrestrial ecosystems in the YZRTT basin in Tibet were primarily composed of grassland and unused land. The grassland area accounted for 53.38% of the total land area. Bare land made up 22.48% of the total land area. Croplands, forests, shrubs, waters, and constructed areas accounted for 3.66%, 10.39%, 7.02%, 2.65%, and 0.42% of the total land area, respectively. In 2050, the YZRTT basin's terrestrial ecosystem landscape will continue to be mostly composed of grassland and unused land across all development scenarios of the SSP-RCP [29]. However, there is a declining trend in the amount of grassland and unused land, while the proportion of forest, shrub,

Table 3. Statistics of AUC, Kappa, and FoM.

Region	AUC-Cropland	AUC-Forest	AUC-Shrub	AUC-Grassland	AUC-waters	AUC-Constructed	AUC-bare land	Kappa	FoM
Chengguan	0.911	0.959	0.961	0.857	0.936	0.945	0.956	0.751	0.146
Doilungdeqen	0.907	0.855	0.874	0.876	0.896	0.924	0.893	0.872	0.071
Dazi	0.869	0.953	0.902	0.853	0.955	0.914	0.855	0.831	0.064
Lhunzhub	0.871	0.958	0.875	0.945	0.925	0.869	0.947	0.814	0.12
Nyemo	0.934	0.935	0.931	0.901	0.956	0.942	0.956	0.827	0.173
Quxu	0.946	0.873	0.883	0.892	0.948	0.936	0.962	0.893	0.063
Maizhokunggar	0.874	0.902	0.908	0.899	0.857	0.868	0.957	0.779	0.178
Xigaze	0.925	0.944	0.858	0.914	0.947	0.903	0.963	0.765	0.151
Namling	0.881	0.941	0.942	0.932	0.887	0.869	0.923	0.842	0.185
Gyangze	0.949	0.893	0.863	0.946	0.898	0.928	0.898	0.835	0.082
Lhatse	0.944	0.894	0.867	0.929	0.901	0.873	0.942	0.794	0.109
Xaitongmoin	0.882	0.915	0.871	0.935	0.863	0.886	0.947	0.893	0.149
Bainang	0.911	0.898	0.894	0.879	0.945	0.926	0.962	0.799	0.106
Nedong	0.932	0.892	0.953	0.936	0.932	0.953	0.863	0.871	0.139
Ngagzha	0.956	0.873	0.958	0.886	0.898	0.869	0.955	0.847	0.167
Gongar	0.874	0.938	0.869	0.866	0.929	0.941	0.914	0.905	0.082
Sangri	0.891	0.898	0.913	0.887	0.942	0.868	0.923	0.895	0.137
Qonggyai	0.933	0.881	0.924	0.951	0.908	0.911	0.905	0.864	0.107

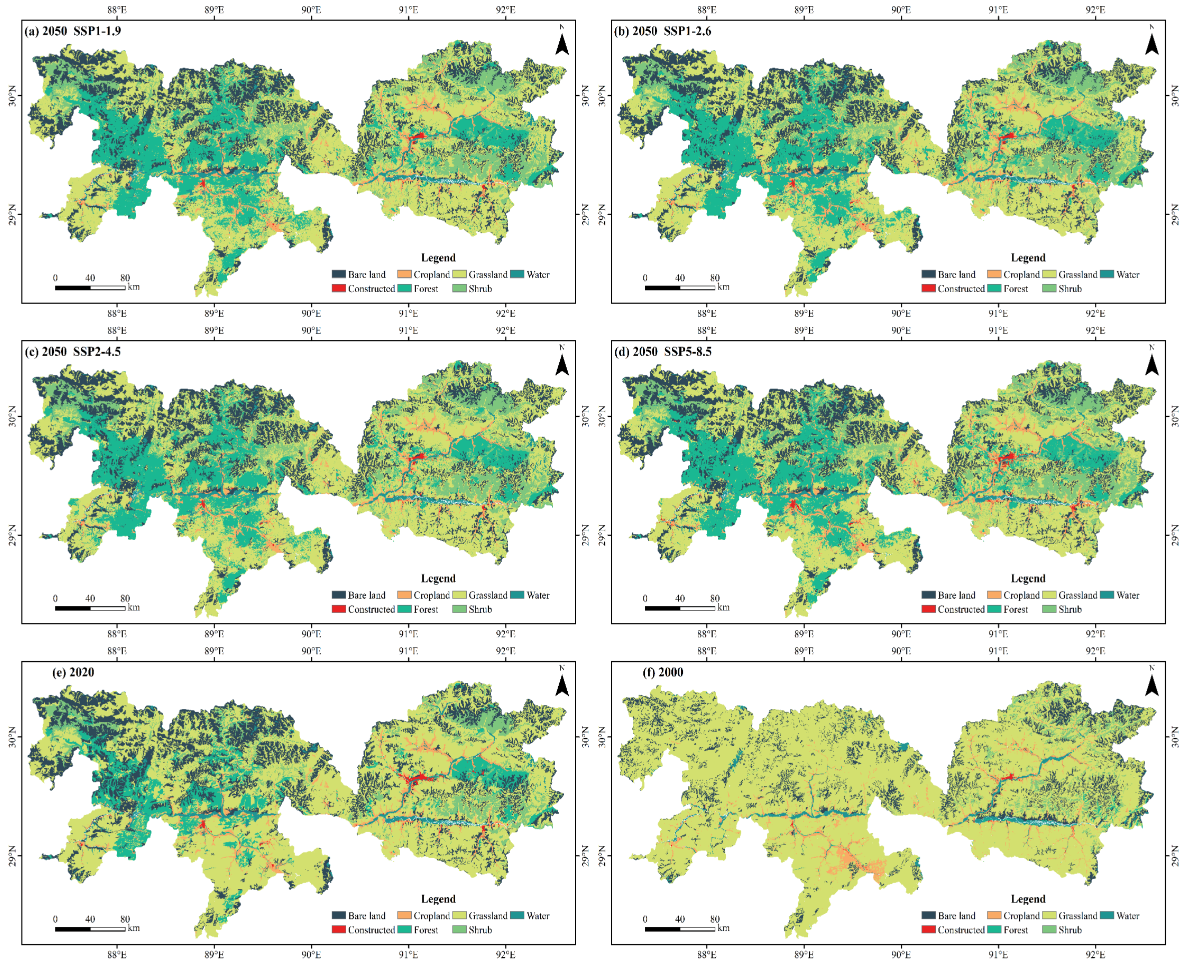

Fig. 2. Distribution of land-use types under different SSP-RCP scenarios.

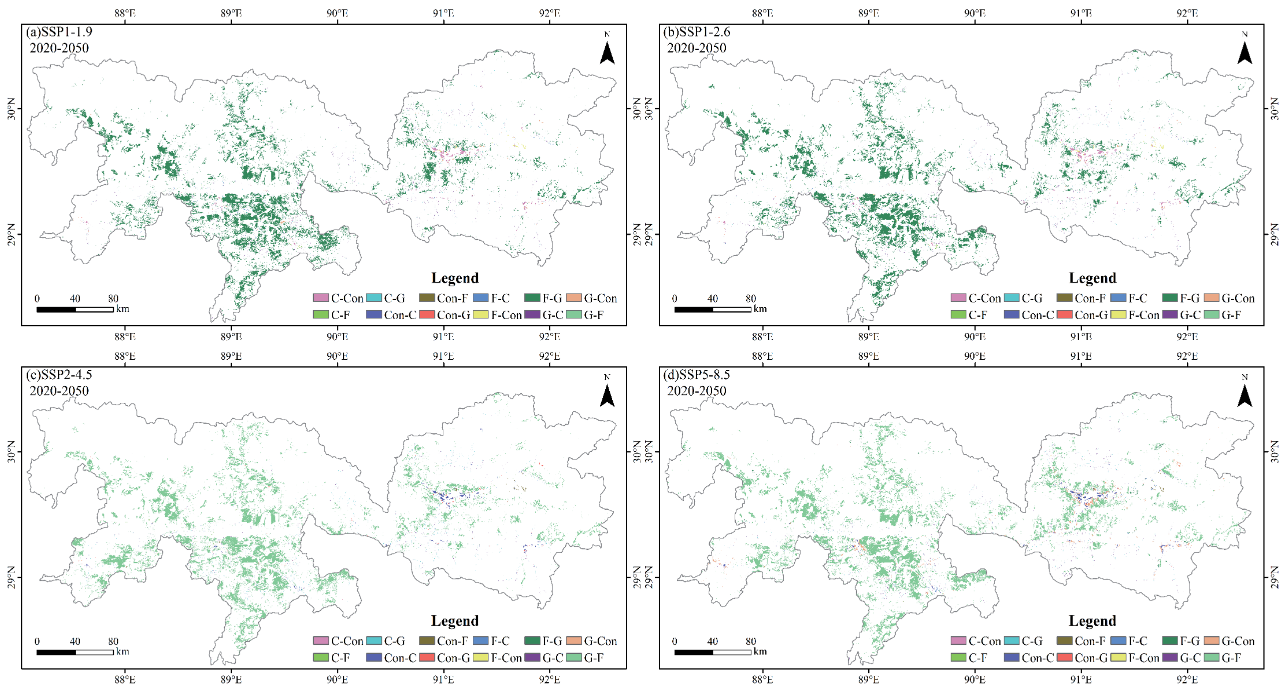

Fig. 3. LUCC under different SSP-RCP scenarios.
Notes: C, Con, G, F, Sus. Represent cropland, constructed land, grassland, forest, and sustainable land, respectively..

and water areas is increasing. The cropland area experiences varying degrees of increase in all scenarios, except for the SSP1-1.9 scenario, where it falls. The amount of constructed land is declining in all scenarios except for the SSP5-8.5 scenario, where it is increasing. It is important to mention that in the YZRTT basin, forests and shrubs experienced a significant increase across all development scenarios of SSP-RCP. Additionally, a portion of grassland and bare land was converted to forest and shrubs [30]. Furthermore, it is expected that with global warming, there will be a more noticeable trend of warming and humidification in certain parts of the plateau, which aligns with the perspectives presented by scholars both domestically and internationally. Under the high RCP development scenario, cropland in the basin will experience a substantial increase, primarily in the more densely populated areas of the basin (Chengguan, Doilungdeqen, and Nedong). The land-use type will shift towards grassland and low-level wetlands near the river. The regional food self-sufficiency balance policy influences this change.

In the high RCP growth scenario, the amount of constructed land in the basin has increased. This increase is mostly seen in the small and medium-sized cities located inside the basin, specifically Chengguan, Doilungdeqen, and Nedong. Under the low RCP development scenario, there was a substantial reduction in the amount of constructed land, primarily due to the shrinking and dissolution of small communities.

LUCC alterations were distributed across the entire basin under various development scenarios of the Shared Socioeconomic Pathways (SSP) and Representative Concentration Pathways (RCP) [31]. The alterations in cropland and constructed land were mostly focused on the low-lying valley regions of the basin, which are comparatively simple to develop and densely inhabited. The most prominent surge in shrub and forest vegetation is mostly found in the northeastern and northwestern areas of the basin, particularly at higher altitudes. These areas are next to the Qiangtang Nature Reserve and benefit from the rigorous conservation measures implemented there, resulting in minimal human interference. Furthermore, except for the high RCP development scenario, there was a notable reduction in the extent of constructed land. The fragmented nature of constructed land shifted towards a more concentrated and connected form.

Changes of TECS in the YZRTT Basin under Different SSP-RCP Scenarios

Table 2 displays the average carbon density values for various land use types, as shown by the study literature. Fig. 4 displays the land use TECS of the YZRTT basin in 2050, considering several SSP-RCP scenarios. According to Table 2, the carbon density of forest land is 20.06 t/ha, which is higher than the carbon density of shrubland (17.817 t/ha), grassland (13.431 t/ha), and cropland (12.901 t/ha). Forest carbon density is also much higher than the carbon density of water (0.091 t/ha), constructed land (0.11 t/ha), and bare land (1.989 t/ha) in terms of land carbon density. The land carbon densities of forest, shrub, grassland, and cropland in the TQP were considerably larger than those of other land types. As a result, the scale and changes of TECS in terrestrial ecosystems were primarily influenced and limited by these specific land use categories. The YZRTT basin exhibits varying levels of carbon density across distinct SSP-RCP scenarios. High-value areas of carbon density characterize the northeastern and northwestern sections of the basin, while the low-value areas are predominantly found in the low-flat regions of the basin's river valleys.

The TECS of the YZRTT basin has shown a significant increase compared to 2020 (Fig. 5). The largest increase is observed under the SSP1-2.6 scenario, followed by a decreasing trend under the high scenario. This trend is closely linked to the increase in forest transferred to grassland and the expanding scale of constructed land in the high scenario. The forest area has been declining since reaching its highest point at SSP1-2.6, with the most significant decrease observed in the southwestern half of the basin. The number of shrubs exhibited a continuous growth pattern, except in the SSP1-2.6 scenario. In this scenario, the increase in shrub area was mainly due to transitions from grassland and water classes. The maximum value on the Waters TECS scale is SSP2-4.5, which mostly results in an expansion of stream and wetland areas.

Analysis of Driving Mechanisms of TECS Changes in the YZRTT Basin

The geographical detector's Spearman (ρ) and (p) values passed the consistency test. From a single-factor perspective, the key single factors were DEM, rural road, distance from township government, and evapotranspiration. Furthermore, a negative association was observed between DEM and TECS, indicating that as DEM increased, TECS decreased. In the SSP1-1.9 scenario, the variables "distance from township government" and "evapotranspiration" carry greater significance compared to "rural road". This suggests that as the distance between a region and the settlement increases, the area's TECS also increases. Additionally, the weight of "population density" is also considered. The presence of livestock is a significant component that influences TECS. A lower population density of livestock has a lesser impact on the land resources of the basin, while a larger population density results in a greater impact on TECS. In the SSP1-2.6 scenario, the proximity to the county government and rural road is given more importance, suggesting that the impact of bigger towns and cities on the nearby rural areas is growing. Additionally, as the distance grows, the TECS also increases. In the SSP2-4.5 scenario, the significance of national and provincial roads is growing. The Transportation Exposure Concentration Score increases

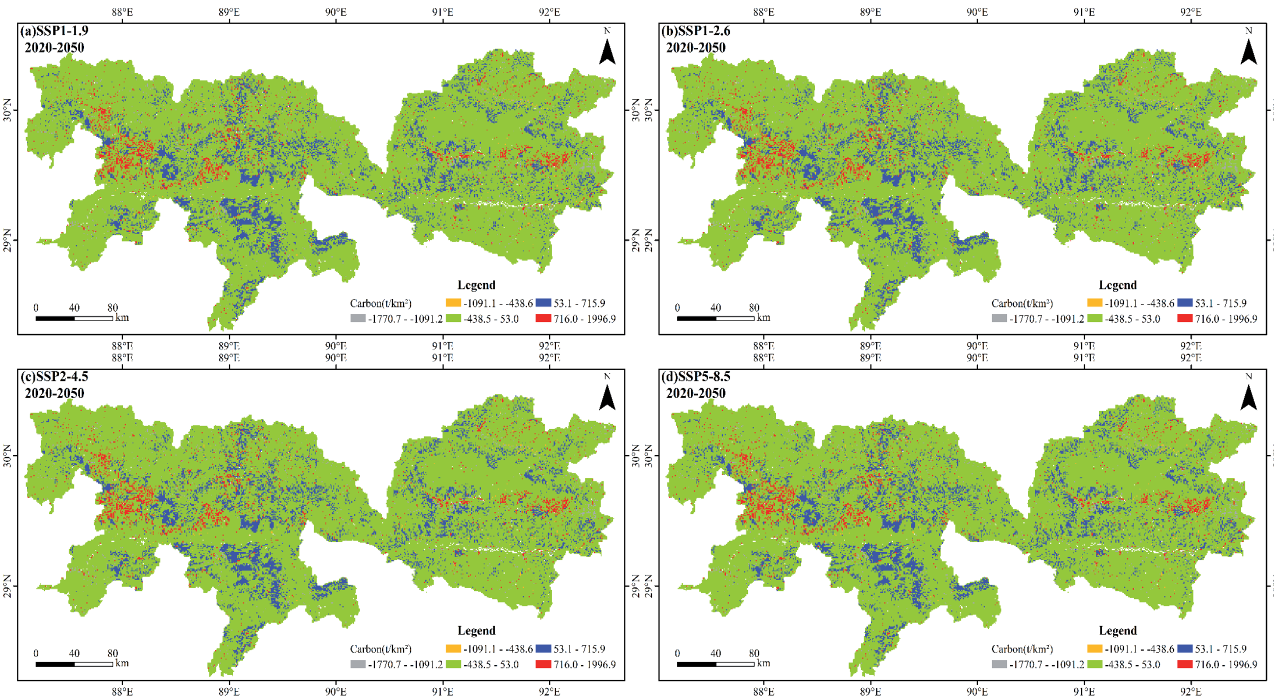

Fig. 4. TECS of different land-use types in the YZRTT basin under different SSP-RCP scenarios.

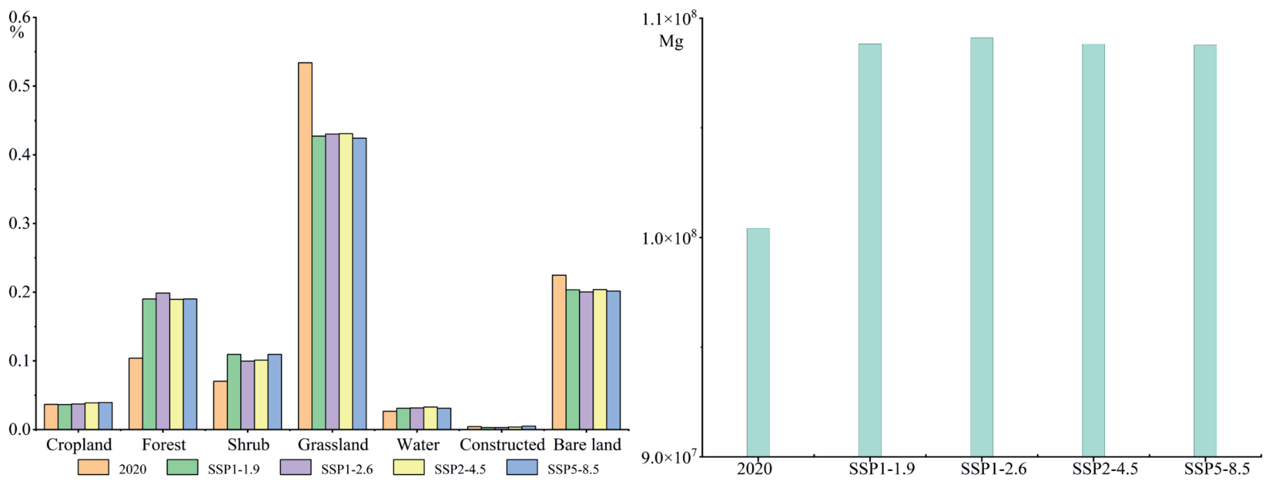

Fig. 5. Proportions of land use change and TECS under different SSP-RCP scenarios in the YZRTB basin in 2050.

as the distance from these roads increases. This suggests that the population concentration in the basin is rising, and human activities are becoming more intense in specific areas. Under the SSP5-8.5 scenario, the impact of precipitation and temperature on basin TECS is more pronounced, suggesting that global warming will exert a substantial influence on basin TECS. Due to rapid economic growth (from SSP1-1.9 to SSP5-8.5), the YZRTT basin is experiencing changes in the factors that influence its TECS. The basin is transitioning from fragmented development in its early stages to the development of small and medium-sized cities, with the road serving as the central axis for the surrounding area's aggregation [32]. Ultimately, the basin is expected to undergo highly concentrated development. To summarize, human factors are increasingly influencing the YZRTT basin TECS, eventually becoming the primary factor (Figs. 6 and 7).

Discussion

Significance of TECS for the YZRTT Basin

Given the frequent global extreme climate events and environmental issues caused by the greenhouse

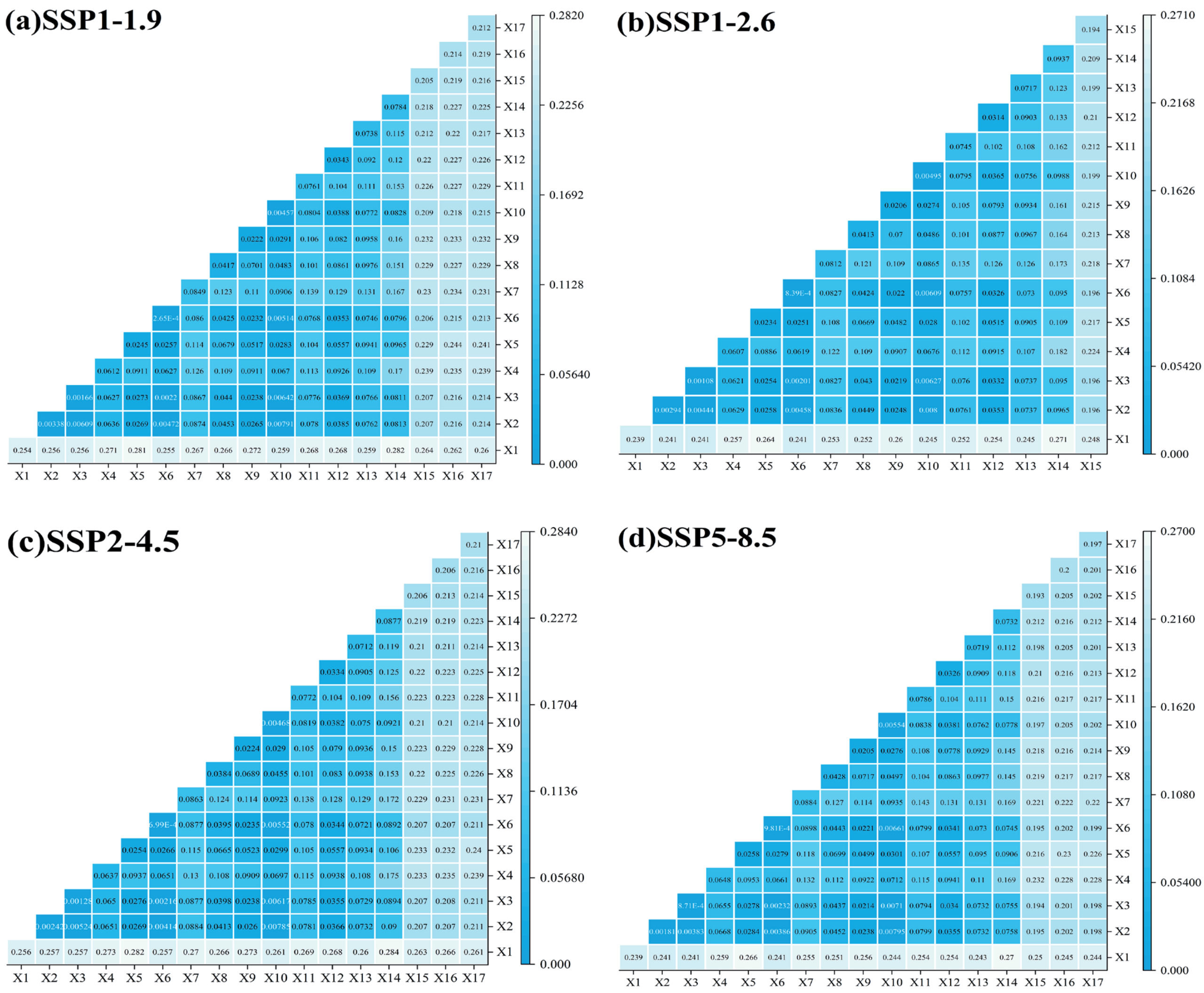

Fig. 6. Interactive detector results of spatial differentiation driving force for carbon storage in the YZRTT Basin.
Notes: X1, X2, X3, X4, X5, X6, X7, X8, X9, X10, X11, X12, X13, X14, X15, X16, X17. Representing DEM, night-time lights, GDP, national road, aridity, slope, population density, livestock, precipitation, soil erosion, temperature, provincial road, livestock density, soil, distance from the county government, rural road, distance from township government, and evapotranspiration, respectively.

effect, achieving carbon neutrality has become a shared objective for governments worldwide. The IPCC has urged all countries to decrease carbon emissions and monitor global TECS changes [33]. Enhancing the carbon sequestration capacity of terrestrial ecosystems and reducing the ongoing increase in CO_2 concentration is crucial in mitigating global warming [34]. The Chinese government aims to reach the highest carbon emissions point by 2030 and attain carbon neutrality by 2060. However, this objective poses a formidable challenge for them. Owing to the varying degrees of economic development and regional development strategies throughout China, different regions exhibit distinct levels of carbon emission efficiency [35]. Consequently, the government has taken a keen interest in developing the YZRTT basin, which serves as a crucial hub for agricultural and livestock growth in the Tibetan Plateau region. Additionally, the YZRTT basin in the TQP region contains a greater number of terrestrial high-carbon sink habitats, including highland natural forests, artificial forests, and highland shrubs in the northeast and northwest. The YZRTT basin offers promising prospects for increasing TECS in the future, thanks to the government's proposed green development plans, which include afforestation, restoring cropland to forest, returning grazing to grassland, and identifying priority regions for ecological environment conservation [36]. Due to the ongoing economic development and rapid population growth in the YZRTT basin, there has been a decline in carbon stocks in the valley area. Consequently, the valley area is transitioning from a carbon sink into a carbon source. Hence, utilizing a variety of remote sensing data sources, we analyzed the LUCC and TECS in the YZRTT basin across various periods [37]. Additionally, we investigate the underlying factors that influence the regional LUCC and TECS.

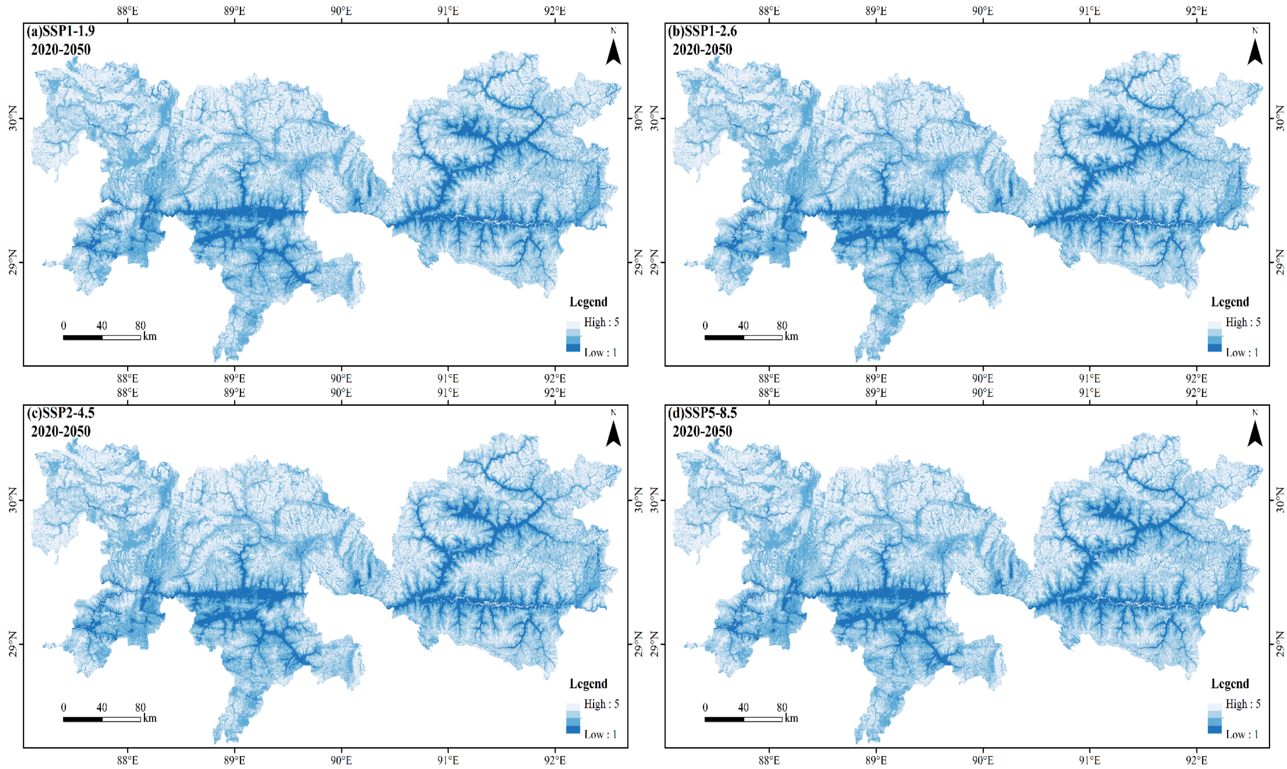

Fig. 7. Comprehensive evaluations of ecological resistance.

Analysis of LUCC in the YZRTT Basin

The YZRTT basin will experience a substantial rise in forest and shrub vegetation, primarily concentrated in the medium and high-elevation regions, such as the northeast and northwest. This expansion trend is continuous and contiguous [38]. Simultaneously, there is an observable pattern of forest supplanting shrubs in certain regions. Human activities in the low-elevation valley area have led to the fragmentation of the valley forest and shrubs, causing a shift from continuous distribution to scattered distribution. This fragmentation threatens the valley ecosystem, potentially causing damage [39].

The grasslands in the YZRTT basin consist primarily of medium-cover and low-cover grasslands. Under various SSP-RCP scenarios, there has been a significant decrease in the grassland area, particularly in the low-elevation river valley edges [40]. There is an increase in cropland in the northeastern and southwestern parts of the basin. This expansion is causing some medium-cover grassland and low-cover grassland to be replaced by cropland. As a result, the potential for TECS in the basin is being reduced. This expansion is especially notable in the outskirts of towns located in economically disadvantaged areas.

Except for SSP5-8.5, the area of constructed land in the YZRTT basin will be halved shortly. This reduction is primarily due to the haphazard growth of towns and cities in the basin during the previous development phase. These urban areas have encroached upon many low-lying valley areas. As towns and cities continue to develop intensively, some of the haphazardly expanded land will be converted from constructed land into cropland, forest, and water areas. The YZRTT basin has a lower economic and social development level than the national average [41]. As urbanization and population increase, population density in urban areas will also increase. This expansion of the economy will harm the basin ecosystem, resulting in a decrease in the potential of the TECS.

Impact of LUCC Changes on TECS in the YZRTT Basin

The YZRTT basin contains forests and shrubs with a higher carbon density, primarily found in the middle and high-elevation mountainous regions in the northern and southern parts of the basin. The distribution of TECS also follows a similar pattern, with higher values in the northern and southern parts and lower values in the river valley areas. This information is illustrated in Fig. 2, Fig. 3, and Fig. 4. In the future, the carbon density in the low-lying valleys and densely populated cities in the YZRTT basin will continue to decrease. The increase in carbon balance is primarily due to the intentional planting of trees in the valley areas and the expansion of forests, shrubs, and grasslands in the higher-elevation mountainous regions to the north and south of the basin. The total economic cost of the YZRTT basin exhibits a rise throughout all SSP-RCP scenarios, reaching its highest point in the SSP1-2.6 scenario, followed by a gradual reduction. The observed phenomenon can be attributed to the increasing spread of cropland and constructed land, as well as the declining presence of grassland, shrubs, and waters in the river valley area, as depicted in Fig. 2, Fig. 3, and Fig. 4. Hence, considering the future scenario of global warming and the ongoing and irreversible trend of rising CO_2 levels, it is crucial to expand the forest area in the river valley region and regulate the growth of cropland and constructed land in the same area. This will be vital in enhancing the TECS in the YZRTT basin.

In the mountainous regions at medium and low altitudes in the northern and southern parts of the YZRTT basin, extensive natural grasslands have been substituted by secondary forests and shrubs. This substitution has resulted in a decrease in ecosystem diversity and stability despite an increase in carbon density [42]. Over the past 20 years, the river valley's low, flat area has experienced a significant rise in artificial forests [43]. However, due to the growing occurrence of extreme weather and abnormal climate patterns, these artificial forests are less stable than natural forests in terms of population and structure. Consequently, the future stability of carbon storage in the YZRTT basin will be diminished, leading to the loss of TECS.

The YZRTT basin will experience a substantial rise in food production and a decline in carbon stores as traditional farming is substituted by contemporary mechanized, large-scale, and chemical agriculture [44]. Given the natural features of the basin, the only way to offset the development of cropland and constructed land in the valley is by reducing the amount of grassland and shrubs in the valley. It is important to mention that cropland expansion is restricted under the SSP1-SSP2 scenario. Only under the traditional fossil energy pathway (SSP5-8.5) will the cropland area continue to increase. This sustained increase in cropland will lead to the destruction of the original grassland and shrub ecosystems in the river valley low-level region. Additionally, the expansion of cropland indirectly reduces the area of grassland and shrubs in the river valley, resulting in a decrease in carbon stocks in the river valley's low-level region. The upper line will diminish.

Due to the growing resource and environmental pressures in the basin, the government is adjusting its environmental policies and promoting the rapid development of towns [45]. As a result, some of the land that was previously expanded in an uncontrolled manner will now be converted into cropland, artificial forests, and water bodies. This will lead to a reduction in constructed land in the YZRTT basin (excluding SSP5-8.5) and, consequently, an increase in the carbon stock in the river valley and low-flat areas of the basin. Given that planted forests have homogeneous and fragmented ecological communities, they cannot offer the full range of ecosystem services [46]. Additionally, the expansion of residential areas and road construction will disrupt ecological corridors, leading to a decrease in ecosystem value. The forest, shrub, and grassland areas in the suburbs and surrounding towns, which experience high levels of human disturbance, will be transformed into small, isolated patches known as "residual patches". These patches will continue to diminish in size. The forests, scrublands, and grasslands in urban suburbs and areas heavily impacted by human activity will gradually turn into small, isolated patches of land. The value of these patches in terms of their contribution to the ecosystem will diminish over time. Eventually, these patches will be transformed into developed areas as urban development intensifies. This transformation will result in a decrease in the TECS and the overall value of ecosystem services in these highly disturbed areas surrounding urban suburbs and towns [47].

Ordered and Sustainable Development Will not Reduce YZRTT Basin TECS

As economic growth (SSP1-SSP5) speeds up, human interference with nature is increasing, leading to a consistent decline in the value of ecosystem services and a shift in the factors that impact basin TECS [48]. The increase in the size of highways, railroads, and town infrastructure leads to an extension of developed areas, resulting in a dense population concentration at the regional level. This, in turn, contributes to a rapid growth in GDP and ultimately alters the total environment capacity of the basins. The YZRTT basin, being a crucial hub for China's engagement with South Asian countries, necessitates substantial infrastructure investments, including railways, highways, roads, and freight yards. However, these developments are expected to result in significant disruptions to the local population. Implementing these intensive infrastructure investments will inevitably result in a significant increase in the rate of urban construction land and transportation infrastructure development [49].

Consequently, this will contribute to a decrease in the total economic cost of supply along the transportation routes in the YZRTT basin. By 2023, the YZRTT basin has established a comprehensive and efficient highway and railroad transportation system, including the Lhasa - Shigatse - Shannan route, as well as national highways, provincial highways, and township roads that cover all townships within the basin. To enhance the total economic contribution of the YZRTT basin, it is imperative for governments at all levels to strategically plan the development of roads and other infrastructure while also controlling the growth of constructed land.

The sustainable development scenarios SSP1-1.9 and SSP1-2.6, particularly SSP1-2.6, are the most advantageous for developing the YZRTT basin. These scenarios result in the forest area reaching its highest point while the expansion of cropland and constructed land area is restricted. Additionally, the TECS of the

YZRTT basin will reach its maximum value by 2050. The SSP1-2.6 scenario is characterized by a modest expansion of the constructed land area, a lower average temperature rise, the transformation of significant grassland areas into forest and grassland in the mountainous regions of the basin's northern and southern parts, and enhanced ecological stability in valleys unaffected by intense human activity, which benefits the remaining patches of forest, shrub, and grassland in the river valleys [50]. These conditions are more conducive to growing "remnant patches" and "secondary patches" of forests, scrub, and grasslands in the river valleys. The growth rates of forest and constructed land areas differ, with forest ecosystems having significantly higher carbon stocks than constructed land [51]. This disparity contributes to an increase in TECS. Hence, implementing a systematic and environmentally conscious approach to development will not lead to a decrease in the TECS in the YZRTT basin.

Innovations and Limitations

Hao et al. [52] observed a significant shift in the land use landscape pattern of the YZRTT basin between 2000 and 2020. Specifically, they found that the area covered by forest and shrubs increased throughout this period. Nevertheless, further exploration is necessary to uncover the precise composition and stability properties of TECS within the basin. The study utilized the PLUS and InVEST models to simulate and forecast the land use types and TECS of the YZRTT basin in 2050. The models' accuracy was calibrated and assessed. Several aspects influence the PLUS model's simulation and prediction accuracy, including parameter selection and input data quality. To enhance the simulation and prediction capabilities of the PLUS model, future studies can incorporate better-resolution remote sensing image data, increase field measurement data, optimize the selection of model parameters, and give comparisons across parameters [53]. This study has two limitations in data gathering. Multiple elements influence the driving force of LUCC and undergo a dynamic change process, which might impact the precision of simulation and prediction. Furthermore, it is crucial to consider the dynamic nature of socioeconomic growth, such as the ongoing process of adjusting agricultural development.

Conclusions

The results indicate that the PLUS model demonstrates strong performance in accurately simulating and forecasting the spatial matching and quantitative accuracy of land use types in the YZRTT basin. According to the SSP1-2.6 scenario, the TECS in the YZRTT basin will reach its highest point by the year 2050. In this scenario, a significant portion of grassland is transformed into forest, with the forest area reaching its maximum capacity. At the same time, the extension of cropland and constructed land is successfully restricted. Within the SSP-RCP scenario, there is a substantial decrease in the extent of grassland, primarily occurring around the edges of low-lying valleys. The land area in the YZRTT basin will decrease, except under the SSP5-8.5 scenario. Due to the rapid urbanization and growth of towns and cities, the existing land will be converted into cropland, artificial forests, and water bodies. The TECS in the YZRTT basin will experience a rise across several Shared Socioeconomic Pathway-Representative Concentration Pathway (SSP-RCP) scenarios. The relationship between DEM and TECS is negatively correlated, meaning that as DEM increases, TECS decreases.

Additionally, the distance of settlements from the area is directly proportional to TECS, with further settlements having higher TECS values. Anthropogenic influences play a significant role in increasing TECS in the YZRTT basin, eventually becoming the dominant factor. To enhance the TECS of the YZRTT basin, it is imperative for all levels of government in the region to strategically plan the development of roads and other infrastructure while also imposing restrictions on the extension of the constructed land area. City clusters within a basin should eliminate administrative barriers and implement unified regional planning. Cross-regional coordinating bodies should be established to consider industrial layout, transportation networks, public services, and other aspects to ensure coordinated development among cities, rationally utilize natural resources (e.g., land, water, energy) and social resources (e.g., manpower, science, and technology), implement a strict land management system, strengthen the protection and utilization of water resources, and promote the mobility of talents and structural optimization. Strengthening ecological environmental protection and restoring and expanding greening areas: In urban planning, increase the proportion of green areas and parks and enhance urban greening coverage and the stability and service functions of ecosystems through afforestation and the construction of urban green areas. Promote green and low-carbon development. Promote a revolution in energy production and consumption, vigorously develop renewable energy sources, such as solar and wind energy, reduce dependence on fossil energy sources, and lower carbon emissions. Promote the transformation and upgrading of industrial structure, vigorously develop high-tech industries and modern service industries, eliminate backward production capacity, and improve economic quality and efficiency. The focus of our effort is to contribute to the preservation of terrestrial ecosystems in the YZRTT basin.

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Conflicts of Interest

The authors declare no conflicts of interest.

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