

Research on the Territorial Ecological Restoration of Counties for the Increase of Carbon Sinks —A Case Study of Wensu County, Xinjiang Uygur Autonomous Region, China

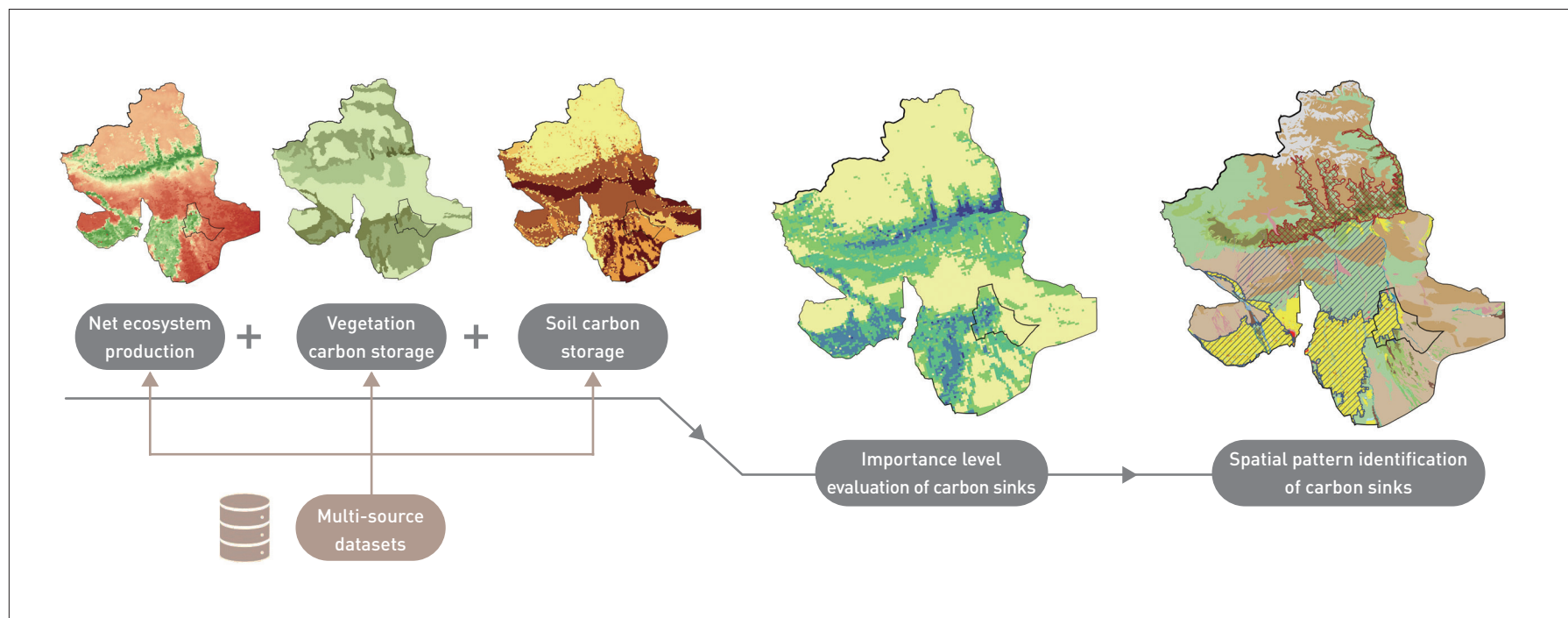
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GRAPHICAL ABSTRACT



ABSTRACT

As global climate continues to change, it is pressing to integrate the carbon peaking and carbon neutrality goals into territorial spatial planning. While little existing ecological restoration research focuses on counties in western China, particularly arid areas of northwest China, this research took Wensu County of the Xinjiang Uygur Autonomous Region in China as the study case, evaluated the carbon sequestration capacity and carbon storage of the

current carbon sinks, identified the spatial pattern of carbon sinks, and proposed the territorial ecological restoration approaches to increasing carbon sinks. The evaluation results show that the importance level of carbon sinks varies significantly across geographical environments of the county, where one primary carbon sink, two secondary carbon sinks, and potential carbon sinks with a total area of 2259.81 km² were identified. This research

extracted eight typical land use patterns based on current land use and proposed ecological restoration strategies accordingly. This research shows a way to integrate carbon peaking and carbon neutrality goals in territorial spatial planning, which is instrumental for carbon sink management in the arid areas of northwest China and provides a referable paradigm for regions with similar geographical conditions.

KEYWORDS

Carbon Sink Increase; Carbon Sequestration; Carbon Storage; County Region; Arid Areas of Northwest China; Ecological Restoration; Territorial Spatial Planning

HIGHLIGHTS

- Focuses on ecological restoration in a county in the arid areas of northwest China, aiming for carbon sink increase
- Evaluates the carbon sequestration and storage patterns of current carbon sinks in the study area and identifies the spatial pattern of carbon sink importance level
- Extracts typical land use patterns based on current land use and proposes ecological restoration strategies accordingly

RESEARCH FUND

Engineering Research Center of Water Resources and Ecological Water Conservancy in Cold and Arid Area of Xinjiang (Academician Workstation) (No. 2023.B-004)

EDITED BY Yuting GAO, Jiayi ZHOU

TRANSLATED BY Jie XIAO, Yuing GAO, Jiayi ZHOU

1 Introduction

Climate change threatens natural ecosystems and socioeconomic systems, with carbon dioxide viewed as the main driving force^[1]. To promote ecological civilization construction and cope with global climate change, China first proposed the carbon peaking and carbon neutrality goals (“dual carbon” goals hereafter) in 2020^[2] and addressed to integrate it into the overall plan of ecological civilization construction in 2021^[3].

The achievement of “dual carbon” goals depends on both controlling carbon emissions and increasing carbon storage in ecosystems, and ecological restoration has been proven effective in enhancing ecosystem carbon sequestration^{[4]~[6]}. To increase carbon sinks via ecological restoration, it is essential to evaluate the current ones with scientific methods. At present, it is common to analyze the spatial pattern or conduct spatio-temporal evolution of carbon sinks based on remote sensing data^[7]. The measuring and calculating methods include the calculation of net ecosystem production (NEP)^[8], simulation with the InVEST Carbon model^[9], and evaluation with carbon sink coefficients^[10]. Based on their evaluation results, some scholars proposed strategies for zoning and managing ecological spaces^[11]. However, most existing research focuses on larger scales of national, regional, or provincial^{[8][10][12]}, some focuses on cities or counties in developed regions^{[11][13]}, while little studies counties in western China, particularly the arid areas of northwest China.

As for ecological restoration, existing research reviewed the impact factors of ecosystem carbon sequestration and the mechanism of carbon sink increase^[14]; analyzed the current situation of utilizing ecological restoration strategies to promote carbon sequestration and carbon sink^[15]; and explored approaches to restoring forest^[16], grassland^[17], cultivated land^[18], wetland^[19], desert^[20], and marine^[21] ecosystems based on field measurement, literature review, case study, and policy interpretation. Yet few studies proposed restoration strategies incorporating ecological spatial patterns.

Focusing on Wensu County in the Xinjiang Uygur Autonomous Region of China, this research evaluated current carbon sinks in the study area, identified spatial pattern of these carbon sinks, and developed ecological restoration strategies according to different land use spatial patterns. Unlike those in the developed Beijing–Tianjin–Hebei region and coastal southeast China, most counties in the arid areas of northwest China cover relatively larger areas with less development land and more ecologically vulnerable non-development land^{[22][23]}, where ecological restoration becomes

a pressing task. This research aims to put forward ecological restoration approaches to increasing carbon sinks in the counties in the arid areas of northwest China, promoting the integration of “dual carbon” goals in territorial spatial planning and providing a referable paradigm for areas with similar geographical conditions. This paper discusses the following questions.

- 1) What is the spatial pattern of carbon sinks in Wensu County?
- 2) What are the territorial ecological restoration approaches to increasing carbon sinks?

And 3) how do the findings of this research contribute to carbon sink management in the arid areas of northwest China and similar regions?

2 Overview of Study Area and Data

2.1 Study Area

Administered by Aksu Prefecture in the Xinjiang Uygur Autonomous Region, Wensu County (40°52′–42°21′N, 79°28′–81°28′E) is located at the south foot of the Tomur Peak in the middle of Tianshan Mountain and borders the north edge of the Tarim Basin. Covering a total area of 14,600 km², Wensu County stretches 153 km from east to west and 167 km from north to south (Fig. 1)^①. With elevations ranging from 800 m to 8,000 m, this county is higher in the northern mountains and lower in the southern plains and hills. Wensu County has a temperate continental arid climate with little rainfall, high evaporation, abundant sunshine, an annual mean temperature of 10.10°C, annual mean precipitation of 65.4 mm, and annual mean frost-free period of 185 days.^② The county has

extensive natural areas indicating high carbon sink potential, with the major soil types being gypsisols, petrified gypsisols, and luvic calcisols; the primary vegetation types being desert and meadow; and the most common land use types being unused land, grassland, and farmland (Fig. 1)^③.

2.2 Data Sources and Preprocessing

The research evaluated the current carbon sinks in Wensu County and identified their spatial pattern based on multiple data sources. Considering the update frequency, availability, spatio-temporal synchronization, and data quality in recent years, the research team utilized the multi-source data of Wensu County from 2015 (Table 1). All data were projected into the Xi’an Geodetic

- ① Part of Aral City is surrounded by Wensu County. Although not administered by Wensu County, this exclave was included in the study area for ecological integrity. Limited by availability of the data, the raster data of this research covers about 14,200 km².
- ② Information about Wensu County was sourced from the official website of the Wensu Government.
- ③ This research adopted the land use classification system proposed in *China’s Multi-Period Land Use and Land Cover Remote Sensing Monitoring Dataset (CNLUCC)* and related data sources from the Resource and Environment Science and Data Center, Chinese Academy of Sciences.

1. Elevation and current land use of the study area (data sources: elevation from Geospatial Data Cloud; satellite images from Bing Maps; and land use from the Resource and Environment Science and Data Center, Chinese Academy of Sciences).

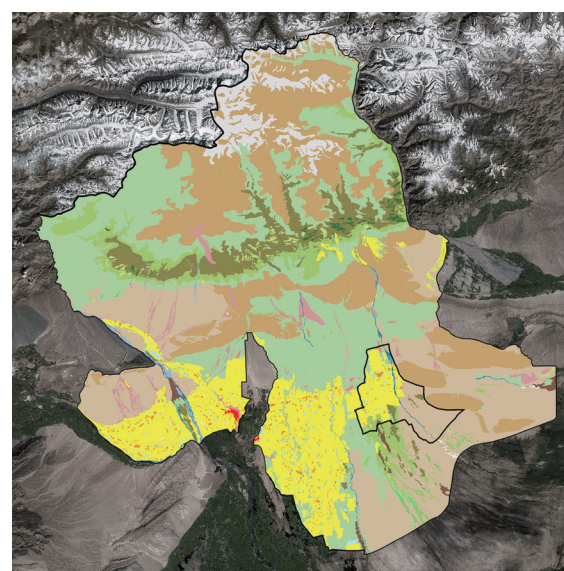
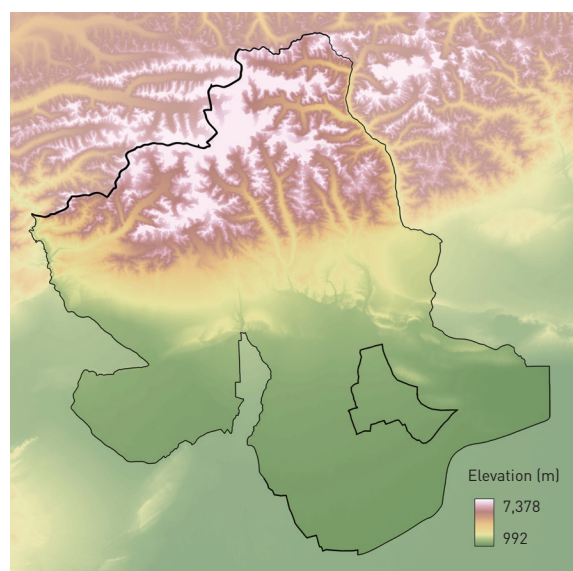


Table 1: Research datasets and data sources

Dataset	Data type	Spatial resolution	Data source
Land use	Raster	1 km	Resource and Environment Science and Data Center, Chinese Academy of Sciences
Net primary production (NPP)	Raster	500 m	United States Geological Survey
Digital elevation model (DEM)	Raster	30 m	Geospatial Data Cloud
Monthly mean temperature	Raster	1 km	Resource and Environment Science and Data Center, Chinese Academy of Sciences
Monthly total precipitation	Raster	1 km	Resource and Environment Science and Data Center, Chinese Academy of Sciences
Spatial distribution of population density	Raster	1 km	WorldPop
Spatial distribution of vegetation types	Vector	1:1,000,000	Resource and Environment Science and Data Center, Chinese Academy of Sciences
China's soil dataset from Harmonized World Soil Database (v 1.1)	Raster	1 km	National Tibetan Plateau Data Center

Coordinate System 1980 and transformed into raster layers (1-km resolution).

3 Research Methods

3.1 Research Framework

The research followed the framework of “current carbon sink evaluation–spatial pattern identification–restoration strategy development.” The research team first evaluated the carbon sequestration, carbon storage, and importance level of the current carbon sinks in Wensu County, then identified the spatial patterns of these carbon sinks. Lastly, based on the above analyses and approaches to increasing carbon sequestration and carbon sinks in existing studies, the research team proposed ecological restoration strategies for local land use spatial patterns (Fig. 2).

3.2 Current Carbon Sink Evaluation

Ecological restoration can disturb the land, affecting vegetation carbon sequestration and storage. Therefore, it is necessary to comprehensively assess the carbon sequestration capacity

(“flow”) and storage (“stock”) patterns of current carbon sinks in Wensu County, thereby analyzing the spatial pattern of the carbon sink importance level. The evaluation tool adopted is ArcGIS 10.3.

3.2.1 Carbon Sequestration Capacity Evaluation

Carbon sequestration capacity was measured with NEP, which is the difference between the net primary production (NPP) and the soil heterotrophic respiration (R_H)^{[24][25]}, i.e.,

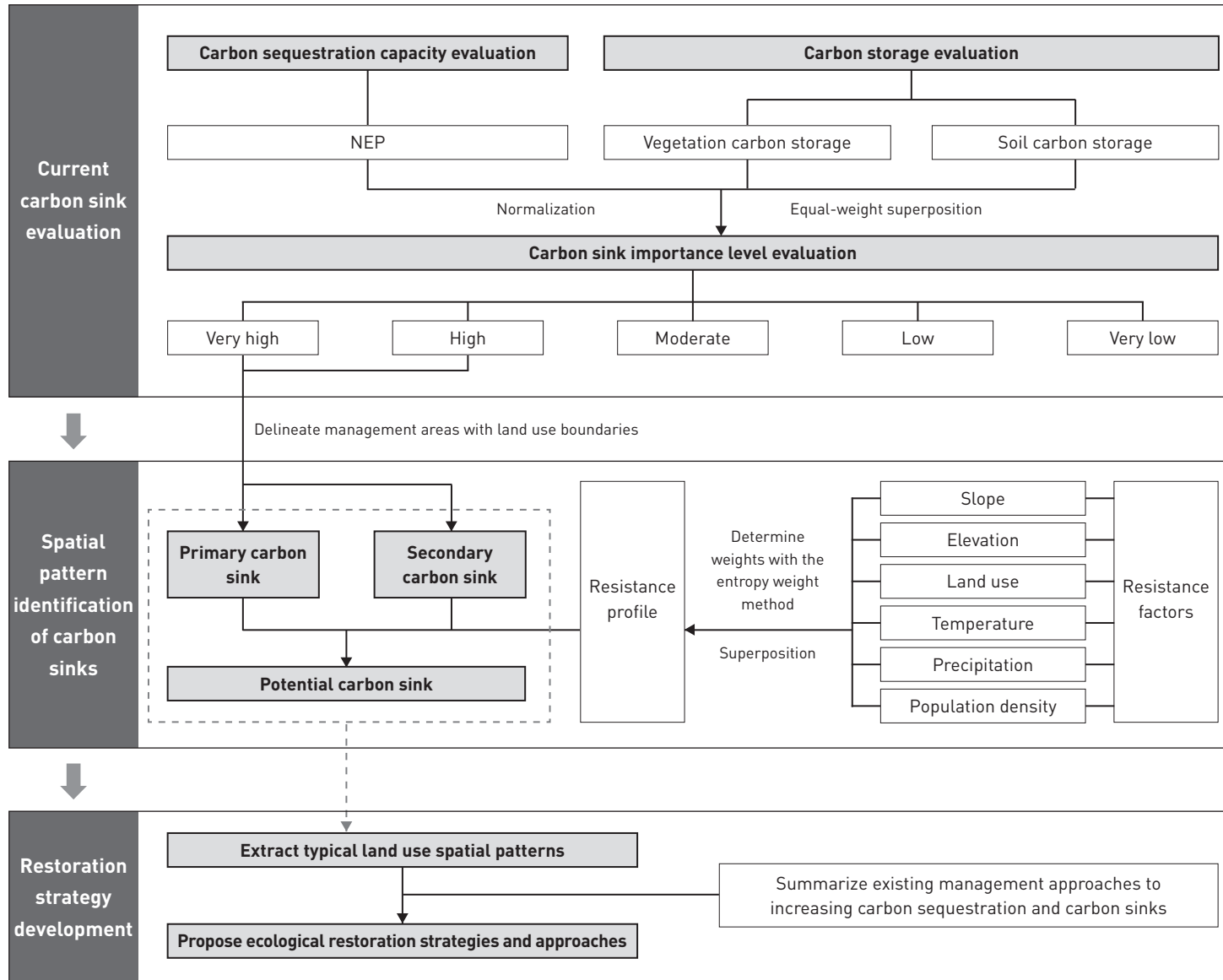
$$NEP = NPP - R_H, \quad (1)$$

$$R_H = 0.22 \times [\exp(0.0913T) + \ln(0.3145A + 1)] \times 30 \times 46.5\%, \quad (2)$$

where T is the monthly mean temperature (°C) and A is the monthly total precipitation (mm).

3.2.2 Carbon Storage Evaluation

Wensu County has a high soil carbonate content. The research team evaluated both soil and vegetation carbon storage. The soil



carbon storage is composed of topsoil inorganic carbon (P_{ic}), topsoil organic carbon (P_{oc}), subsoil inorganic carbon (S_{ic}), and subsoil organic carbon (S_{oc}). Topsoil and subsoil are the soil within 30 cm depth and 30 ~ 100 cm depth, respectively. The total carbon storage of the soil within 100 cm depth (C_{soil}) can be calculated with Eq. (3):

$$C_{soil} = (P_{ic} + P_{oc}) \times 0.3 + (S_{ic} + S_{oc}) \times 0.7. \quad (3)$$

As vegetation carbon density largely depends on vegetation types^[26], of which carbon densities were determined based on existing research and site conditions including location, elevation, and climatic characteristics^{[27]~[29]} (Table 2, Fig. 3).

3.2.3 Carbon Sink Importance Level Evaluation

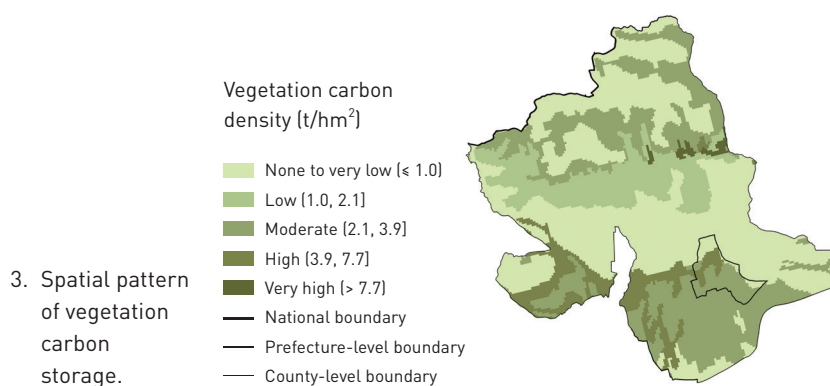
Addressing equal importance on carbon sequestration capacity and carbon storage, the researchers gave equal weight to those indicators. First, normalize NEP, vegetation carbon density, and soil carbon density according to Eq. (4). Second, overlay the obtained results to score the carbon sink importance level (I) with Eq. (5). Then, rate the results as “very high,” “high,” “moderate,” “low,” and “very low” with natural breaks classification method.

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}, \quad (4)$$

$$I = 0.5 \times X'_{NEP} + 0.25 \times X'_{veg} + 0.25 \times X'_{soil}, \quad (5)$$

Table 2: Vegetation carbon density and carbon storage

Vegetation type	Vegetation subtype	Carbon density (t/hm ²)	Area (×10 ⁴ hm ²)	Carbon storage (×10 ⁴ t)
Coniferous forest	Cool temperate and temperate montane coniferous forest	52.3	1.09	57.007
Scrub	Subalpine deciduous broad-leaved scrub	7.7	0.22	1.694
Desert	Temperate shrub desert	1.0	27.67	27.670
	Temperate steppe shrub desert	1.0	0.80	0.800
	Temperate subshrub and dwarf subshrub desert	1.0	13.49	13.490
	Temperate succulent halophyte dwarf subshrub desert	1.0	4.16	4.160
Steppe	Temperate bunch grass typical steppe	2.1	9.05	19.005
	Temperate grass and forb meadow steppe	2.1	2.11	4.431
	Temperate bunch short grass and dwarf subshrub desert steppe	2.1	4.57	9.597
Meadow	Temperate grass and forb halophyte meadow	3.7	24.07	89.059
	Temperate grass, sedge, and forb marsh meadow	3.9	0.07	0.273
	Alpine Kobresia and forb meadow	1.8	3.50	6.300
Alpine vegetation	Alpine cushion-like vegetation	3.3	0.65	2.145
	Alpine talus vegetation	3.3	18.20	60.060
Cultivated vegetation	Two-year triple cropping or one-year double cropping dry farming and deciduous orchard	5.7	11.46	65.322
Non-vegetation area		0.0	21.04	0.000
Total		—	142.15	361.013



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where X' is the normalization result; X'_{NEP} , X'_{veg} , and X'_{soil} are the normalization results of NEP, vegetation carbon density, and soil carbon density, respectively.

3.3 Spatial Pattern of Carbon Sinks

Referring to the relevant concepts of spatial pattern in landscape ecology, this research recognized the carbon sinks in Wensu County in three spatial categories based on their importance level, namely primary, secondary, and potential carbon sinks (Table 3).

Table 3: Spatial categories of carbon sinks in Wensu County

Category	Description
Primary carbon sink	<ul style="list-style-type: none"> Continuous carbon sinks that are mostly rated as “very high” and “high” level of importance, critical to maintaining and increasing carbon sinks They are mostly covered by natural vegetation with little human intervention, featuring a healthy ecosystem and abundant natural endowments Ecological protection should be prioritized
Secondary carbon sink	<ul style="list-style-type: none"> Continuous carbon sinks that are rated as “high” level of importance They are mainly covered by cultivated vegetation It requires site-specific ecological protection and restoration approaches
Potential carbon sink	<ul style="list-style-type: none"> Areas between the primary and secondary carbon sinks, rated as “moderate,” “low,” and “very low” level of importance They are mainly covered by natural vegetation, surrounded by large areas of unused land such as Gobi desert and bare rock or gravel; the vegetation is in fair condition, easily to be disturbed and generate carbon emissions Key areas to increase carbon sinks with gradual ecological restoration while avoiding large amount of carbon emissions from disturbances

Based on the importance level evaluation results of carbon sinks, areas rated as “very high” and “high” were identified as the primary and secondary carbon sinks that should be managed according to land use boundaries.

As natural land with higher connectivity can better perform ecological functions^{[30][31]}, the research team proposed to identify the potential carbon sinks to connect the primary and secondary carbon sinks, which have high feasibility of restoring ecosystem and increasing carbon sinks at low cost and are prone to generate carbon emissions that need to be sequestered locally. Accordingly, the research team selected relevant resistance factors and calculated with the minimum cumulative resistance (*MCR*) model. Areas with low resistance level were identified as potential carbon sinks. Areas featuring higher elevation, steeper slopes, lower annual accumulated temperature, or less annual precipitation are less suitable for plant growth^{[32]~[34]} and more vulnerable to human intervention^[35], making ecological restoration more challenging^[36]. In this sense, slope, elevation, land use, annual accumulated temperature, annual precipitation, and population

density were chosen as the resistance factors and then graded based on site conditions. Weights of these resistance factors were drawn with the entropy weight method^{[37][38]} in Stata (Table 4). The resistance level of each factor (Table 5) was assigned a value before a weighted superposition was applied in ArcGIS

Table 4: Entropy weight method results

Resistance factor	Information entropy (e)	Difference coefficient (d)	Weight (w)
Slope	0.8898	0.1102	28.8111%
Elevation	0.8758	0.1242	32.4634%
Land use	0.9680	0.0320	8.3713%
Annual accumulated temperature	0.9101	0.0899	23.4966%
Annual precipitation	0.9881	0.0119	3.1203%
Population density	0.9857	0.0143	3.7373%

Table 5: Levels of resistance factors

Resistance factor	Level	Value
Slope (°)	< 20	1
	[20, 40)	3
	[40, 60)	5
	[60, 80)	7
	≥ 80	9
Elevation (m)	< 2,000	1
	[2,000, 3,000)	2
	[3,000, 4,000)	4
	[4,000, 5,000)	6
	[5,000, 6,000)	8
	≥ 6,000	10

(Continued)

Table 5: Levels of resistance factors (Continued)

Resistance factor	Level	Value
Land use	Forest	1
	Grassland	1
	Farmland	3
	Water area	5
	Urban land, rural settlement, and other development land	10
	Unused land	5
Annual accumulated temperature (°C)	≥ 4,000	1
	[3,000, 4,000)	3
	[2,000, 3,000)	5
	[1,000, 2,000)	7
	< 1,000	9
Annual precipitation (mm)	≥ 600	1
	[450, 600)	3
	[300, 450)	5
	[150, 300)	7
	< 150	9
Population density (people per square kilometer)	< 1,000	1
	[1000, 2000)	3
	[2000, 3000)	5
	[3000, 4000)	7
	≥ 4,000	9

(Figs. 4, 5). By setting the primary and secondary carbon sinks as source patches, the potential carbon sinks were identified with Eq. (6),

$$MCR = f_{\min} \sum_{j=n}^{i=m} (D_{ij} \times R_i), \quad (6)$$

where D_{ij} is the physical distance between the ecological source patch j and the landscape unit i , R_i is the resistance coefficient, and f is the positive correlation between minimum cumulative resistance and ecological processes^{[35][39]}.

3.4 Ecological Restoration Strategy Development

After analyzing the current land use in the primary, secondary, and potential carbon sinks, this research extracted typical spatial patterns of land use. Referring to existing research^{[40]~[46]}, varied ecological restoration strategies, as well as management approaches were proposed specifically for different land use spatial patterns (Table 6) to maintain carbon sinks in unused land, moderately increase those in forests, and significantly boost those in grasslands and farmlands.

4 Results and Analyses

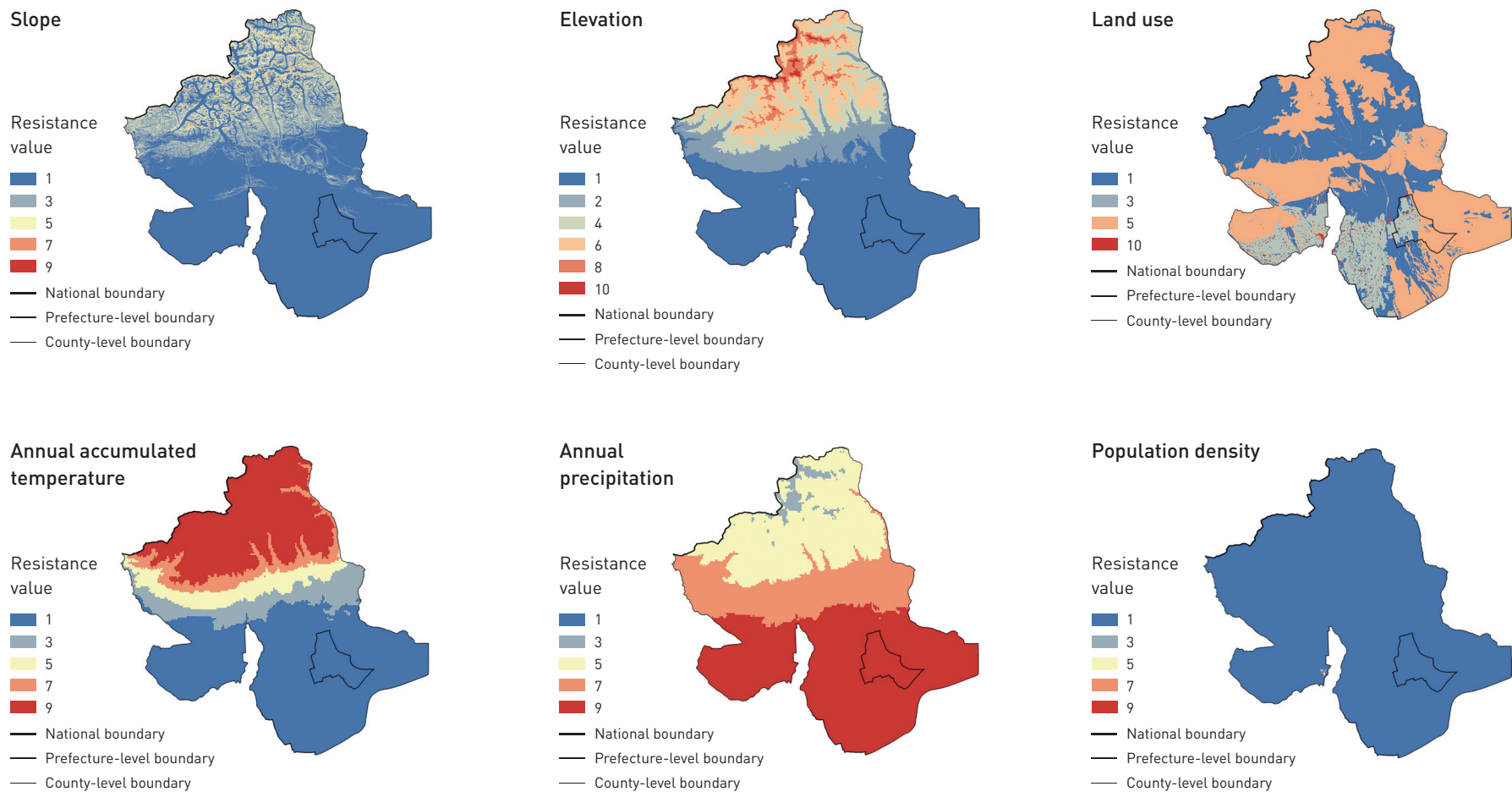
4.1 Current Carbon Sinks in Wensu County

4.1.1 Current Carbon Sequestration Capacity

According to the results, the NEP of Wensu County ranges between $-229.125 \sim 293.020 \text{ gC} \cdot \text{m}^{-2} \cdot \text{a}^{-1}$ and varies significantly across different areas, indicating a staggering pattern of carbon sequestration capacity. Gobi deserts and bare rock or gravel areas in southern Wensu County show low NEP with the weakest carbon sequestration capacity. The high northern areas of Tianshan Mountain exhibit poor NEP and carbon sequestration capacity due to year-round snow cover and scarce vegetation. The belt of the southern foothills of Tianshan Mountain with an elevation of $2,000 \sim 3,000 \text{ m}$, where the natural forest and grassland flourish, has a high NEP, suggesting the best carbon sequestration capacity in the county. In addition, the cultivated vegetation area (mainly farmland) in the southern Wensu County is characterized by a higher NEP with a great carbon sequestration capacity (Fig. 6).

4.1.2 Current Carbon Storage

The central area of Wensu County has the highest soil carbon storage, followed by the southern area, and the northern area has the least (Fig. 7). Higher inorganic carbon content are found in both topsoil and subsoil in the central and some southern areas of the



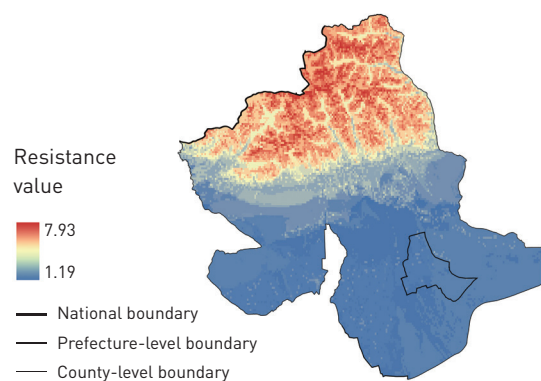
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county, and in the southeastern alluvial plain (Figs. 8, 9). Topsoil in the southern foothills of Tianshan Mountain with an elevation of 2,000 ~ 3,000 m is richer in organic carbon (Fig. 10). Overall, Wensu County subsoil contains little organic carbon, with higher content found only in the central (1,500 ~ 2,000 m in elevation) and a few southern plain patches in the county (Fig. 11).

Total vegetation carbon storage in Wensu County is 361.013×10^4 t (Table 2). The temperate grass and forb halophytic meadows contribute the most (89.059×10^4 t), followed by cultivated

vegetation, featuring two-year triple cropping or one-year double cropping dry farming and deciduous orchard (65.322×10^4 t). The cool temperate and temperate montane coniferous forest covers a small area but boasts the highest carbon density and high carbon storage (57.007×10^4 t). The carbon storage of the temperate steppe shrub desert is the lowest (0.8×10^4 t) due to the small area and low carbon density.

Combining vegetation and soil carbon storage, the plain in the southern county and the southern foothills of Tianshan Mountain have the largest total carbon storage. These areas are currently dominated by forest land, grassland, and farmland. Future ecological restoration should focus more on land development and transfer, and ensure that the carbon storage remains largely undisturbed.



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4. Resistance factors of the study area.
5. Resistance profile of the study area.

4.1.3 Spatial Pattern of Carbon Sink Importance Level

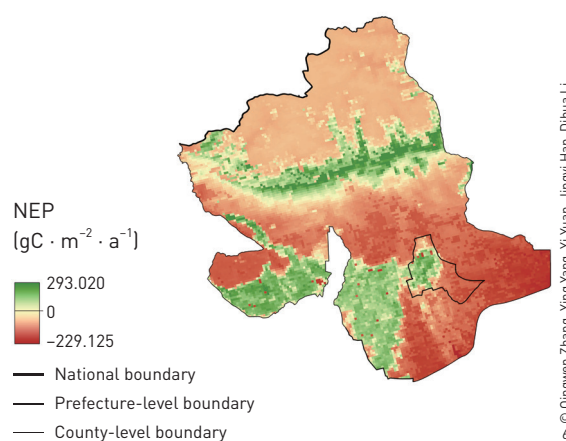
According to the evaluation results, the importance level of carbon sinks in different geographical environments of Wensu County varies significantly. Carbon sinks in the southern foothills of Tianshan Mountain areas (2,000 ~ 3,000 m elevation) are of “very high” and “high” importance level; those continuous in the southern

Table 6: Management approaches to increasing carbon sequestration and carbon sinks

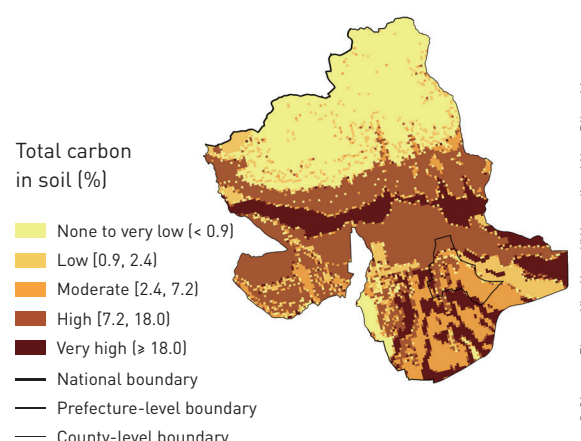
Land use type	Land use subtype	Management approaches
Forest	Forest land, shrub land, open forest land, other forest land	Afforestation and reforestation, converting farmland to forest, natural forest protection, forest tending, naturalization of man-made forests, mixed forest plantation, agroforestry
Grassland	High coverage grassland, medium coverage grassland, low coverage grassland	Natural grassland enclosure, converting farmland to grassland, degraded grassland restoration, perennial mixed grassland interplanting, grazing intensity control, rotational grazing, deferred grazing
Farmland	Paddy land, dry land	Straw mulching, applying organic fertilizers, conservation tillage, farmland rotation, irrigation management, composite system intercropping, recycling wasted farmland resources
Water area	River and canal, lake, reservoir, glacier and perennial snowfield, floodplain	Wetland conservation, degraded floodplain restoration, wetland management, garbage disposal, artificial wetland construction
Unused land	Sandy land, Gobi desert, saline-alkali land, bare soil, bare rock or gravel	Soil remediation and maintenance, planting saline-tolerant and sand-fixing species, introducing new biotechnology to cultivate species (trees, grasses, or microorganisms) that can adapt to local conditions and efficiently sequester carbon

NOTE

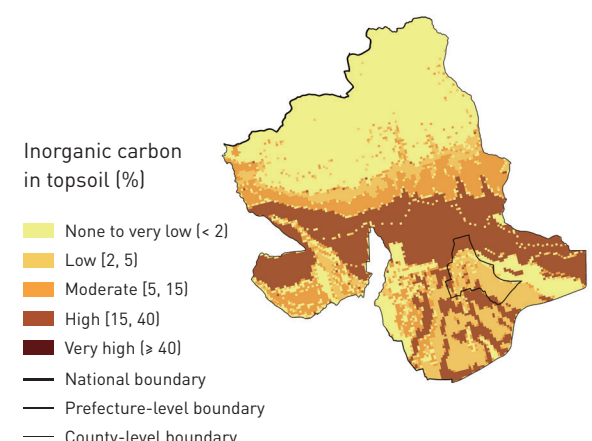
The management approaches to increasing carbon sequestration and carbon sinks are sourced from Refs. [36]-[42].



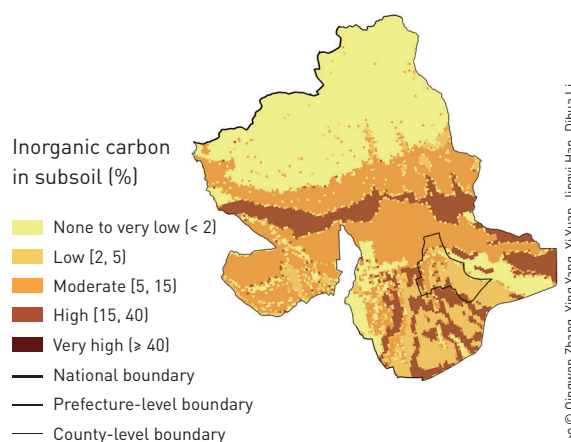
6. Spatial pattern of NEP.



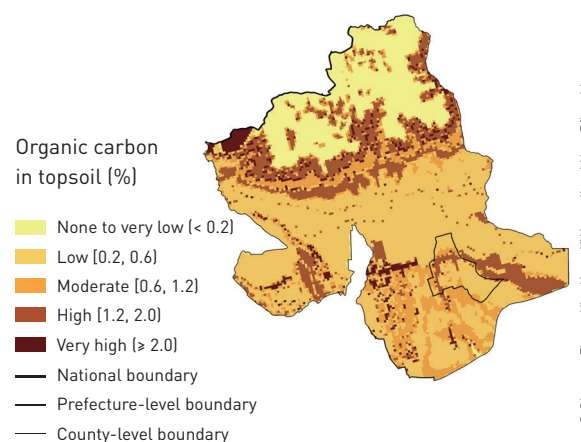
7. Spatial pattern of total carbon in soil .



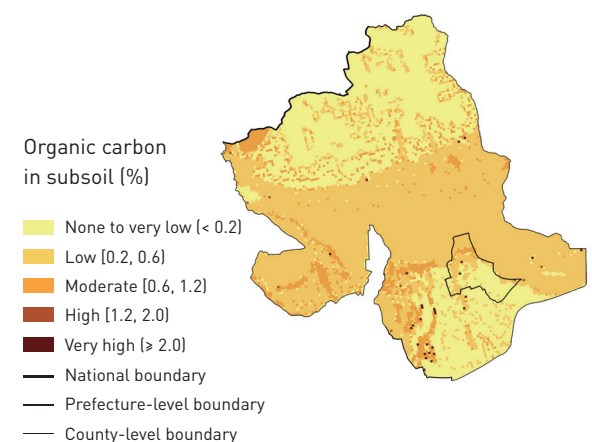
8. Spatial pattern of inorganic carbon in topsoil.



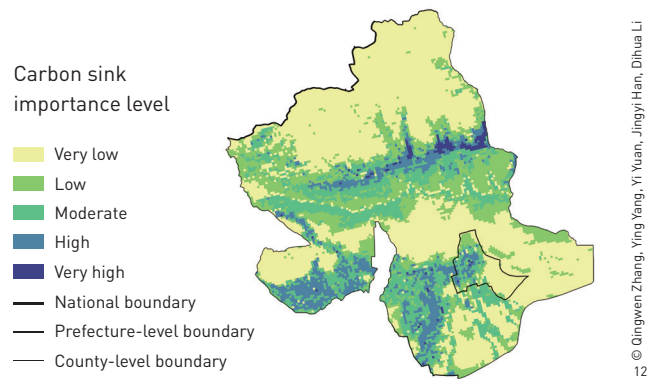
9. Spatial pattern of inorganic carbon in subsoil.



10. Spatial pattern of organic carbon in topsoil.



11. Spatial pattern of organic carbon in subsoil.



12. Spatial pattern of carbon sink importance level.

and southeastern plains are of “high” and “moderate” importance level; and those in the northern Tianshan Mountain areas elevated above 3,000 m and Gobi desert and bare rock and gravel areas in the central and southeastern county are of “low” and occasionally “very low” importance level (Fig. 12).

4.2 Spatial Pattern Identification of Carbon Sinks

One primary, two secondary, and one potential carbon sinks are identified in Wensu County. The primary carbon sink (1,083.87 km²) lies in the southern foothills of Tianshan Mountain, with an elevation of 2,000 ~ 4,000 m. Two secondary carbon sinks (1,899.69 km² in total) are located in the southern and southwestern plains of the county. The potential carbon sinks (2,259.81 km²) are found in the central part of the county. The land uses in the primary carbon sink are mainly high-, medium-, and low-coverage grasslands, occupying 48.60%, 11.48%, and 31.76% of the total area, respectively (Table 7). The secondary carbon sinks are mainly dry land, which account for 86.63% of the total area (Table 8). The potential carbon sinks feature the low-coverage grassland and bare rock and gravel, covering 51.28% and 24.81% of the total area, respectively (Table 9, Fig. 13).

4.3 Ecological Restoration Strategies

Based on the land use patterns in Wensu County, this research extracted eight typical spatial patterns of land use—one in the primary, two in the secondary, and five in the potential carbon sinks. To boost carbon sinks, the research proposed ecological restoration strategies for each typical land use spatial pattern, namely high-carbon reinforcement; carbon conservation, low-carbon development; carbon conservation expansion, replanting

Table 7: Land use in primary carbon sink

Land use subtype	Area (km ²)	Percentage	Total area (km ²)
Dry land	2.88	0.27%	1,083.87
Forest land	41.29	3.81%	
Shrub land	0.12	0.01%	
Open forest land	36.54	3.37%	
High coverage grassland	526.79	48.60%	
Medium coverage grassland	124.45	11.48%	
Low coverage grassland	344.26	31.76%	
River and canal	5.70	0.53%	
Floodplain	1.84	0.17%	

Table 8: Land use in secondary carbon sinks

Land use subtype	Area (km ²)	Percentage	Total area (km ²)
Paddy land	4.65	0.24%	1,899.69
Dry land	1,645.65	86.63%	
Forest land	0.12	0.01%	
Other forest land	51.65	2.72%	
High coverage grassland	15.16	0.80%	
Medium coverage grassland	12.21	0.64%	
Low coverage grassland	78.79	4.15%	
River and canal	8.18	0.43%	
Reservoir	0.57	0.03%	
Floodplain	13.55	0.71%	
Urban land	2.21	0.12%	
Rural settlement	65.66	3.46%	
Gobi desert	0.31	0.01%	
Bare soil	0.98	0.05%	

Table 9: Land use in potential carbon sinks

Land use subtype	Area (km ²)	Percentage	Total area (km ²)
Dry land	16.13	0.71%	2,259.81
High coverage grassland	5.11	0.23%	
Medium coverage grassland	146.40	6.48%	
Low coverage grassland	1,158.73	51.28%	
Gobi desert	330.84	14.64%	
Bare soil	41.88	1.85%	
Bare rock or gravel	560.72	24.81%	

for carbon sequestration, restoring for carbon sequestration, maintaining high carbon storage, and carbon sequestration monitoring. Approaches to promoting ecological restoration and carbon sink benefits were proposed based on local conditions (Table 10, Fig. 14).

5 Conclusions and Discussion

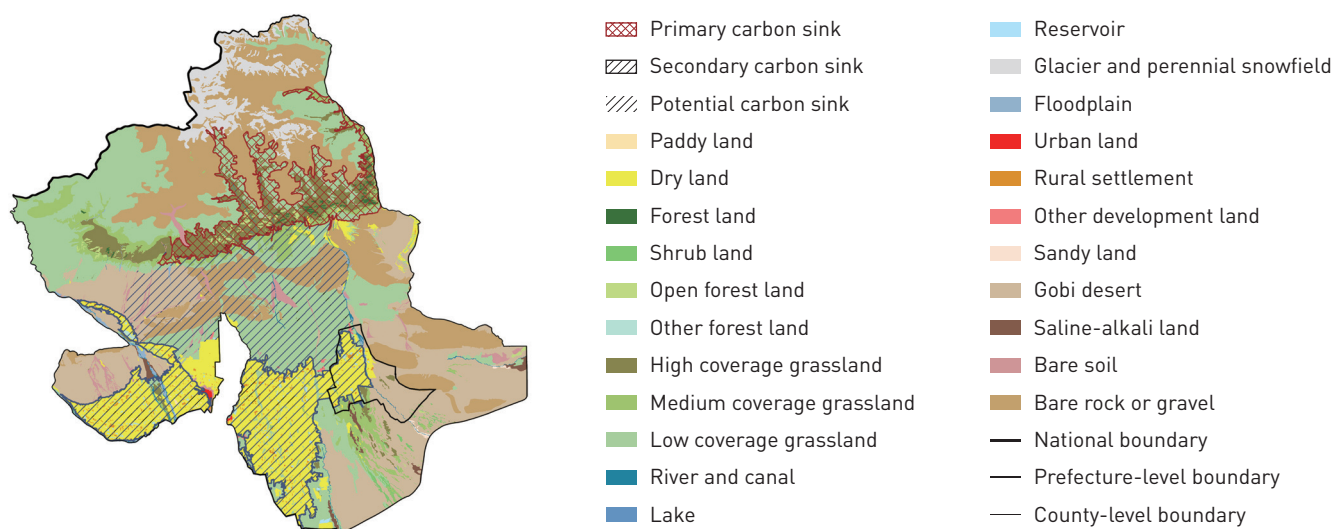
5.1 Conclusions

This research evaluated current carbon sinks in Wensu County based on data from multiple sources, identified the pattern of carbon sinks in the county, and proposed ecological restoration

strategies to increase carbon sinks. According to the findings, carbon sequestration capacity varies across the county. The southern foothills of Tianshan Mountain, with an elevation of 2,000~3,000 m, have the best carbon sequestration capacity. The plain in the southern county and southern foothills of Tianshan Mountain have the largest carbon storage. Carbon sink importance level varies significantly across geographical environments of the county. That in the southern foothills of Tianshan Mountain and in the southern and southeastern plains of the county are graded higher than the others. Based on the carbon sink importance level evaluation, one primary, two secondary, and potential carbon sinks with a total area of 2,259.81 km² are identified. Eight ecological restoration strategies are proposed based on local conditions to achieve the main goal of boosting carbon sinks.

5.2 Inspirations for Carbon Sink Management in the Arid Areas of Northwest China

The findings suggest that grassland and farmland are the key land use types when aiming at carbon sequestration and carbon sink enhancement in the arid areas of northwest China (Tables 7 ~ 9). Although the carbon sink capacity of forests is higher than that of grasslands^[47], in Wensu County, where forests cover a small area due to the arid climate, their carbon sink benefits are therefore insignificant. Meanwhile, grassland and dry land are of higher carbon sink importance level and function as the main carbon sinks in the county. Existing research evaluating the vegetation carbon sink capacities in the arid areas of northwest China also concludes that temperate grasslands and high-quality farmlands function better as carbon sinks^[24], which further supports the



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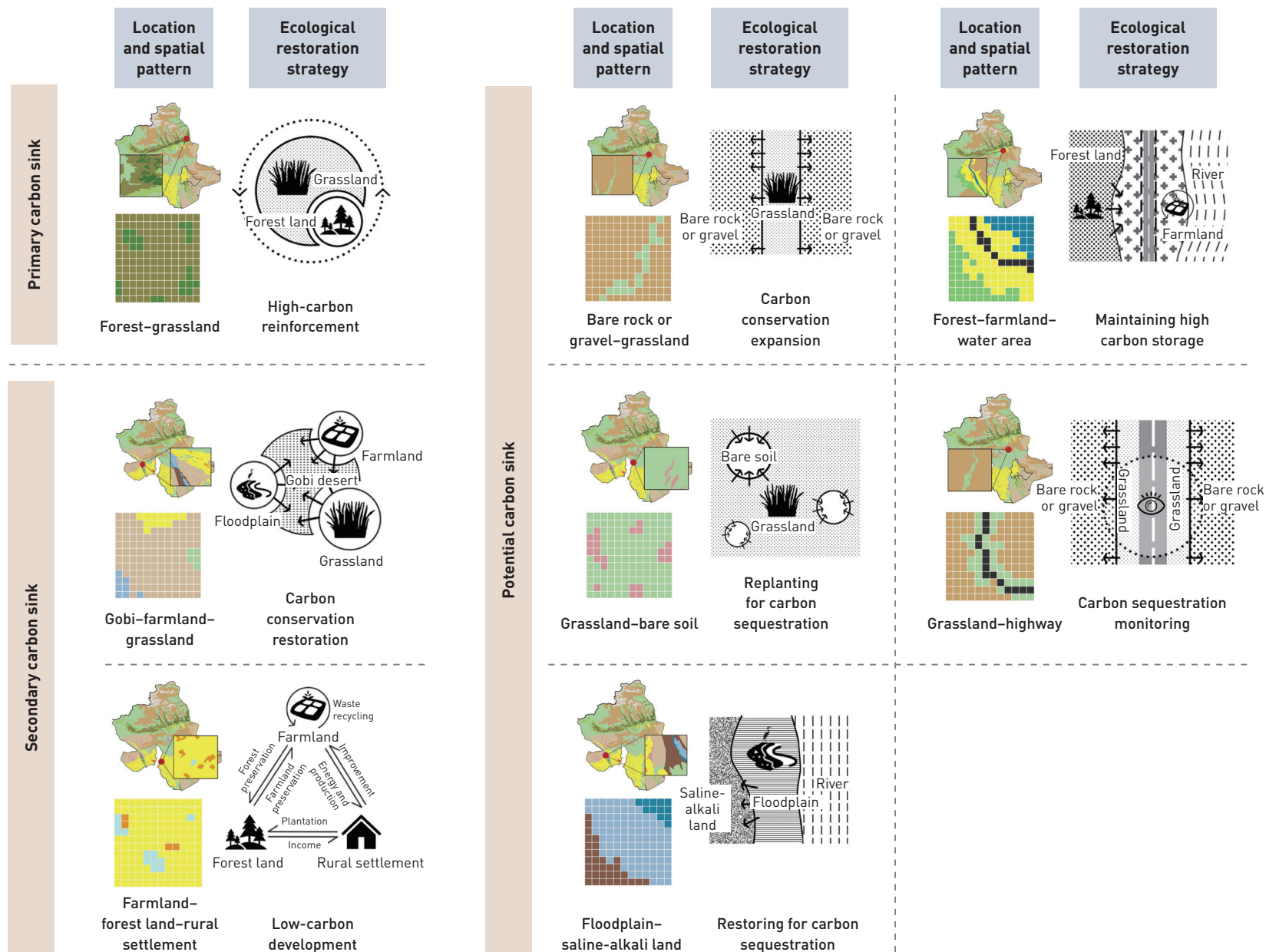
13. Spatial pattern identification of carbon sinks.

Table 10: Land use spatial patterns, ecological restoration strategies and approaches

Category	Spatial pattern of land use	Characteristic	Ecological restoration strategy	Approach
Primary carbon sink	Forest–grassland	Continuous grassland scattered with forest patches	High-carbon reinforcement	Conserving existing carbon pools, restoring soil fertility, and increasing grassland carbon sink and storage by growing mixed forest on abandoned grasslands, forestation and reforestation, grazing intensity control, and natural grassland enclosure
Secondary carbon sink	Gobi–farmland–grassland	Continuous Gobi desert with floodplain, grassland, and farmland along the borders	Carbon conservation restoration	Increasing the above-ground biomass, restoring soil fertility, conserving existing soil carbon pools, and enhancing grassland carbon sink via boundary restoration, floodplain ecological conservation, degraded grassland reseeding and maintenance, and converting farmland to grassland
	Farmland–forest land–rural settlement	Continuous farmland with scattered rural settlements and plantations	Low-carbon development	Recycling the agricultural, forest, and residential resources, reducing resource consumption, and enhancing farmland carbon sequestration and storage (soil and vegetation) via conservation tillage, agroforestry, and agricultural waste recycling
Potential carbon sink	Bare rock or gravel–grassland	Bare rock or gravel areas with belts of low-coverage grassland	Carbon conservation expansion	Maintaining natural succession, restoring soil fertility, and thus enhancing grassland carbon sink by soil mediation and maintenance of saline-alkali land, planting saline-tolerant and sand-fixing vegetation, and building shelterbelts along the boundaries
	Grassland–bare soil	Continuous low-coverage grassland interspersed with few bare soil areas	Replanting for carbon sequestration	Increasing grassland carbon sink (soil and vegetation), the above-ground biomass, and then carbon sink and storage of the region via bare soil land management, grazing management, and ecological replanting
	Floodplain–saline-alkali land	Floodplain near river and canals, bordered by saline-alkali land with sparse vegetation	Restoring for carbon sequestration	Improving soil fertility and maintaining soil carbon pool by soil mediation and maintenance of the saline-alkali land, planting saline-tolerant species, and introducing new planting technologies
	Forest–farmland–water area	Shrub land–dry land–river and canal patches, with roads traversing through	Maintaining high carbon storage	Maintaining soil carbon pool and boosting vegetation carbon sink by conservation tillage, converting farmland to forest, naturalization of man-made forests, and mixed forest plantation
	Grassland–highway	Narrow low-coverage grassland belts traversing bare rock or gravel areas, with highways in the center	Carbon sequestration monitoring	Maintaining grassland carbon pool (soil and vegetation) by natural grassland enclosure, rotational grazing, grazing intensity control, and shelterbelt construction; maintaining area carbon sink by planting along the highway

carbon sink potential of grasslands and farmlands. In this sense, ecological restoration in the arid areas of northwest China should take characteristics of local vegetation into consideration to avoid changing vegetation types or maintaining non-local vegetation,

which causes material and energy consumption that leads to carbon emissions. Also, it is important to avoid large disturbances in grasslands, optimize management measures, and increase organic matter in the soil to boost carbon storage^[48]. On farmlands,



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14. Ecological restoration models.

while photosynthesis helps carbon sequestration, respiration and production activities emit carbon^[49]. Agricultural activities such as cropping system adjustment and agricultural investment control that minimize soil disturbance, as well as management upgrade^{[50][51]}, can further increase carbon sequestration and carbon sinks.

The identified spatial pattern of carbon sinks in Wensu County could be instrumental to carbon sink management in the arid areas of northwest China. Compared with more developed regions where most carbon sinks are found in the natural areas distant

from downtown^{[9][52]}, in Wensu County, apart from the southern foothills of Tianshan Mountain, the rural settlements and farmlands featuring intensive human activities in the southern county have shown significant carbon sink benefits. In other words, landscapes under human intervention play an essential role in increasing carbon sequestration and carbon sinks in arid areas. More research is expected to further evaluate carbon sink potentials of cultivated vegetation in arid areas, thereby guiding the efforts for increasing carbon sequestration and carbon sinks.

5.3 Values to the Territorial Ecological Restoration

China has launched a number of ecological restoration projects since the 1950s. Many forest, grassland, wetland, and farmland ecosystems have been restored, with their carbon sequestration capacity improved remarkably^[15]. Focusing on more than any singular factor, territorial ecological restoration aims to enhance the stability and security of the whole regional ecosystem^[53]. The proposal of “dual carbon” goals makes carbon sequestration and carbon sink increase an integral component of ecological restoration, boosting the number of related research^{[17][18]}. Yet, most research focuses on a single ecosystem and provides specific ecological restoration approaches, or makes theoretical discussions on carbon sequestration approaches only^[14]. With a spatial perspective, this research took Wensu County as the study area, and proposed ecological restoration strategies that increase carbon sequestration and carbon sinks by current carbon sink evaluation, spatial pattern analyses, and feasible restoration strategies development. The MCR employed to identify the spatial pattern of carbon sinks can also be applied in territorial ecological restoration focused on biodiversity protection^[54] and mountain disaster prevention^[55]. The framework of this research integrates carbon sink increase with other ecological restoration goals, and the findings contribute to the holistic preservation, restoration, and governance of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts.

5.4 Prospects

The application of MCR, basing the resistance of developing potential carbon sinks on restoration difficulties and demand for local absorption of carbon emission, is still in the early development stage. Further post-implementation validation is required. In addition, more measured data with better precision over a longer period are expected in future research, so as to make the carbon sink evaluation more comprehensive and accurate. Moreover, carbon sink increase should be integrated with other ecological problems to emphasize the carbon problems in territorial ecological restoration and holistic maintenance.

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以碳增汇为导向的县域国土空间生态修复研究 ——以中国新疆维吾尔自治区温宿县为例

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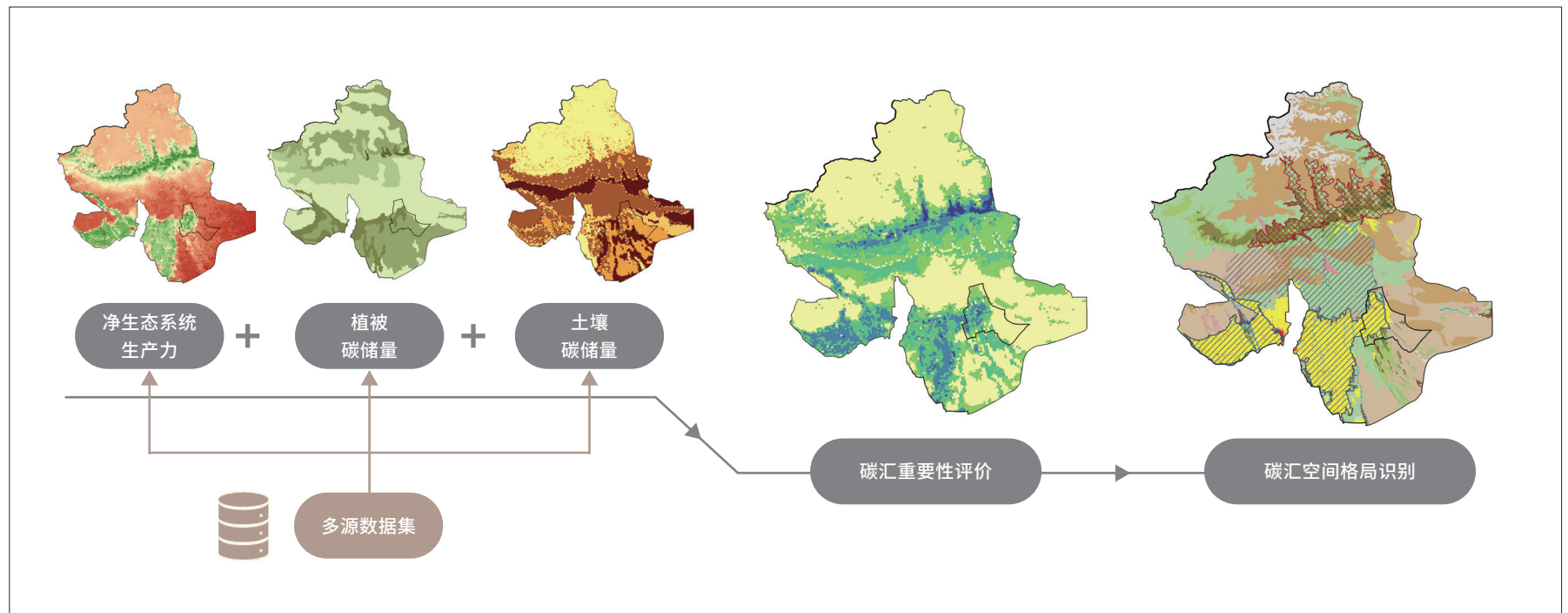
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图文摘要



摘要

面对全球气候变化, 亟需将“双碳”目标纳入国土空间规划实践。目前, 以碳增汇为导向, 针对中国西部地区、特别是西北干旱区县域的生态修复研究较少。本研究以中国新疆维吾尔自治区温宿县为例, 从碳吸收能力与碳储量两方面综合评估温宿县碳汇现状, 并以此为基础识别温宿县碳汇空间格局, 探索以碳增汇为导向的县域国土空间生态修复规划的途径。现状评估结果表明, 温宿县的碳汇重要性在不同地理区域呈

现出较大差异。在研究区域内识别出一处碳汇腹地、两处碳汇重要区, 以及总面积达2 259.81km²的碳汇潜力带, 进而结合土地利用现状提炼出8种土地利用典型空间模型, 并拟定了相应的生态修复策略。研究有助于促进“双碳”目标在国土空间规划中的落实, 对中国西北干旱区域碳汇管理实践具有积极意义, 并可为地理条件相似的地区提供固碳增汇的经验。

关键词

碳增汇；碳吸收；碳储量；县域；西北干旱区；生态修复；国土空间规划

文章亮点

- 以中国西北干旱地区县域为案例开展以碳增汇为导向的生态修复研究
- 综合评价研究区域的碳吸收和碳储量现状，并识别碳汇重要性空间格局
- 结合土地利用现状提炼土地利用典型空间模型，并拟定了相应的生态修复策略

基金项目

新疆维吾尔自治区寒旱区水资源与生态水利工程研究中心（院士专家工作站）课题（编号：2023.B-004）

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1 引言

气候变化威胁着自然生态系统与社会经济系统，而二氧化碳被认为是气候变化的主要驱动因素^[1]。为推进生态文明建设、落实应对全球气候变化的共同责任，中国于2020年首次提出碳达峰、碳中和（以下简称“双碳”）的目标^[2]，并于2021年进一步确认，要将其“纳入生态文明建设整体布局”^[3]。

实现“双碳”目标不仅需要控制碳排放，还需要提升生态系统碳储量。实践经验表明，生态修复对提升生态系统固碳能力有积极影响^{[4]-[6]}。科学的现状评估是实现生态修复碳增汇目标的实践基础。目前，基于遥感数据对碳汇空间格局与时空演变规律进行分析的研究方法已经相对成熟^[7]，主要包括净生态系统生产力（net ecosystem production, NEP）的计算^[8]、InVEST模型碳储量模块的模拟^[9]及利用碳汇系数的碳汇估算^[10]。同时，也有学者在现状评估的基础上提出生态空间的分区与管控策略^[11]。

然而，现有研究大多聚焦于全国、省域与区域的中、大尺度场地^{[8][10][12]}，部分关注发达地区的市域与县域^{[11][13]}，但对中国西部地区、特别是西北干旱区的县域研究较少。

在生态修复方面，已有研究综述了生态系统固碳的影响因素与碳增汇原理^[14]；分析了生态系统修复在固碳增汇方面的现状^[15]；并以碳增汇为导向，通过数据实测、研究综述、实践案例分析与政策文件解读等方式探讨了林地^[16]、草地^[17]、耕地^[18]、湿地^[19]、荒漠^[20]、海洋^[21]等各类生态系统的修复方法。然而，现有研究较少结合生态空间格局提出生态修复策略。

本研究以中国新疆维吾尔自治区温宿县作为研究场地，首先评价县域碳汇现状，在此基础上识别其碳汇空间格局，继而结合土地利用类型拟定相应的生态修复策略。有别于中国京津冀、东南沿海等发达地区的县市，西北干旱地区的县域面积普遍较广，建设用地占比极小，同时非建设用地的生态较为脆弱^{[22][23]}，亟待生态修复。为了在碳增汇导向下探究中国西北干旱地区县域的国土空间生态修复途径，从而促进“双碳”目标在国土空间规划中的落实，并为地理条件相似的地区提供可参考的范式，研究旨在探讨以下问题：

- 1) 温宿县碳汇空间格局具有哪些特征？
- 2) 有哪些基于碳增汇的国土空间生态修复途径？
- 3) 本研究可以为中国西北干旱区及相似地区的碳汇管理提供哪些参考？

2 研究区域与数据概况

2.1 研究区域

温宿县（40° 52′—42° 21′N，79° 28′—81° 28′E）隶属中国新疆维吾尔自治区阿克苏地区，位于天山中段的托木尔峰南麓、塔里木盆地北缘，东西宽约153km，南北长约167km，行政区划总面积1.46万平方公里（图1）^①。温宿县地形总体呈“北高南低”的特征，地貌形态分为北部山区和南部丘陵平原区，海拔位于800~8 000m之间。温宿县属温带大陆性干旱气候，干旱少雨、蒸发量大、光照充足，年均气温为10.10℃，年均降水量65.4mm，年均无霜期185天^②。温宿县土地利用类型^③主要为未

① 阿拉尔市部分区域被温宿县县域所环绕，虽行政上不属其管辖，但考虑研究区域的生态完整性，将该区域纳入研究范围。受数据获取限制，本研究所采用的栅格数据覆盖面积约为1.42万平方公里。

② 温宿县基本资料来源于温宿县人民政府网站。

③ 本研究沿用《中国多时期土地利用遥感监测数据集（CNLUCC）》中的土地分类系统，数据来源中国科学院资源环境科学与数据中心。

利用土地、草地与耕地（图1），土壤类型主要为钙积石膏土、石化石膏土、粘化钙积土等，植被类型主要为荒漠和草甸，其县域具有广阔的自然空间，碳汇潜力巨大。

2.2 数据来源与预处理

研究基于多源数据评价温宿县碳汇现状、识别碳汇空间格局。在对数据的更新时间、可获取性、时空同步情况，以及不同年份的数据质量进行综合考虑后，选用2015年多源数据展开研究（表1）。将所用数据在ArcGIS 10.3中统一投影为1980西安坐标系，并转化为1km精度的栅格。

3 研究方法

3.1 研究框架

研究按照“碳汇现状评价—空间格局识别—修复策略拟定”的框架展开：首先，对温宿县碳汇的现状（碳吸收、碳储量）和重要性进行评估；其次，识别温宿县碳汇空间格局；最终在前期分析的指导下，通过总结现有研究中的固碳增汇管理措施，针对温宿县土地利用现状拟定生态修复策略（图2）。

3.2 碳汇现状评价

生态修复将在一定程度上对土地产生扰动，并影响生态系统碳吸收能力和碳储量的变化。因此，需要综合考虑碳吸收能力的“流量”特征与碳储量的“存量”特征对温宿县的碳汇现状进行评价，进而分析温宿县不同重要性等级碳汇的空间分布。研究借助ArcGIS 10.3完成碳汇现状评价。

3.2.1 碳吸收能力评价

碳吸收能力通过NEP进行度量，取值为净初级生产力（NPP）与土壤微生物呼吸碳排放（ R_H ）的差值^{[24][25]}，即：

$$NEP = NPP - R_H, \quad (1)$$

$$R_H = 0.22 \times [\exp(0.09137T) + \ln(0.3145A + 1)] \times 30 \times 46.5\%, \quad (2)$$

式中， T 为逐月平均气温（ $^{\circ}\text{C}$ ）， A 为逐月总降水（mm）。

3.2.2 碳储量评价

温宿县土壤碳酸盐含量较高，因而在进行碳储量评价时应与土壤与植被进行综合考量。土壤碳储量由表土无机碳含量（ P_{ic} ）、表土有机碳含量（ P_{oc} ）、底土无机碳含量（ S_{ic} ）、底土有机碳含量（ S_{oc} ）构成，

其中，表土指深度为0~30cm的土壤，底土指深度为30~100cm的土壤。

由公式（3）计算可得100cm深的土壤中碳储量总量（ C_{soil} ）：

$$C_{soil} = (P_{ic} + P_{oc}) \times 0.3 + (S_{ic} + S_{oc}) \times 0.7. \quad (3)$$

由于植被碳密度和植被类型直接相关^[26]，研究结合现有研究与场地地理位置、海拔高度、气候特征等场地情况确定植被碳密度^{[27]-[29]}，并计算温宿县植被碳储量（表2，图3）。

3.2.3 碳汇重要性评价

为体现对碳吸收能力与碳储量的同等重视，研究采用等权重方式对二者的指标进行叠加。首先，分别对NEP、植被碳密度、土壤碳密度

表1：研究数据及来源

数据	数据类型	空间分辨率	数据来源
土地利用	栅格	1km	中国科学院资源环境科学与数据中心
净初级生产力（NPP）	栅格	500m	美国地质勘探局
数字高程模型（DEM）	栅格	30m	地理空间数据云
逐月平均气温	栅格	1km	中国科学院资源环境科学与数据中心
逐月总降水	栅格	1km	中国科学院资源环境科学与数据中心
人口密度空间分布	栅格	1km	WorldPop
植被类型空间分布	矢量	1 : 1 000 000	中国科学院资源环境科学与数据中心
基于世界土壤数据库的中国土壤数据集（v1.1）	栅格	1km	中国国家青藏高原科学数据中心

表 2: 植被碳密度及碳储量统计表

植被类型	植被亚类	碳密度 (t/hm ²)	面积 (×10 ⁴ hm ²)	碳储量 (×10 ⁴ t)
针叶林	寒温带和温带山地针叶林	52.3	1.09	57.007
灌丛	亚高山落叶阔叶灌丛	7.7	0.22	1.694
荒漠	温带灌木荒漠	1.0	27.67	27.670
	温带草原化灌木荒漠	1.0	0.80	0.800
	温带半灌木、矮半灌木荒漠	1.0	13.49	13.490
	温带多汁盐生矮半灌木荒漠	1.0	4.16	4.160
草原	温带丛生禾草典型草原	2.1	9.05	19.005
	温带禾草、杂类草草甸草原	2.1	2.11	4.431
	温带丛生矮禾草、矮半灌木荒漠草原	2.1	4.57	9.597
草甸	温带禾草、杂类草盐生草甸	3.7	24.07	89.059
	温带禾草、苔草及杂类草沼泽化草甸	3.9	0.07	0.273
	高寒嵩草、杂类草草甸	1.8	3.50	6.300
高山植被	高山垫状植被	3.3	0.65	2.145
	高山稀疏植被	3.3	18.20	60.060
栽培植被	两年三熟或一年两熟旱作和落叶果树园	5.7	11.46	65.322
无植被		0.0	21.04	0.000
合计		—	142.15	361.013

计算按照公式(4)进行极差标准化。然后按照公式(5)进行叠加,得到碳汇重要性(I)的评价结果,并采用自然断点法分为“极高”、“高”、“中”、“低”和“极低”5个等级。

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}}, \quad (4)$$

$$I = 0.5 \times X'_{\text{NEP}} + 0.25 \times X'_{\text{veg}} + 0.25 \times X'_{\text{soil}}, \quad (5)$$

式中, X'为极差标准化后的结果, X'_{NEP}、X'_{veg}与X'_{soil}分别为NEP、植被碳密度与土壤碳密度极差标准化后的结果。

3.3 碳汇空间格局

参考景观生态学中的空间格局相关概念,本研究将温宿县碳汇空间识别为碳汇腹地、碳汇重要区与碳汇潜力带三大空间类型(表3)。

在碳汇重要性评价的基础上,提取评级为“极高”与“高”的区域,以土地利用的边界作为管控的边界,识别碳汇腹地与重要区。

考虑到连通度更高的自然用地能够更好地发挥生态功能^{[30][31]},研究提出通过“有潜力”和“有需求”的原则识别碳汇潜力带,用以连接碳

表 3: 温宿县碳汇空间类型

类别	说明
碳汇腹地	· 碳汇重要性以“极高”与“高”为主的连片区域,对碳汇的保持与提升起关键作用 · 植被类型以自然植被为主,人工干预相对较少,生态本底和自然禀赋良好 · 需以生态保护为重点
碳汇重要区	· 碳汇重要性为“高”的连片区域 · 植被类型以人工植被为主 · 需因地制宜开展生态保护与修复
碳汇潜力带	· 位于碳汇腹地与碳汇重要区之间的区域,碳汇重要性为“中”“低”及“极低” · 植被类型以自然植被为主,周围存在较大面积戈壁、裸岩石质地等未利用土地,植被状态一般、易受扰动而产生碳排放 · 未来固碳增汇的重点区域,在避免因扰动产生大量碳排放的基础上,逐步开展生态修复

表 4: 熵值法权重系数结果

阻力因子	信息熵值 (e)	差异系数 (d)	权重系数 (w)
坡度	0.8898	0.1102	28.8111%
高程	0.8758	0.1242	32.4634%
土地利用类型	0.9680	0.0320	8.3713%
年积温	0.9101	0.0899	23.4966%
年降水	0.9881	0.0119	3.1203%
人口密度	0.9857	0.0143	3.7373%

汇腹地与重要区。其中，“有潜力”指能以较低的成本进行生态修复、提高碳汇；“有需求”指易产生碳排放、需考虑就地消纳。根据上述原则选取相应的阻力因子，采用最小累积阻力模型 (minimum cumulative resistance model, *MCR*) 计算，将低阻力区域识别为碳汇潜力带：由于海拔越高、坡度越陡、年积温越低、年降水越少的环境往往越不利于植被生长^{[32]~[34]}，并且人类干扰也会对当地生态系统造成影响^[35]，进而增加生态修复的难度^[36]，故选取坡度、高程、土地利用、年积温、年平均降水量和人口密度6项阻力因子。基于场地特征确定阻力因子的阻力值，并在Stata软件中运用熵值法^{[37][38]}确定各阻力因子权重 (表4)。在ArcGIS中对6项阻力因子进行分级赋值与权重叠加后 (表5, 图4, 5)，以碳汇腹地与碳汇重要区作为源地，运用公式 (6) 识别碳汇潜力带，

$$MCR = f_{\min} \sum_{j=n}^{i=m} (D_{ij} \times R_i), \quad (6)$$

式中， D_{ij} 是生态源地斑块*j*到景观单元*i*的空间距离， R_i 为阻力系数， f 表示最小累积阻力与生态过程的正相关关系^{[35][39]}。

表 5: 阻力面构建参数表

阻力因子	分级指标	阻力值	阻力因子	分级指标	阻力值	阻力因子	分级指标	阻力值
坡度 (°)	< 20	1	土地利用类型	林地	1	年降水 (mm)	≥ 600	1
	[20, 40)	3		草地	1		[450, 600)	3
	[40, 60)	5		耕地	3		[300, 450)	5
	[60, 80)	7		水域	5		[150, 300)	7
	≥ 80	9		城镇用地、农村居民点、其他建设用地	10		< 150	9
高程 (m)	< 2 000	1	未利用土地	5	人口密度 (人/km ²)	< 1 000	1	
	[2 000, 3 000)	2	年积温 (°C)	≥ 4 000		1	[1000, 2000)	3
	[3 000, 4 000)	4		[3 000, 4 000)		3	[2000, 3000)	5
	[4 000, 5 000)	6		[2 000, 3 000)		5	[3000, 4000)	7
	[5 000, 6 000)	8		[1 000, 2 000)		7	≥ 4000	9
	≥ 6 000	10		< 1 000		9		

表 6: 固碳增汇管理措施综述

一级土地利用类型	二级土地利用类型	管理措施
林地	有林地、灌木林、疏林地、其他林地	造林与再造林、退耕还林、天然林保护、森林抚育、人工林天然化、混交林种植、林粮间植
草地	高覆盖度草地、中覆盖度草地、低覆盖度草地	天然草地封育、退耕还草、退化草地恢复、多年生混播草地间植、合理控制放牧强度、划区轮牧、延迟放牧
耕地	水田、旱地	秸秆还田、施用有机肥、保护性耕作、轮作、灌溉管理、复合系统间作、农田废弃资源循环利用
水域	河渠、湖泊、水库坑塘、永久性冰川雪地、滩地	湿地保育、退化滩地恢复、湿地管理、垃圾清理、人工湿地营造
未利用土地	沙地、戈壁、盐碱地、裸土地、裸岩石质地	土壤基底修复维稳, 种植耐盐碱固沙植物, 引入新型生物技术培育能够适应环境且高效固碳的树种、草种与微生物

注

表格中国碳增汇管理措施来源: 参考文献 [36]~[42]。

3.4 生态修复策略拟定

对碳汇腹地、重要区与潜力带的土地利用现状进行分析, 提炼土地利用的典型空间模型。参考已有研究^{[40]~[46]}, 针对不同土地利用空间模型拟定生态修复策略与管理措施(表6), 以期实现维持林地碳汇、适当提升未利用土地碳汇、显著提升耕地与草地碳汇的目标。

4 研究结果与分析

4.1 温宿县碳汇现状

4.1.1 碳吸收能力现状

结果显示, 温宿县的NEP值位于 $-229.125\sim 293.020\text{gC}\cdot\text{m}^{-2}\cdot\text{a}^{-1}$ 之间, 不同区域间NEP值相差较大, 碳吸收能力的高低整体呈错落分布。NEP低值区域主要位于温宿县南部戈壁和裸岩石质地区域, 其碳吸收能力最弱; 同时, 常年积雪覆盖、植被稀少的北部天山高海拔区域碳吸收能力也较弱。NEP高值区域主要位于天山南麓海拔2 000~3 000m的带状区域, 该区域自然林地与草地生长状态良好, 碳吸收能力最强; 同时, 南部以农田为主的人工植被区域也具有较强的碳吸收能力(图6)。

4.1.2 碳储量现状

在土壤碳储量方面, 温宿县中部土壤总碳储量最高, 南部次之, 北

部最低(图7)。其中, 县域中部和南部部分区域、东南部冲积平原的表土与底土无机碳含量均较高(图8, 9); 天山南麓海拔2 000~3 000m区域的表土有机碳含量相对较高(图10); 而底土有机碳则整体较低, 仅在县域中部海拔1 500~2 000m的区域及南部平原的少量区域有着较高的底土有机碳含量(图11)。

温宿县植被碳储量总值为 $361.013\times 10^4\text{t}$ (表2)。其中, 温带禾草、杂类草盐生草甸碳储量最高, 共计 $89.059\times 10^4\text{t}$; 以两年三熟或一年两熟旱作和落叶果树园为代表的栽培植被次之, 碳储量为 $65.322\times 10^4\text{t}$; 寒温带和温带山地针叶林虽然面积较小, 但其碳密度值最大, 碳储量也相对较高, 为 $57.007\times 10^4\text{t}$; 温带草原化灌木荒漠由于面积积极少且碳密度值较低, 其碳储量最少, 仅为 $0.8\times 10^4\text{t}$ 。

综合植被碳储量和土壤碳储量情况可知, 温宿县现有碳储量最丰富的区域主要为县域南部平原与天山南麓, 其现状土地利用以林地、草地、耕地为主。在后续生态修复过程中, 应重点关注其土地开发和流转情况, 保证其碳储量不被大面积扰动。

4.1.3 碳汇重要性空间分布

碳汇重要性评价结果显示, 温宿县不同地理环境的碳汇重要性差异较大。其中, 天山南麓海拔2 000~3 000m的区域碳汇重要性最高, 评级结果以“极高”和“高”为主; 南部和东南部平原的连片农田区域具有

表 7: 碳汇腹地土地利用类型统计

土地利用类型	面积 (km ²)	百分比	总面积 (km ²)
旱地	2.88	0.27%	1 083.87
有林地	41.29	3.81%	
灌木林	0.12	0.01%	
疏林地	36.54	3.37%	
高覆盖度草地	526.79	48.60%	
中覆盖度草地	124.45	11.48%	
低覆盖度草地	344.26	31.76%	
河渠	5.70	0.53%	
滩地	1.84	0.17%	

较高的碳汇重要性, 评级结果以“高”和“中”为主; 而在北部天山海拔3 000m以上的区域、县域中部和东南部的戈壁与裸岩石质地区域, 碳汇重要性评级结果都以“极低”为主, 其中穿插有少量“低”值区(图12)。

4.2 碳汇空间格局识别结果

研究识别得到温宿县碳汇腹地一处、碳汇重要区两处, 以及总面积达2 259.81km²的碳汇潜力带。其中, 碳汇腹地位于温宿县北部海拔2 000~4 000m的天山南麓区域, 面积为1 083.87km²; 两处碳汇重要区分别位于温宿县南部与西南部的平原区域, 总面积为1 899.69km²; 碳汇潜力带主要位于县域中部。碳汇腹地的土地利用类型以高、中、低覆盖度草地为主, 面积占比分别为48.60%、11.48%和31.76%(表7); 碳汇重要区的土地利用类型以旱地为主, 面积占比高达86.63%(表8); 碳汇潜力带土地利用类型以低覆盖度草地与未利用裸岩石质地为主, 面积占比分别为51.28%和24.81%(表9, 图13)。

4.3 生态修复策略

基于温宿县土地利用现状组合类型, 团队提炼得到八种土地利用

表 8: 碳汇重要区土地利用类型统计

土地利用类型	面积 (km ²)	百分比	总面积 (km ²)
水田	4.65	0.24%	1 899.69
旱地	1 645.65	86.63%	
有林地	0.12	0.01%	
其他林地	51.65	2.72%	
高覆盖度草地	15.16	0.80%	
中覆盖度草地	12.21	0.64%	
低覆盖度草地	78.79	4.15%	
河渠	8.18	0.43%	
水库坑塘	0.57	0.03%	
滩地	13.55	0.71%	
城镇用地	2.21	0.12%	
农村居民点	65.66	3.46%	
戈壁	0.31	0.01%	
裸土地	0.98	0.05%	

表 9: 碳汇潜力带土地利用类型统计

土地利用类型	面积 (km ²)	百分比	总面积 (km ²)
旱地	16.13	0.71%	2 259.81
高覆盖度草地	5.11	0.23%	
中覆盖度草地	146.40	6.48%	
低覆盖度草地	1 158.73	51.28%	
戈壁	330.84	14.64%	
裸土地	41.88	1.85%	
裸岩石质地	560.72	24.81%	

表 10: 土地利用空间模型、生态修复策略与具体措施

空间类型	土地利用空间模型	特征描述	生态修复策略	措施
碳汇腹地	林—草	连片草地，其中分布有少量团簇状的有林地	高碳巩固	通过废弃草地的混交林种植、造林与再造林、合理放牧管理及天然草场封育等方式稳定现有碳库，恢复土壤肥力，增强草原碳汇
碳汇重要区	戈壁—农—草	连片戈壁，边缘分布有滩地、草地与耕地	保碳修复	通过边界修复、滩地生态涵养、退化草场补播养护及退耕还草等方式提高地上生物量，恢复土壤肥力，稳定现有土壤碳库，增强草原碳汇
	农—林—居	大面积连片耕地与零星散布的农村居民点和种植园	低碳利用	通过保护性耕作、林粮间作、农田废弃资源循环利用等方式，达成农—林—居资源的循环利用，降低资源消耗率，提升农田土壤及覆被的碳储量
碳汇潜力带	裸岩石质地—草地	在裸岩石质地中，分布有呈条带状的低覆盖度草地	保碳扩展	通过盐碱地土壤基底修复、种植耐盐碱固沙植被、在边界地带构建防护林带等方式保证自然演替，恢复土壤肥力，从而保证并提升草地碳汇
	草地—裸土地	以大面积连片的低覆盖度草地为主，其中分布有少量裸土地	固碳补植	通过裸土地治理、放牧管理、生态补植等方式增强草地土壤及覆被碳汇能力，同时提高地上生物量，进而提升区域总体碳汇
	滩地—盐碱地	河渠旁的滩地，边缘为植被稀少的盐碱地	固碳防治	通过盐碱地土壤基底修复、种植耐盐碱植被及植入新技术的方式培肥土壤，保证区域土壤碳汇稳定
	林—田—水	灌木林、旱地和河渠组团斑块，有道路从中穿过	高碳维持	通过保护性耕作、退耕还林、人工林天然化、混交林种植等方式，稳定土壤碳库，有效提升碳汇
	草地—公路	在裸岩石质地中的狭窄条带状低覆盖度草地，有道路从中穿过	重点固碳监测	通过天然草场封育、划区轮牧、控制放牧强度及种植防护林带的方式保证草地土壤及覆被碳库稳定；同时，提升公路段周边植被碳吸收能力，保持区域整体碳汇的稳定

典型空间模型，其中碳汇腹地一种、碳汇重要区两种、碳汇潜力带五种。研究团队以碳增汇为导向提出了相应的生态修复策略，即高碳巩固，戈壁保碳、低碳利用，保碳扩展、固碳补植、固碳防治、高碳维持、重点固碳监测；并因地制宜地拟定生态修复和碳汇效应提升措施（表10，图14）。

5 结论与讨论

5.1 结论

研究基于多源数据评估了温宿县碳汇现状，识别了县域碳汇空间格局，并提出了以碳增汇为导向的国土空间生态修复规划策略。研究发

现,温宿县碳吸收能力呈现高低错落分布的空间格局,天山南麓海拔2 000~3 000m的带状区域碳吸收能力最强,碳储量最丰富的区域主要位于县域南部平原与天山南麓。碳汇重要性水平则在温宿县不同地理区域之间呈现较大差异,天山南麓、南部和东南部平原碳汇重要性整体较高。基于碳汇重要性,研究识别出碳汇腹地一处、碳汇重要区两处,以及总面积为2 259.81km²的碳汇潜力带;并以碳增汇为首要目标,拟定八种生态修复策略,因地制宜开展生态修复。

5.2 对中国西北干旱区碳汇管理的启示

研究表明,草地与农田或可成为中国西北干旱区固碳增汇重点关注的土地利用类型(表7~9)。虽然林地的碳汇能力往往高于草地^[47],但就本案例而言,干旱少雨的气候导致林地在温宿县面积占比较小、可以提供的碳汇效应有限,而草地与旱地则在本案例中表现出较高的碳汇重要性,是温宿县碳汇的主要来源。现有中国西北干旱区植被碳汇评估的相关研究也指出,温带草原与高质量农田具有较大的碳汇量^[24],进一步说明了草地与农田的碳汇潜力。因此,在开展中国西北干旱区生态修复时,应充分尊重本土植被的特点,避免在植被类型转换及维系非原生植被生长过程中因物料、能源等投入带来的碳排放;并在保证大面积草地不被扰动的基础上,改善草地管理措施,增加土壤的有机质含量,从而提高碳储量^[48]。在农田的碳汇提升上,虽然农作物光合作用可以固定大气中的二氧化碳,但土壤呼吸和农业生产活动依旧会产生一定量的碳排放^[49],因此,可通过改变耕作制度、控制农资投入等减少土壤扰动的农作方式,以及优化人工管理措施^{[50][51]}的方法,进一步提高农田固碳增汇的能力。

温宿县碳汇空间格局的识别结果也对中国西北干旱区的碳汇管理具有一定的借鉴意义。虽然相较于城镇化程度较高的区域,碳汇高值区往往位于远离城区的自然地带^{[9][52]},但温宿县的碳汇空间格局表明,除天山南麓的自然区域外,南部人类活动强度较高的农村居民点及农田区域仍然可以产生明显的碳汇效应。这再次凸显了经人为干预的景观对干旱区固碳增汇的重要性,未来研究可进一步细化干旱区人工栽培植被的碳汇评估,从而为实践中人为管理固碳增汇措施的细化提供参考。

5.3 对国土空间生态修复的意义

中国自20世纪50年代以来开展了众多生态修复工程,大量森林、草地、湿地、农田等生态系统得到了有效修复,其固碳增汇能力也显著增加^[15]。有别于过去仅针对单一要素的生态修复,国土空间生态修复强调提升区域生态系统整体的稳定性与安全性^[53],而“双碳”目标的提出使得固碳增汇成为其重要目标之一,越来越多的研究开始探讨如何通过生态修复来实现“双碳”目标^{[17][18]}。当前,这些研究大多聚焦于单一生态

系统,重点讨论具体的生态修复措施,抑或仅从理论上对国土空间生态修复的碳增汇路径进行探讨^[14]。本研究则从空间视角出发,通过具体案例,将碳汇现状评估、空间格局分析与规划及具体修复策略拟定相结合,提出了一种固碳增汇的空间途径;碳汇空间格局识别中所采用的MCR方法也可用于侧重生物多样性保护^[54]、山地防灾^[55]等目标的国土空间生态修复。因此,本研究的技术路线有助于将碳增汇目标与其他生态修复目标相结合,助力山水林田湖草沙的整体保护、系统修复和综合治理的实现。

5.4 展望

本研究将生态修复的难易程度和碳排放就地消纳的需求程度作为建立碳汇潜力带的阻力,运用MCR识别碳汇潜力带的方法具有试验性质,在后续研究成果转向实践的过程中,需要进一步加强实地验证。此外,后续研究可进一步补充收集实测数据,完善数据的时间与精度,提高碳汇评估的全面性与准确性;同时,整体统筹碳汇与其他生态问题,将促进国土空间生态修复与综合治理进一步朝碳增汇的方向发展。

图1. 研究区域高程与土地利用现状(数据来源:高程数据来源于地理空间数据云,卫星影像来源于必应地图,土地利用数据来源于中国科学院资源环境科学与数据中心)

图2. 研究框架

图3. 植被碳储量空间分布

图4. 研究区域阻力因子赋值

图5. 研究区域综合阻力面

图6. NEP空间分布

图7. 土壤总碳储量空间分布图

图8. 表土无机碳空间分布图

图9. 底土无机碳空间分布图

图10. 表土有机碳空间分布图

图11. 底土有机碳空间分布图

图12. 碳汇重要性水平空间分布

图13. 碳汇空间格局识别结果

图14. 生态修复策略



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