

Research into ecological suitability zoning and expansion patterns in agricultural oases based on the landscape process: a case study in the middle reaches of the Heihe River

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Abstract Given the complexity of land use activities, land ecological suitability analysis can reflect the advantages of regional natural resources and the potential of socioeconomic development. Thus, it could provide scientific evidence for environmentally land use planning in agricultural oasis cities. This research analyzes the principal conflicts and restrictive conditions of regional land use in the main agricultural oasis of the middle reaches of the Heihe River, and identified two kinds of antagonistic forces, i.e., agricultural oasis expansion and ecological conservation land expansion. Then, the minimum accumulative resistance theory and ecology assessment method are introduced to construct a comprehensive land use security model that meets ecological suitability. Furthermore, the strategic patches and radiation corridors for agricultural oasis expansion in the region are recognized through the model calculation. The main conclusions of the model are as follows. First, land use in the region can be clearly divided into four categories: key protected zone, buffer protected zone, moderate developed zone and optimized developed zone. Second, agricultural oasis expansion shows significant strategic patches and radiation corridors information. The strategic point locations are characterized by high-quality soil, rich water resources and outstanding location advantages; while the

radiation corridors of each county indicates the direction for ecological suitability, which is significantly affected by the spatial distribution of traffic arteries and ecologically sensitive areas. Third, rural residents can be divided into five categories by the unit of town. Only after effectively identifying the potential and limiting factors of each type could the objective of sustainable management in the arid oasis be achieved.

Keywords Land ecological suitability · Landscape process model · Oasis expansion pattern · Strategic recognition · The agricultural oasis in the middle reaches of the Heihe River

Introduction

As one of the areas strongly disturbed by human activities, the agricultural oasis has a high degree of heterogeneity and diversity; it is the center of land use in arid areas and has always been characterized by a vulnerable ecological environment (Chen et al. 2005). The development of land resources in arid agricultural oases is highly dependent on water resources. In recent decades, the over-exploitation of land and water resources is ubiquitous in the arid regions of Western China (Chang et al. 2012) and has led to a series of ecological and environmental problems, i.e., water shortages, groundwater decline, shrinking wetlands, downstream oasis degradation and soil salinization. Centering on the theory of ecological security, land ecological suitability management seeks to optimize land use patterns that are adapted to the local environment in order to guide the human activities of land resource development, utilization, management and protection in an appropriate direction. Further, it seeks to positively coordinate space

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conflicts between water resource development and land use conflicts in arid oases.

Recently, as studies in land use changes, sustainable land use assessment and ecological security have progressed, land ecological analysis has been widely acknowledged as an important means for regional sustainable management, and corresponding design models have emerged. Land ecological suitability reflects the degree of ecological need and the adaptation capabilities of a land unit for a particular usage (Meng 2011). Early analysis methods originated from the qualitative means of overlaying ecological factors as proposed by McHarg (1969), an American landscape architect. This was known as the “sieving method,” referring to the process of gradually screening out areas that fail to meet the requirements through a series of “sieves,” until finally only the areas in line with all of the rules remain. On this basis, integrated quantitative analysis methods, i.e., mathematical combinations, factor analysis and logic rules, have been established and are widely used in agriculture (Campbell et al. 1992), animal and species habitats (Pereira and Duckstein 1993), geological suitability (Bonham-Carter 1994), public infrastructure locations (Eastman et al. 1993), urban expansion (Janssen and Rietveld 1990), environmental impact assessment (Moreno and Seigel 1988), landscape planning (Miller et al. 1998) and other fields. With the improvement in landscape ecology theory and GIS spatial analysis technology, the study of land ecological suitability began turning to mechanisms and ecology processes at different temporal and spatial scales. A series of pattern–process coupling models were constructed (Fortin and Agrawal 2005; Fischer et al. 2008), and gray cluster methods (Tang et al. 1991), nonlinear models (Marull et al. 2001), fuzzy comprehensive evaluation (Stoms et al. 2002) and artificial neural networks (Jiao and Liu 2007) have also been introduced. For instance, the niche model (Ouyang et al. 1996; Yu et al. 2006; Li et al. 2007; Meng et al. 2011) and the source-resistance model (Yu 1999; Liu et al. 2010) have been applied to land use suitability evaluation. In general, existing studies mainly focus on quantifying the vertical process of land units: both the mathematical overlaying of the map superposition method and the logic combinations of the logical rules method are just a vertical overlay process of ecological elements, which can hardly reveal the relationship between ecological processes and the assessment unit. Furthermore, the selection of assessment factors primarily emphasizes the natural properties of land resources, and the combination of social and economic factors is insufficient.

Compared to traditional ecology research, landscape ecology is a comprehensive discipline that addresses the landscape type, its spatial pattern and their interaction. It focuses particularly on the impacts of spatial heterogeneity,

hierarchical structure and scale of the ecosystem, especially the mutual interaction of spatial structure and ecological processes at multiple scales. Therefore, this study intends to construct a comprehensive ecological model through the introduction of MCR and integrated niche theory, which are both known for the analysis of ecological processes, to spatially recognize and optimize the landscape patterns in the area under the constraints of water resources, thus providing guidance in the sustainable development of agricultural oasis land and the adaptive management of regional agroecosystems.

Study area and data

Study area

The middle reaches of the Heihe River are located in the western part of Gansu Province and the middle of the Hexi Corridor, a crucial location in China’s history. The administrative divisions include the Ganzhou District of Zhangye City, Gaotai County, Linze County, Minle County, Shandan County and the Minghua District of the Autonomous County of Sunan, with a total area of approximately 19,600 km² (Fig. 1). With steep terrain and lush grass, the southern Qilian Mountains are the most important water conservation area in the Hexi Corridor, and the central oasis is abundant in water and soil, being the core of the modern agricultural base. The northern Heli and Longshou Mountains are covered by deserts, serving as a strong barrier against sand invasion. The middle reaches of the Heihe River have a continental climate with scarce precipitation and abundant sunshine. The region is the main water and runoff consumption area of the Heihe River, concentrating 80 % of the river basin oasis, 91 % of the population, more than 80 % of GDP and 95 % of the arable land. It has both developed agriculture and prominent contradictions in water and land resources.

Data

Land use data used in this study include the four periods of 1986, 1995, 2000 and 2010. Data for the first three periods came from the “Eight-Five” scientific project of the Chinese Academy of Sciences, and the data for 2010 were acquired based on 2010 Landsat Thematic Mapper (TM) images of the Heihe River. Through visual interpretation and other conventional image preprocessing techniques, land use in the region was divided into six types, i.e., farmland, forest, grassland, water, construction land and desert, in which classification accuracy was more than 90 %. The basic terrain object data, including the administrative divisions, roads, rivers and lakes, railways and

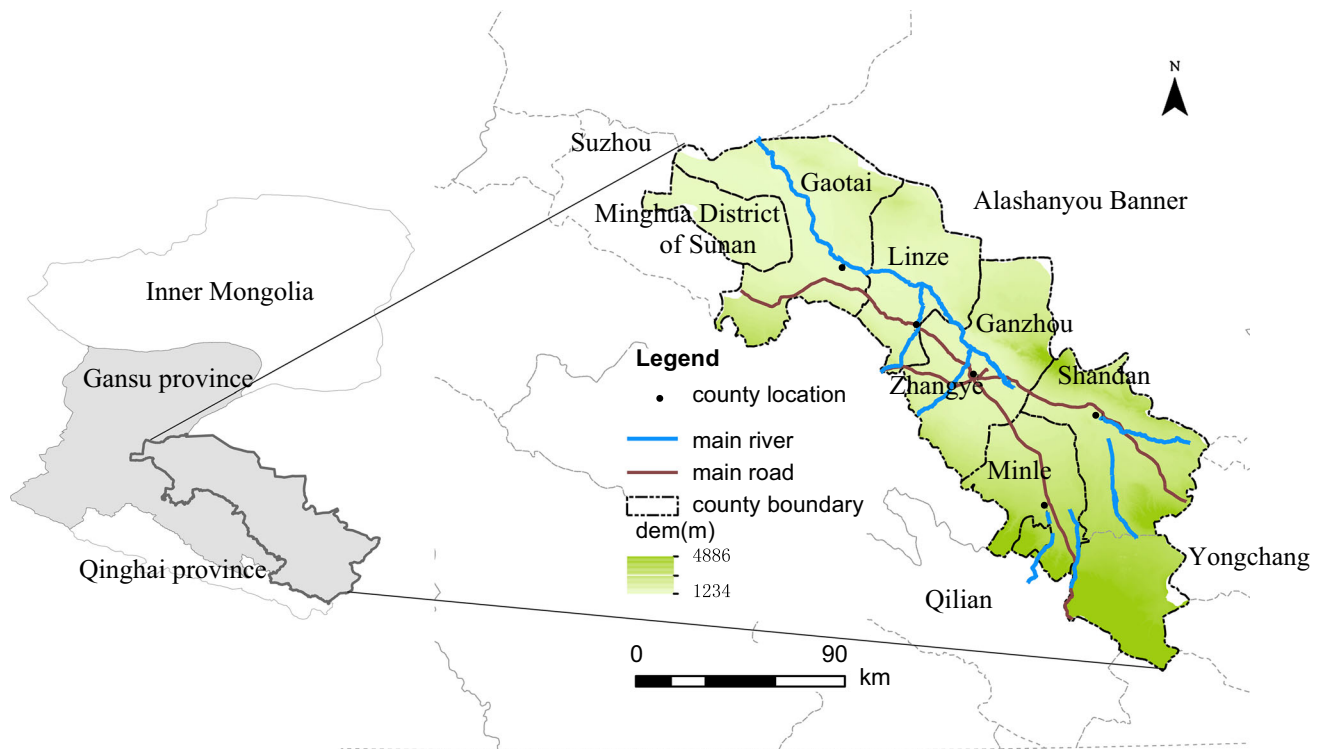


Fig. 1 Location of study area (the middle reaches of the Heihe River)

irrigation canals, and the data for temperature, precipitation and groundwater depth all came from the “Digital Heihe” Project of the Cold and Arid Regions Science Data Center of the Chinese Academy of Sciences (Heihe Data Management Center 2011; Liu and Ma 2011). The soil data came from the Chinese Soil Dataset (version 1.1) in the FAO World Soil Database (HWSD) (Fischer et al. 2008), and the vegetation data came from the Chinese Academy of Sciences Vegetation Map Editorial Committee (2007). The DEM came from the Global LUCC Database of Maryland University, with a resolution of 30 m × 30 m. Socioeconomic and other relevant statistical data were from the “Statistical Yearbook of Zhangye City” (1986, 1995, 2000 and 2010). DMSP/OLS data in 2010 were obtained from the US National Geophysical Data Center. Policy and management information were summarized from text data provided by the Statistical Bureau, the Forestry Bureau, the Environmental Protection Agency, the Planning Bureau and the Agricultural Bureau in Zhangye City.

Theoretical framework and methods

Landscape structure refers to the spatial permutation and combination of elements, which could be described by the pattern of patch-corridor-matrix (Forman and Godron 1986). Patches are areas of interior homogeneous

features which are different from the background region. Corridors refer to long and narrow areas that connect different patches in the region. Matrix means the background ecosystem or land use structure in the region. Different elements and their organization forms have distinct ecological functions, in which some local structures (sources, sinks, channels, etc.) exert crucial and controlling impacts for the ecological processes. Therefore, the recognition of landscape pattern and its controlling elements is of vital importance for the background ecosystem.

This study introduces MCR and ecology assessment method in the analysis of land use changes from 1986 to 2010 and constructs a conceptual model of land suitability zoning for further ecological suitability and sustainable management study, attempting to recognize the inner landscape pattern and its ecological process in the agricultural oasis.

Theoretical framework

The MCR theory has been derived from the research on species diffusion. Species’ utilization of the landscape is seen as a competitive control and coverage process that must be achieved by overcoming resistance (Knaapen et al. 1992; Yu 1999); the accumulation path with the least resistance is the most appropriate channel. The advantages

of MCR lie in its consideration of horizontal processes among land units instead of the general vertical overlay process of ecological elements. Thus, it can reveal the ecological evolution process and the ecological relationship between those units. In recent years, the theory has been applied to the simulation of urban land expansion and ecological land protection (Li and Liu 2006).

Niche theory reveals that biology is affected by multiple environmental factors instead of a single one and that each factor has a certain threshold for the species. Traditional ecology assessment model tends to overlay various ecological factors by their weights in a vertical way, ignorant of the horizontal ecological process, while in virtual geographical space, the distribution of resistance is never homogeneous owing to the differences in surface conditions and the interactions of various factors (Li and Liu 2006). In this study, ecological factors were assumed as the landscape resistance coefficients, which revealed the potentiality and limitations of specific factors diffusing outwardly over different distances by the origin of sources in ecological processes.

Combining the MCR and ecology niche theory, this article simulates regional land use changes as the horizontal ecological process of overcoming the resistance from “source” to “sink,” assuming that the source patches are the most suitable for ecological land use and could fully reflect the landscape characteristics of the study area; then, the resistance surface in the region is constructed, assessing the “connectivity” and “similarity” between each unit and the source unit to determine the ecological suitability of land use. After calculating the resistance value of each unit, the region has been divided into four ecological zones, and the controlling elements of the landscape pattern in the background ecosystem are recognized.

The practical implication of each element (source patches, resistance surface, strategic patches and radiation corridors) in the zoning system is explained in Table 1, and the modified MCR model can be expressed by formula (1):

$$\text{MCR} = f \min \sum_{j=n}^{i=m} (D_{ij} \times R_i) \quad (1)$$

where f represents the positive correlation between the minimum cumulative resistance and the ecological processes; D_{ij} is the spatial distance in the region from source j to landscape unit i ; R_i is the resistance coefficient of a certain ecology factor to landscape unit i ; $D_{ij} \times R_i$ represents the cumulative value of distances and resistances while crossing all of the landscape units between unit i and source j ; \min is the minimum resistance accumulation value among all of the source patches for a certain assessment patch.

Model assumptions

By analyzing the land use change processes from 1986, 1995 and 2000 to 2010 in the middle reaches of the Heihe River, we could clearly identify the two main contradictions in land use in the region. (a) The first contradiction is the expansion of the artificial oasis (i.e., farmland and construction land) and the shrinking of the natural oasis (i.e., grassland and forest). In the arid zone, the development of agriculture relies largely on the oasis, and the oasis distributes among the desert. Under natural conditions, oasis and desert are in a state of equilibrium; as agriculture develops, the natural balance is gradually broken due to the high intensity of land development, especially the rapid expansion of farmland-based artificial oases. The occupation of ecological land (i.e., grassland and forest) by farmland and construction land can be clearly seen in this period. Since 2000, a series of ecological engineering policies, such as the conversion of cropland to forest, have been implemented and have led to the reversal of farmland to ecological land; thus, future changes in farmland reveal instability. (b) The second contradiction is the mutual restraint between rural settlement-based construction land and farmland. As the social economy develops, the scale of construction land, such as urban, industrial and other

Table 1 Practical implication of each element in the zoning system

Elements	Basic meaning	Ecological implications
Source patches	Areas that could promote positive ecological process	The most suitable for ecological land use that could fully reflect the landscape characteristics of the study area
Resistance surface	The “connectivity” and “similarity” between each unit and the source unit	Reflecting the potential or limits of oasis expansion
Strategic patches	Stepping stones among different sources	Areas with the most fertile water and soil resources and outstanding location conditions near the traffic artery (including the railway and national roads)
Radiation corridors	The channels among different patches	Showing the ecologically suitable directions and trends for built-up area expansion for counties

construction sites, continues to show an upward trend. Considering the constraints of geographical location and water resources, the expansion of urban and rural settlements primarily consumes the farmland nearby, which ultimately results in the occupation of ecological land for the balance of the total amount of arable land. Therefore, another trend in land use changes is revealed in the inevitability of construction land expansion and the uncertainty of ecological land changes. The following assumptions are proposed to build the model:

1. Land use in this region can be divided into two categories: artificial oasis occupied by human activities and ecological conservation land that provides crucial ecosystem services and exerts dominating ecological functions. The former mainly refers to farmland and construction land, while the latter includes forest, grassland and water. Because the water area in the region is small and somehow stable, it is not considered in the following expansion process.
2. To maximize ecological benefits, ecological conservation land should be largely retained, and to maximize social–economic benefits, artificial oasis land should expand as much as possible. The two processes are not isolated but linked and constrained by each other, and the balance between the two reveals the balance between farmland, construction land, forest and grassland.
3. The conservation of ecological land is stimulated and promoted by the land’s ecological importance, while the expansion of artificial oasis is restricted by the land’s ecological importance. Therefore, from the perspective of ecological functions, the same land unit, respectively, hinders or promotes different processes.

Zoning model

Based on the above assumptions, a pair of resilient forces were identified: The agricultural oasis expansion resistance surface reflects the inherent potential of oasis expansion, and the ecological conservation resistance surface reflects the external limits of oasis expansion. As shown in Fig. 2, A and B represent the source patches of the expansion of artificial oasis and conservation land. P and L represent the minimum cumulative resistance curve of the two expansion processes, respectively. C represents the unit that has equal minimum cumulative resistance value in the two processes. Between the period of A and C, the minimum cumulative resistance of ecological conservation land expansion is greater than that of artificial oasis, revealing that the land use patches are relatively closer to the agricultural oasis expansion sources, which should be used as the oasis development. In this way,

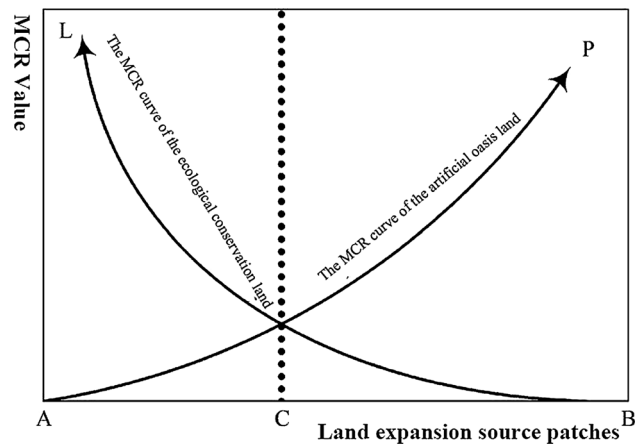


Fig. 2 Conceptual diagram of the relationship between the resilient forces

the patches between B and C are more suitable for ecological land use. Then the regional land ecological suitability assessment model is constructed based on the difference value between the minimum cumulative resistances of the two landscape processes, using formula (2):

$$MCR_i = MCR_{(ecological\ conservation\ land\ expansion)} - MCR_{(artificial\ oasis\ expansion)} \tag{2}$$

where MCR_i refers to the minimum cumulative resistance value of land unit i . When $MCR_i < 0$, the unit is determined to be suitable as ecological land; when $MCR_i > 0$, the unit is identified as suitable for human activities; and $MCR_i = 0$ refers to the critical state between the two.

Determining the source patches

Based on the principles of representativeness, stability and homogeneity, a differentiated extraction method of source patches is adopted for different types of land use. Considering the agglomeration trend of farmland and forest, grids of the two types that remain unchanged during the periods of 1986, 1995, 2000 and 2010 are extracted, from which patches with an area over 8100 m² in consecutive units of eight neighborhoods are determined to be the sources of farmland and forest. The area of grassland is relatively large. The low-coverage grassland demonstrates the characteristics of strong seasonality and instability; thus, the patches of high- and medium-coverage grassland with an area of over 8100 m² are determined to be the sources of grassland. The construction land in the region includes built-up urban areas and a large number of rural settlements, from which the county built-up areas and large-scale towns in 2010 are extracted as the source of construction land, and the 53 most important towns are determined to be the “spots” of the region. The four types of source patches are processed in ArcGIS.

Table 2 Index system for the assignment of landscape process resistance in the region

Main Factors	Resistance to ecological conservation land expansion	1	2	3	4	5
	Resistance to artificial oasis expansion	5	4	3	2	1
Landscape type	Land use type ^a	Forest, high-coverage grassland, water	Medium-coverage grassland	Low-coverage grassland, unutilized land	Farmland	Construction land
	Vegetation type ^b	Alpine vegetation, coniferous forest	Meadow, grassland, shrub	Swamp, desert, land without vegetation	–	Cultural vegetation
Site conditions	Elevation (m) ^c	>3800	3000–3800	2500–3000	1800–2500	<1800
	Slope ^d	>35°	25°–35°	15°–25°	8°–15°	0°–8°
	Evapotranspiration (mm) ^e		<960	960–1050	1050–1120	1120–1250
	Soil quality ^f	The fifth grade	The fourth grade	The third grade	The second grade	The first grade
Water conditions	Groundwater depth ^g (m)	>200	100–200	30–100	10–30	2–10
	Groundwater mineralization (g/L) ^h	–	–	>10	3–10	1–3
	Irrigation convenience degree ⁱ	–	<0.1	0.1–0.45	0.45–0.85	>0.85
	Water source influence degree (m) ^j	<50 or <150	–	Other situations	500–1000	50–500 or 150–500
Ecological limits	Ecologically sensitive regions ^k	Core region of the type I areas	500 m buffer region of the type II areas	–	–	1000 m buffer region of the type III areas
	Soil cultivation limitations ^l	Permafrost, degeneration	–	–	–	Other situations
Location conditions	Spatial GDP (RMB) ^m	<400	400–1000	1000–3482	3482–62,073	>104,928
	Population density (people/km ²) ^m	0	0–35	35–357	357–3744	>3744
	Road accessibility ⁱ	<10	10–30	30–45	45–85	>85
	Important node accessibility ⁿ	0	0–20	20–40	40–80	>80

^a Refer to Wu et al. (2013)

^b Refer to Liu et al. (2010)

^c Determined by the natural resource conditions of the district

^d Refer to the National Farmland Classification Rules

^e Refer to Cao et al.'s study (2012)

^f Refer to the National Farmland Classification Rules and Records of Zhangye Soil; evaluation factors of soil type, surface soil texture, organic carbon, available water, PH are extracted from the Chinese Soil Dataset

^g Determined by the appropriate phreatic level and critical phreatic level for representative vegetation growth

^h Refer to Du et al.'s study (2004)

ⁱ Refer to Yu's study (2006)

^j Determined by the Wetland Protection Plan of Zhangye City

^k Determined by the Environmental Protection Plan of Zhangye City, the Ecological Protection Twelfth Five Year Plan of Zhangye City, wherein the type I region is the national nature reserve, i.e., the Qilian Mountain Nature Reserve and the Heihe River Wetland National Nature Reserve in Zhangye; the type II region includes all other nature reserves, scenic spots, important sites, wetland, forest, pasture and reservoirs; the type III region includes farms and agricultural stations

^l Refer to Records of Zhangye Soil

^m Determined by comprehensive calculation and graded according to the social and economic development conditions of Zhangye City and other counties

ⁿ Determined by Qu et al.'s study (2010)

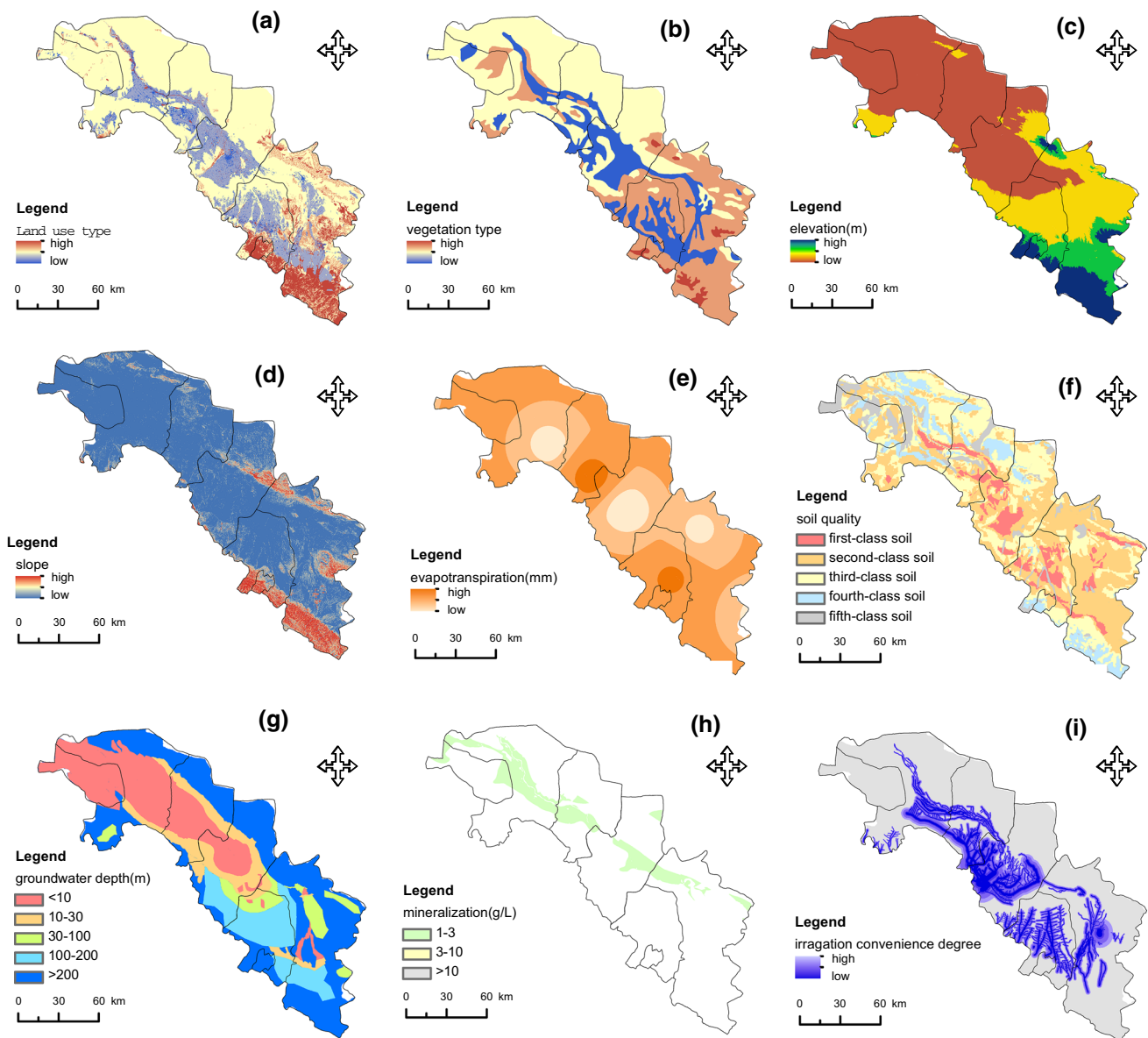


Fig. 3 Spatial distribution of resistance factors in the middle reaches of the Heihe area. **a** land use type; **b** vegetation type; **c** elevation; **d** slope; **e** evapotranspiration; **f** soil quality; **g** groundwater depth; **h** groundwater mineralization; **i** irrigation convenience degree; **j** water

source influence degree; **k** ecological sensitive regions; **l** soil cultivation limits; **m** spatial GDP; **n** population density; **o** road accessibility; **p** important node accessibility

Determining the resistance surfaces

To fully quantify the drivers of land use in the region, methods of factor selection used in ecology are introduced for the five aspects: landscape type, site condition, water condition, ecological limits and geographical location (Table 2). When a particular condition of the assessment unit plays an intensive role in promoting land use expansion in the region, the resistance value of the unit would be the minimum, i.e., 1. When a condition of the assessment unit exerts an absolute limit on the expansion, its resistance

value would be the maximum, i.e., 5. As shown in Table 2, the assignment of resistance values for each factor in the two expansion processes is just the opposite. To be more specific, for a certain assessment land unit, the conditions of a more naturalized vegetation type, a more complex site condition, greater ecological value, stronger sensitivity and higher ecological function are more conducive to the development of the ecological conservation land use type. Higher soil quality and sounder water and location conditions are more conducive to the expansion of farmland and construction land. In the following table, the specific

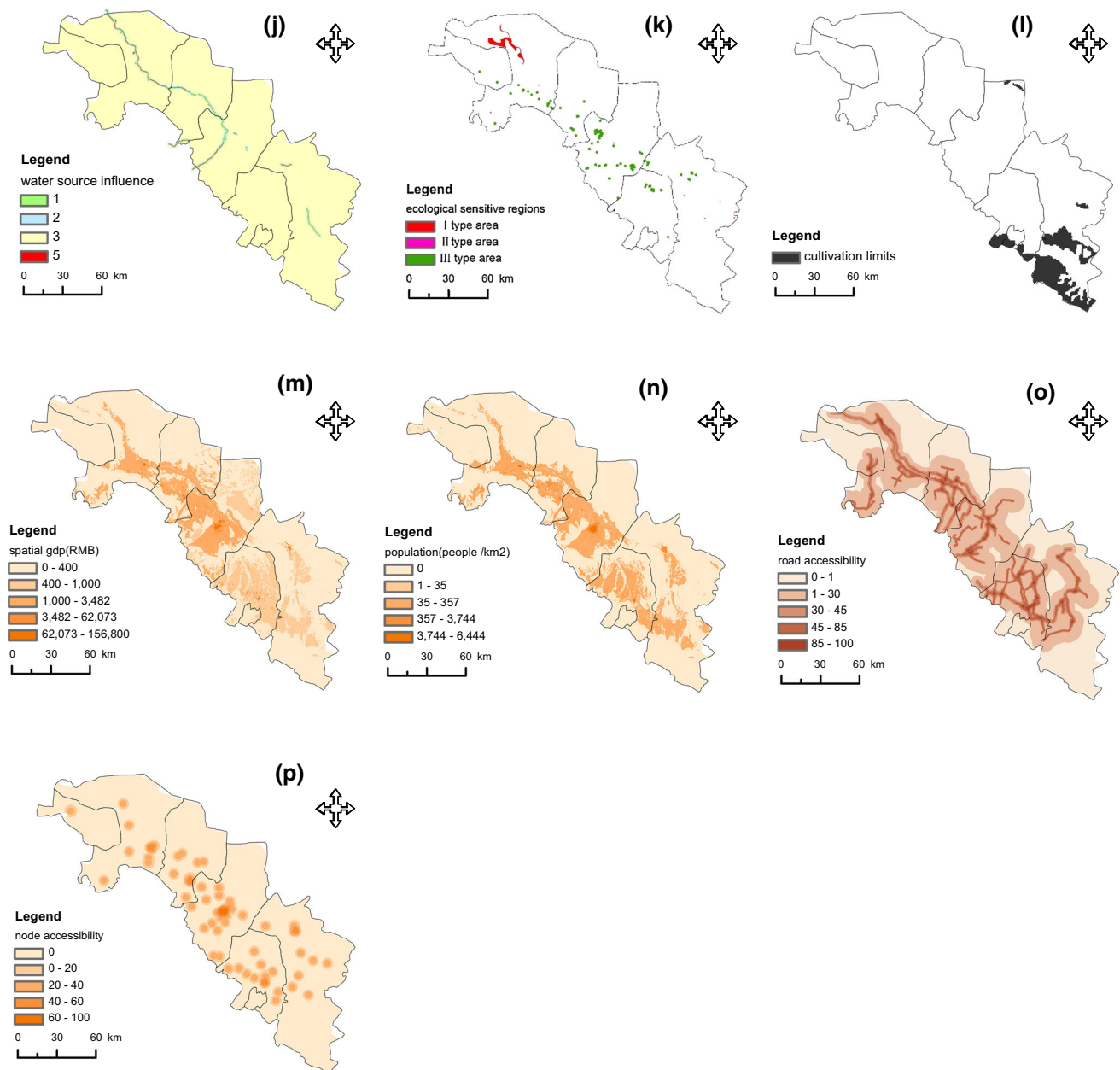


Fig. 3 continued

resistance value is divided into ranks from 5 to 1, in which a higher value means greater resistance and a lower value means lower resistance.

The spatiality of the resistance factors

Quantification methods for calculating resistance factors in the study can be divided into three categories: (1) Through simple mathematical or map operation calculations, such as land use/land cover types, vegetation type, elevation, slope, groundwater mineralization, soil cultivation limitations,

water source influence degree and ecological sensitive zones. (2) Through mathematical models. For instance, the quantification of the irrigation convenience degree mainly considers the spatial attenuation characteristics of the main and branch canals of all of the irrigated regions, and their degree of influence on the surrounding spaces (i.e., F_i) has been divided into several typical grades using the secondary decay model (formula 3–5) to measure their impact (Yu et al. 2006):

$$d_i = d_0 * (1 - \sqrt{F_i}) \quad (3)$$

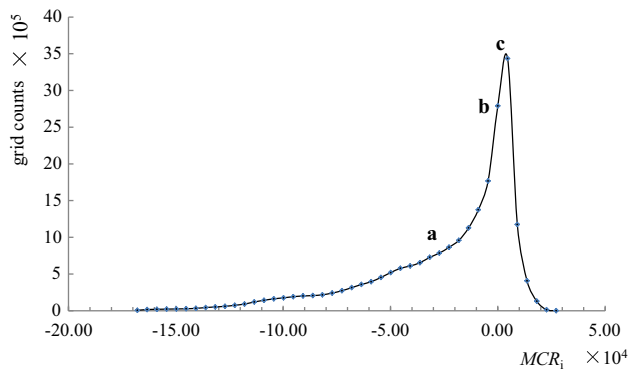


Fig. 4 Relationship of grid counts and minimum cumulative resistance value. Three apparent catastrophe points are marked, i.e., $MCR_i = -19,608$ (point a), $=0$ (point b) and $=5630$ (point c)

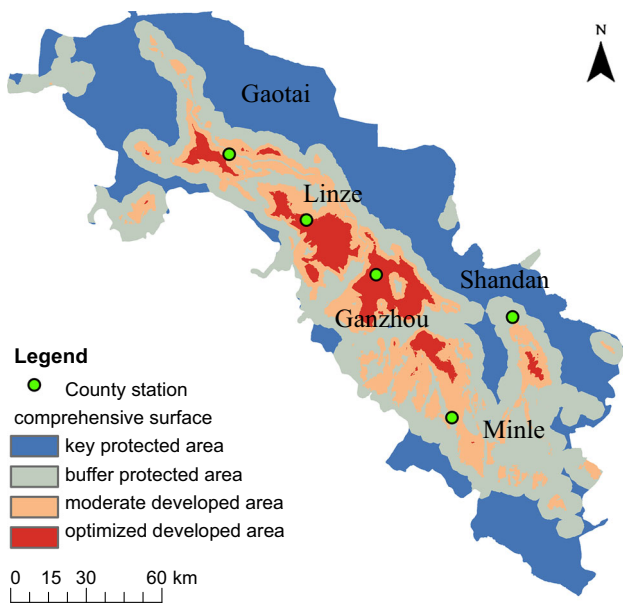


Fig. 5 Zoning of minimum cumulative resistance surface. Different colors mean different categories of ecological area

$$d_{01} = S/2L_a \tag{4}$$

$$d_{02} = S/2(L_a + L_b) \tag{5}$$

where F_i is divided into 9 grades, namely 0.01, 0.1, 0.2, 0.3, 0.4, 0.45, 0.65, 0.85, 1; d_0 is the longest influential distance of the canal; S is the effective area of each irrigation region; L_a is the total length of all of the main canals in each irrigation region; L_b is the total length of all of the branch canals in each irrigation region; d_{01} is the longest influential distance of the main canals; and d_{02} is the longest influential distance of the branch canals.

Resistance factors can also be calculated (3) by synthesizing a variety of methods. For example, the quantification of groundwater is based on the groundwater observation data. The existing basic observation wells

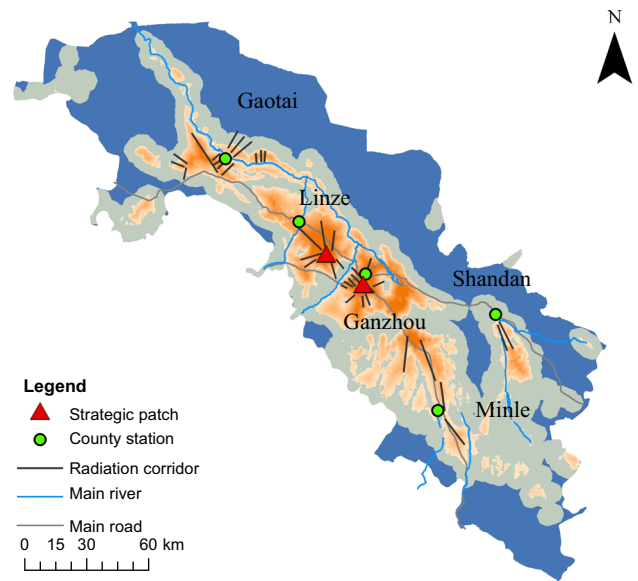


Fig. 6 Strategic patches and radiation corridors of the region. *Black line* refers to the radiation channel between adjacent grids, and *red triangle* refers to the local points having the minimum value

are mainly located in the counties of Ganzhou, Linze and Gaotai; interpolating from these to the entire study area would generate lower accuracy. Therefore, a method combining GIS interpolation and map digitization is adopted to obtain the spatial distribution of groundwater depth. Spatial GDP could reflect intra-regional economic distribution. Considering the relationship between land use type and output value, the study relates the output of agriculture, forest and husbandry, respectively, to the land use types of farmland, forest and grassland in the area and the output of secondary and tertiary industries to the construction land. Then, the light intensity factor is used to revise the value and the level of socioeconomic development within the county, and other similar areas of the Heihe River are used to grade the value. All of the above quantification processes are achieved in the ArcGIS platform through a $30\text{ m} \times 30\text{ m}$ grid (Fig. 3).

Generating a comprehensive resistance surface

According to Shelford's law (Odum 1971), when a certain current condition in the region approaches the threshold for artificial oasis expansion in quantity or quality, it becomes the limiting factor for oasis land. Because the resistance value in this study is relative and dimensionless, Liebig's law of the minimum limit factor in ecology is introduced, and the extreme value method is used to determine the eventual landscape resistance value, which can be expressed in the following formulas:

Table 3 Classification of rural settlements in the region

Ecological zones	Intervals of comprehensive resistance value	Common features of the type
Key developed type	>8733	All located in Ganzhou District, forming a beaded distribution along the 3-1-2 national road as well as the Xi-Zhang highway and Lan-Xin high-speed railway
Optimized developed type	4266–8733	Possessing relatively more fertile water and soil resources and sound location conditions, which exert an impact on promoting the development of nearby towns and villages
Preferential renovated type	0–4266	Distributed along the Heihe River and in the northern piedmont of Qilian Mountain, which is the transitional area between the ecological buffer and the moderate developed areas
General protected type	–689–0	Located in the southeastern part and all are in the ecologically sensitive zones of each county and have a fragile environment
Key protected type	<–689	The ecological environment has severely degraded, posing problems with water resource scarcity and low agricultural outputs

MCR (conservation land expansion) = min(landscape type, site conditions, water conditions, ecological limits, geographic conditions);

(6)

MCR (artificial oasis expansion) = max(landscape type, site conditions, water conditions, ecological limits, location).

(7)

With the cost-distance module of ArcGIS Spatial Analyst tools, the minimum cumulative resistance surfaces of the two types of land expansion processes are obtained. Referring to the theory of cost–benefit analysis and the ecological footprint (Zong et al. 2007), the comprehensive resistance surface, i.e., MCR_i , is obtained by subtracting the two expansion resistance surfaces. In Fig. 4, the relationship between the resistance surface difference and grid count is analyzed, and we find three apparent catastrophe points, i.e., $MCR_i = -19,608$ (point a), $= 0$ (point b) and $= 5630$ (point c): a is the pale point that grid counts dramatically increase, b is the zero-value point of MCR_i and c is the peak point that grid counts fall to decrease. Considering the general principles of the main functional zoning (Fan 2007), the overall region from low to high MCR_i is divided into key protected area ($MCR_i < -19,608$), buffer protected area ($-19,608 < MCR_i < 0$), moderate utilization area ($0 < MCR_i < 5630$) and optimized utilization area ($MCR_i > 5630$) (Fig. 4).

Results

The zoning of land ecological suitability

The following can be seen in Fig. 5. (1) The key protected areas occupy 43 % of the total area, including the deserts and desert steppes in the north and the forests in the south, which create a zone surrounding the entire middle reaches that poses as an ecological barrier to “withstand the sand in

the north and protect the water in the south” of the study area. This is the fundamental guarantee of the arid oasis area in terms of maintaining ecological safety, and it should be managed under the most stringent ecological conservation measures. (2) The buffer protected area accounts for 1/3 of the total area. It ranges between the ecological conservation region and the oasis development region and includes the trunk stream of the Heihe River, Shandan River and Maying River, all of the reservoirs, watershed forest protected areas and the large quantity of unused land between the counties. This unused land has a sensitive environment and serves as the ecological outer space of human activity; it provides an important ecological restoration region in the Heihe River Basin and should be aggressively protected from human activities with a strong impact. (3) The moderate utilization areas include the Zhanglingao Plain and parts of Shandan and Minle counties that are located in the foothills of the alluvial fan and are covered with farmland and scattered rural settlements in the middle reaches of the Heihe River. These are the main areas offering traditional oasis agriculture, and they serve as buffer areas for future expansion of construction land, which should be managed considering aspects of efficient agriculture, the optimized distribution of residents, a moderate concentration of settlements, industrial development and ecological conservation. (4) The optimized utilization area only accounts for 6 % of the entire region. This is mostly represented by oasis core regions of considerable scale, originating from the core of the five counties and spreading along the main axis. They are the leading regions for oasis development and also show the main direction of future rural labor transfer.

The cognition of strategic patches and radiation corridors in the agricultural oasis expansion process

Using the flow direction tool of ArcGIS, the flow of the comprehensive resistance surface is calculated. As seen in

Fig. 6, there exist two regional strategic patches in the center and in northwestern Ganzhou County; the former point mainly influences Liangjiadun Town, Xindun Town and Chang'an Town, as well as Minle County in the south, and the other point affects Mingyong Town, Ganjun Town and Shajin Town, as well as Linze County in the north. Surrounding the strategic patches are those regions with the most fertile water and soil resources and outstanding location conditions near the traffic artery (including the railway and national roads). Therefore, these should be considered as important regions for future urban expansion.

Other counties do not have obvious strategic patches, but they do have outstanding radiation corridors, showing the directions and trends in built-up area expansion in the counties. (1) In Gaotai County, there exists an obvious south to north axial radiation channel, revealing that the ecologically suitable direction for county expansion should shift from the traditional east–west to south–west; the towns in the eastern county mostly radiate outwards along the Heihe River, and Luotuocheng Town has become a local focus, indicating that the emphasis of Gaotai's future oasis expansion should be the restoration and governance of the deserts in western Heiquan–Luotuocheng Town. (2) Linze County has a tendency to develop into the southwest areas along the 3-1-2 national road and to connect with the towns in northwestern Ganzhou. With the construction of the high railway station in Zhangye City and the completion of electrified railway from Wuwei to Jiayuguan, the advantage of expansion would be more distinct. (3) The radiation channel of Minle County is in a northwestern to southeastern axial direction along the Xi-Zhang highway, and the important expansion nodes emerge in northwestern Liuba Town. Most towns in the northern piedmont of Qilian Mountain show a tendency to spread to the north, which would be strengthened after the opening of Lan-Xin high-speed railway. Moreover, Nanfeng Town in southern Minle has become a local expansion region due to its vast amount of farmland and important traffic position compared with other nearby towns. (4) The radiation channel of Shandan County also deviates from the residential area of the county but spreads to southeastern Weiqi Town and Chenghu Town; large tracts near the northern piedmont of Qilian Mountain in southern Shandan Horse Farm have been classified within the buffer protected area. As the core of environmental governance areas, the northern Dahuang Mountain, Longshou Mountain and southern Shandan Horse Farm are focal areas for the policies converting cropland to forest and grassland. Future development should be concentrated into the center from the north and south, thus condensing the square of the artificial oasis and shifting from traditional agriculture to energy and other secondary industries.

The classification of residents in the agricultural oasis expansion process

In the middle reaches of the Heihe River, the town is always the main unit of residential concentration, and its resistance value can be used to measure its future development suitability and provide guidance for the orientation of its scale of development. The comprehensive resistances mean values in a certain neighborhood of 50 towns in the region have been extracted from the model calculation values, based on which the residents of the towns are classified into 5 types (Table 3). (1) The four towns of the key developed type are all located in Ganzhou District, forming a beaded distribution along the 3-1-2 national road as well as the Xi-Zhang highway and Lan-Xin high-speed railway, which, respectively, pose as the hinterlands of the southern and northern sections of Ganzhou. By attracting the population from nearby villages and integrating peripheral land resources, these towns have played a vital role in regional development. (2) The 13 optimized developed towns encompass large sections of Ganzhou District and several towns in nearby counties; they have relatively more fertile water and soil resources and sound location conditions, which exert an impact on promoting the development of nearby towns and villages. Their future development should focus on water savings and modern efficient agriculture, promoting a fundamental shift in water structure and production mode. (3) The 28 preferential renovated towns are distributed in each county, especially along the Heihe River and in the northern piedmont of Qilian Mountain, which is the transitional area between the ecological buffer and the moderate developed areas. These towns not only function as important ecological barriers but also have basic resources for future land expansion, and their utilization would undoubtedly affect the ecological security of the entire region. Future governance should be closely connected to the planning and development of the Qilian Mountain and Heihe River Natural Reserves. For example, these towns could utilize the advantageous cash crops and processed aquaculture industry, properly develop hydro, wind, solar and other resources, and explore techniques for sand control and utilization to achieve harmony between ecological protection and economic development. (4) A total of 4 towns of the general protected type are located in the southeastern part and all are in the ecologically sensitive zones of each county and have a fragile environment. The assessment results show that they are not suitable for intense oasis utilization. Future management should emphasize regional labor force transfer and the exploration of ecologically beneficial land use patterns. (5) Only Laojun Town in Shandan County is being categorized as the key protected type. Although the town has relatively good traffic location

conditions, the ecological environment has severely degraded, posing problems with water resource scarcity and low agricultural outputs and thus requiring strict protection and control measures.

Discussion

Significance for the construction of land ecological suitability model

Located in the middle of the Hexi Corridor, the middle reaches of the Heihe River serve as an important ecological security barrier, and the traditional oases and sections of desert have become significant sources of regional land expansion. Based on the MCR and ecology theory, the landscape process model focuses on the “connectivity” of each land unit and could appropriately simulate land expansion processes in ecological security barrier zones: A “source–resistance” analysis method could simulate the horizontal processes of landscape units, and the niche theory could strengthen the comprehensiveness of assessment factors. Moreover, the weakening of weights and the intuitive expression of thresholds also make the method feasible, thereby providing an operable method for zoning in agricultural oasis ecosystems.

Significance for the strategic recognition of agricultural oasis land expansion patterns

The hydrology flow model in ArcGIS reflects the drop height between adjacent grids by calculating the local minimum points, thus recognizing the strategic patches and radiation corridors in a certain bound. The regions surrounding the strategic patches have the most fertile water and soil resources and outstanding location conditions near traffic arteries; therefore, they should be considered to be the important regions for future urban expansion and the concentration of rural settlements. The radiation channel information shows ecologically suitable directions and trends for built-up area expansion for counties; these are significantly influenced by the spatial distribution of traffic arteries and ecologically sensitive areas. Future oasis development should closely rely on the two strategic patches in central and northwestern Ganzhou District, taking their advantages in land and water resources and geographical conditions while considering the ecologically suitable land expansion directions for each county to develop adaptive land management policies.

Significance for the management of rural settlements

In the middle reaches of the Heihe River, the town is always the main unit of residential concentration, and its

resistance value can be used to measure its future development suitability and provide guidance for the orientation of its scale of development. The scattered rural residents can be divided into five categories: the key developed type, optimized developed type, preferential renovated type, general protected type and key protected type. The division of rural settlements could effectively promote identification of potential and limiting factors of various types of settlements; this could allow targeted conservation and control measures and ultimately lead to sustainable development in arid area of oasis.

Conclusion

After identifying the principal conflicts and potentially restrictive conditions of regional land use, this research has uncovered some antagonistic forces in this region, i.e., agricultural oasis expansion and ecological conservation land expansion. The MCR and ecology assessment theory were then introduced to create a conceptual model of the land expansion process and to further build a land use security pattern that is ecologically suitable. Analyzing the model calculation values, the strategic patches and radiation directions of oasis expansion in the region are recognized, and adaptive regulation countermeasures for rural settlements of different categories are proposed. The research results show that the landscape process model could effectively simulate the land expansion processes in arid areas based on the recognition of potential and constraints in land development, thus providing a reference for regional ecosystem adaptive management.

However, the connotation of land ecological suitability is confined in this study based on the limitations of assumptions and the macroscopic view of the model itself. Specifically, the accuracy of the model is confined to macroscale, and it could only explain the importance of each land unit based on the aspects of oasis utilization and ecological conservation, while could not clearly distinguish which type of land use, i.e., farmland, construction land, forest and grassland, the unit is suitable for. The assumption of the model, to some extent, depicts the principal conflicts of land use in the region, while the assessment results are not sufficiently practical. Therefore, future study should try to detail the land expansion type according to the actual circumstances at each scale, thus uncovering the coupling relationship between macro- and micro-suitability, gradually realizing the transition of land use zoning from a macro- to a micro-degree, and ultimately gaining finer scale land suitability assessment results.

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Authors' contribution XYY originally formulated the idea and designed the model. MJJ performed statistical analyses, and XYY wrote the manuscript. All the authors conceived the study.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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