Landscape Pattern Evolution and Influencing Factors of Alpine Wetlands in Yanchiwan (Postprint)

Authors: Zeng Hongxia

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Abstract

Alpine wetlands are crucial water source conservation areas and biodiversity hotspots. Investigating the evolution of their landscape patterns and influencing factors contributes to understanding the unique functions, evolutionary dynamics, and environmental impact mechanisms of wetland ecosystems. Based on six-phase Landsat remote sensing imagery from 1989 to 2019, this study integrated GIS technology, landscape pattern indices, and correlation analysis to examine the spatiotemporal evolution characteristics and driving factors of the Yanchiwan alpine wetland landscape pattern. The results indicate: (1) The total area of Yanchiwan wetland exhibited an increasing trend from 1989 to 2019, with marshy meadows, permanent rivers, and inland salt marshes increasing by 31.02%, 17.53%, and 3.77%, respectively, while herbaceous marshes and bare patches decreased by 54.28% and 9.5%, respectively. (2) At the class level, fragmentation of permanent rivers and marshy meadows decreased during 1989–2019, whereas fragmentation of other wetland types increased; at the landscape level, wetland landscape shape tended toward simplification, wetland fragmentation increased, contagion and Shannon diversity indices decreased, and wetland landscape distribution developed toward equilibrium. (3) Differentiated correlations exist between temperature/precipitation and wetland area/landscape pattern indices. Climate change represents the key factor driving area changes and landscape pattern evolution in the Yanchiwan alpine wetland. Investigating the temporal dynamic evolution characteristics of alpine wetland landscape patterns holds significant theoretical importance for comprehending wetland ecological functions and processes, and practical significance for sustainable wetland development and landscape planning management.

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Abstract

Alpine wetlands are critical for water conservation and biodiversity. Investigating the evolution of wetland landscape patterns and their driving factors enhances understanding of the unique functions, ecological processes, and environmental mechanisms of wetland ecosystems. This study analyzed the spatiotemporal evolution of alpine wetland landscape patterns in Yanchi Bay using six periods of Landsat remote sensing imagery from 1989 to 2019, combined with GIS technology, landscape pattern indices, and correlation analysis.

The results revealed three key findings. First, the total area of Yanchi Bay wetland exhibited an increasing trend from 1989 to 2019. Swamp meadows, permanent rivers, and inland salt marshes increased by 31.02%, 17.53%, and 3.77%, respectively, while herbaceous marshes and bare patches decreased by 54.28% and 9.5%. Second, at the class level, fragmentation of permanent rivers and swamp meadows decreased, whereas fragmentation of other wetland types increased. At the landscape level, wetland shapes simplified, overall fragmentation increased, contagion and Shannon' s diversity indices decreased, and the wetland landscape distribution became more even. Third, differentiated correlations existed among temperature, precipitation, wetland area, and landscape pattern indices. Climate change emerged as the key factor driving area changes and landscape pattern evolution in Yanchi Bay's alpine wetlands. Examining the dynamic evolution characteristics of alpine wetland landscape patterns through time series analysis holds important theoretical significance for understanding wetland ecological functions and processes, as well as practical significance for sustainable wetland development and landscape planning management.

Keywords: landscape index; wetland landscape pattern; Yanchi Bay; spatiotemporal evolution; alpine wetland

1.1 Study Area

The study area is located within the Yanchi Bay National Nature Reserve in Subei County, Jiuquan City, with geographic coordinates of 38°18 10 ~39°34 11 N, 94°59 42 ~97°21 32 E. The region features a typical inland alpine and arid climate, with an average annual temperature of 4-6°C and annual precipitation of approximately 200 mm. Precipitation shows large seasonal variation, concentrated in summer and autumn, while evaporation reaches 2500 mm. Elevation ranges from 600–2200 m. Soil types include aeolian sandy soil, brown desert soil, meadow soil, swamp soil, and alpine cold desert soil. The area is characterized by mountain-basin alternating topography between the Danghe Nanshan and Yema Nanshan mountains, with wetlands primarily receiving water from alpine snowmelt and natural precipitation. This region serves as the source area of the primary tributary of the Shule River, the second largest endorheic river in the Hexi Corridor, which flows into the Dunhuang oasis. Vegetation consists mainly of wetland and desert species, dominated by *Leymus secalinus*, *Achnatherum splendens*, *Triglochin maritimum*, *Kobresia myosuroides*, *Carex caespititia*, *Glaux maritima*, *Sophora alopecuroides*, and *Thermopsis lanceolata*.

1.2 Data Sources

To accurately reveal dynamic changes in landscape patterns, Landsat remote sensing images were selected based on image quality and acquisition timing, ensuring cloud cover below 10%. Images were chosen from years with notable precipitation variation and during peak vegetation growth (early August to early September) to facilitate accurate extraction of different underlying surface information. All remote sensing imagery underwent geometric correction, orthorectification, band composition, and clipping preprocessing. Image data were obtained from the United States Geological Survey (http://earthexplorer.usgs.gov/) and the Geospatial Data Cloud website (http://www.gscloud.cn/). Meteorological data including annual average temperature and precipitation were sourced from the China Meteorological Science Data Sharing Service Network (http://data.cma.cn/) for the Subei Mongolian Autonomous County standard meteorological station.

1.3 Wetland Classification and Information Extraction

Prior to supervised classification, wetland classification standards were referenced from domestic and international systems [**?**, **?**], combined with field surveys in the study area. Following the wetland classification system from the Ramsar Convention and existing land use classification systems, the study area wetlands were divided into swamp wetlands and river wetlands (permanent river wetlands) based on remote sensing imaging principles. Swamp wetlands were further classified into herbaceous marshes, swamp meadows, inland salt marshes, and bare patches. presents the interpretation signatures for Yanchi Bay alpine wetlands. [Figure 1: see original paper] shows the location of the study area. Band combination display was used to extract spatial distribution maps of various wetland types for different periods. Classification accuracy was verified by comparing sampling points with high-resolution imagery from Google Earth for historical classification results. Confusion matrices were generated, with overall accuracy and Kappa coefficient serving as accuracy metrics. The overall accuracy of classification results exceeded 85%, and the Kappa coefficient exceeded 0.80.

1.4 Landscape Index Selection and Calculation

Landscape indices were selected at both class and landscape levels. At the class level, indices included Class Area (CA), Number of Patches (NP), and Largest Patch Index (LPI). At the landscape level, indices included Patch Density (PD), Landscape Shape Index (LSI), Contagion Index (CONTAG), and Shannon’ s

Diversity Index (SHDI). presents the calculation formulas and ecological significance of these landscape pattern indices.

2.1 Spatiotemporal Evolution of Wetland Landscape Patterns

The classification results from 1989–2019 ([Figure 2: see original paper]) and change rates of various wetland types ([Figure 3: see original paper]) reveal distinct spatial distribution patterns. Inland salt marshes were primarily distributed at the terminal ends of alluvial fans and river floodplains on both sides of the Dang River, accounting for the largest proportion of total wetland area (26.32%–37.81%). Herbaceous marshes were mainly distributed in the Dang River floodplain and spring water emergence zones, showing large area fluctuations (9.01%–33.92%) with a change rate of -0.73% to 0.71% and a fluctuating increasing trend from 1989–2019. Permanent river wetlands were widely distributed around the main Dang River channel where connectivity was high and terrain was gentle, accounting for 9.69%–22.6% of the area with large variation amplitude. Swamp meadows were mainly distributed around the river floodplain, decreasing from 95.14 km^2 in 1989 to a minimum of 36.37 km^2 in 2019, with a change rate of -67.16%. Bare patches were primarily located at the transition zone between inland salt marshes and desert, forming at higher elevations due to evaporation and special eco-hydrological processes. Their area changed relatively smoothly with a change rate of -0.34% to 1.24%, reaching a maximum of 76.33 km^2 in 2019.

2.2.1 Landscape-Level Wetland Landscape Indices

Landscape-level indices reflect regional overall landscape characteristics at broad spatial scales. Analysis of four indices revealed that PD first increased then decreased then increased again from 1989–2019, indicating an increasing trend in wetland landscape fragmentation. LSI showed a fluctuating decreasing trend, with wetland geometric shapes simplifying and patch irregularity gradually declining. CONTAG exhibited a decreasing trend, indicating reduced landscape connectivity and increased fragmentation. SHDI showed a decreasing trend after 1999, suggesting declining landscape richness and more uneven distribution of patch types. However, SHDI increased from 1989–1999, indicating increased landscape richness and more even distribution of wetland landscapes.

2.2.2 Class-Level Wetland Landscape Indices

At the class level, herbaceous marshes had the highest number of patches. NP for herbaceous marshes showed a fluctuating increasing trend from 1989–2019, decreasing to a minimum of 0.12% in 2009 then increasing again. This indicates that fragmentation of herbaceous marshes initially increased then decreased. For swamp meadows and permanent rivers, NP showed a decreasing trend, indicating reduced fragmentation. Inland salt marsh NP showed an increasing then decreasing trend, indicating fluctuating fragmentation. Bare patch NP increased from 1989-1999, indicating increased fragmentation, then decreased after 1999, indicating gradually weakening fragmentation.

The Largest Patch Index (LPI) for all wetland types showed an overall decreasing trend, indicating that the proportion of the largest patch decreased and landscape fragmentation increased. The degradation pattern was characterized by fragmentation of large patches and proliferation of small patches. LPI for herbaceous marshes gradually decreased from 1989-1999, indicating increased fragmentation, then increased after 1999, indicating reduced fragmentation. LPI for swamp meadows, permanent rivers, bare patches, and inland salt marshes showed fluctuating increasing then decreasing trends, with swamp meadows showing the largest variation amplitude and permanent rivers and bare patches remaining relatively stable. Inland salt marshes had relatively large LPI values, indicating they were the dominant landscape type in the study area.

2.3.1 Interannual Variation of Temperature and Precipitation

The average temperature and precipitation in Yanchi Bay from 1989-2019 showed overall increasing trends, with interannual variation rates of 0.09°C · $(5a)^{-1}$ and 0.703 mm · $(5a)^{-1}$, respectively. The multi-year average temperature was 5.83°C, fluctuating between 4.9-6.6°C. Temperatures before 2000 were below the multi-year average, while temperatures after 2000 were above average. The multi-year average precipitation was 80.17 mm, fluctuating between 26.82-120.37 mm. Precipitation showed a decreasing trend before 2000 and an increasing trend after 2000, with the maximum value of 120.37 mm occurring in 2019.

2.3.2 Correlation Analysis Between Climate Factors and Wetland Area

From a climatic perspective, Yanchi Bay wetland belongs to a typical alpine, high-altitude ecologically fragile zone with poor stability and high sensitivity to climate change. Correlation analysis between temperature, precipitation, and various wetland areas revealed differentiated relationships. Temperature showed significant positive correlations with swamp meadow and permanent river areas ($P < 0.05$), indicating that as temperatures rose, snowmelt from Danghe Nanshan increased water supply to these wetlands, leading to gradual area expansion. Temperature showed negative correlations with herbaceous marsh and bare patch areas ($P > 0.05$), with areas decreasing as temperature increased. Precipitation showed significant positive correlation with permanent river area ($P < 0.05$), as river wetlands are primarily supplied by atmospheric precipitation, so increased precipitation expanded river area. Precipitation showed positive correlations with herbaceous marsh and inland salt marsh areas ($P > 0.05$) and negative correlation with swamp meadow patch number ($P > 0.05$), though not statistically significant. Compared with precipitation, temperature had a greater influence on wetland area changes.

2.3.3 Correlation Analysis Between Climate Factors and Landscape Indices

Correlation analysis between climate factors and landscape indices revealed that temperature was significantly positively correlated with patch number of herbaceous marshes ($P < 0.01$) and inland salt marshes ($P < 0.05$), indicating that temperature changes altered hydrological conditions, affecting landscape fragmentation. Temperature was negatively correlated with patch number of swamp meadows and permanent rivers ($P < 0.05$). Precipitation showed significant positive correlation with patch number of bare patches ($P < 0.05$), indicating that increased precipitation increased bare patch proliferation. In addition to meteorological factors, human disturbance activities such as grazing also influenced wetland landscape fragmentation.

3.1 Analysis of Factors Influencing Wetland Area Changes

Hydrological processes play a crucial role in wetland development, maintenance, succession, and eventual disappearance. Surface water and groundwater transport conditions and sediment deposition are important factors affecting wetland area changes. Climate change alters surface water spatial distribution patterns by influencing wetland hydrological processes, ecological processes, and ecological patterns. Wetland changes represent important ecological processes in ecosystems, significantly influenced by the spatial patterns and transport dynamics of surface water, soil water, and groundwater.

The total area of Yanchi Bay alpine wetland showed a fluctuating increasing trend from 1989-2019, with a change rate of -0.14 to 0.13. The largest wetland area occurred in 2019, while the smallest occurred in 2009. Different wetland types showed varying area change trends: herbaceous marsh and bare patch areas decreased, while the other three wetland types increased. Average temperature showed negative correlations with herbaceous marsh and bare patch areas ($P > 0.05$), while temperature and precipitation showed positive correlations with inland salt marsh area ($P > 0.05$). Permanent rivers, swamp meadows, and inland salt marshes showed significant positive correlations with temperature and precipitation ($P < 0.05$), consistent with findings from Sun et al. [**?**]. This occurs because permanent river wetlands are distributed around the main Dang River channel with strong connectivity and gentle terrain. Increased temperature and precipitation supplied adequate water to the Dang River through seasonal flooding, gradually widening the river channel and increasing water surface area and peripheral drawdown zones, promoting river wetland development.

Swamp meadows are distributed outside the floodplain, influenced by groundwater and seasonal precipitation, maintaining the soil water and capillary water zones in a connected state. Desalination and soil microbial activity reduce soil pH, developing neutral to slightly acidic conditions favorable for swamp meadow formation. Increased temperature and precipitation expanded swamp meadow area. Inland salt marshes are mainly distributed at the junction of alluvial fan terminals and floodplains. Research by Zhao et al. [?] indicates that increased extreme precipitation events and seasonal flooding have expanded alluvial fan areas. Sediment deposition from floods raised floodplain elevations, causing disconnection between soil water and capillary water zones. Under climate warming, intense evaporation enhanced soil salt accumulation speed and surface salt concentration, with large amounts of salts transported and accumulated in plant root zones and surface layers, causing swamp meadows to gradually transform into inland salt marshes () and expand toward floodplains, consistent with findings from Du et al. [?].

Herbaceous marsh and bare patch areas showed decreasing trends ([Figure 3: see original paper]) and negative correlations with temperature and precipitation (). Bare patches are mainly distributed in higher elevation areas with good drainage, where water evaporates and dissipates, causing slight area reduction. Herbaceous marshes showed negative correlations with temperature and precipitation, consistent with Wang et al. [?]. Temperature is an important factor affecting water loss in herbaceous marshes; increased temperature enhances evapotranspiration and deepens permafrost thaw layers, causing gradual soil water loss and wetland degradation. Temperature increase also promotes soil carbon mineralization in alpine wetlands, accelerating litter decomposition and affecting material cycling and carbon sink functions. Herbaceous marshes in Yanchi Bay are distributed near river channels and freshwater springs. While river discharge increased, substantial sediment deposition caused slight elevation increases in the floodplain, extending the floodplain outward and gradually expanding valley waterlogged depressions to inundate herbaceous marsh areas, causing rapid reduction in herbaceous marsh area.

3.2 Analysis of Factors Influencing Wetland Landscape Pattern Changes

Landscape pattern changes are driven by patch transformation processes under changing surface water and groundwater hydrological processes [?]. Increased precipitation and temperature enhanced Dang River discharge and sediment deposition, increasing river meanders and tributaries. Precipitation and temperature showed positive correlations with river patch number ($P < 0.05$). As wetland water supply increased, prolonged continuous water input created superimposed effects, causing water to spread to surrounding areas and transforming numerous small peripheral patches into herbaceous marsh wetlands. Many large herbaceous marsh patches were destroyed, increasing fragmentation. As water levels declined, small patches at bare patch margins became exposed, increasing patch numbers. Inland salt marshes were primarily affected by water-salt transport, with large patch fragmentation as the main pattern. Meanwhile, numerous small patches scattered around swamp meadow peripheries gradually transformed into inland salt marsh patches under the influence of vadose zone changes. The landscape patch shapes and edges showed certain obstruction effects, with adjacent landscapes gradually aggregating toward them [?], enhancing edge ecological effects and making patch shapes more regular while gradually weakening wetland ecosystem stability.

Yanchi Bay is a pastoral area with small-scale urban and road construction that has minimal impact on landscape patterns. Livestock development is the primary influencing factor [?]. Due to strong market demand for yak and mutton, herders substantially increased livestock numbers. Large livestock increased from 15,000 in 1989 to 23,000 in 2019, and sheep increased from 80,000 to 140,000. The grassland-livestock relationship became severely imbalanced, causing excessive grazing that prevented grasslands from recovering. Under heavy grazing and trampling, grassland compaction and wetland fragmentation processes were accelerated.

4 Conclusions

From 1989–2019, the total area of Yanchi Bay alpine wetland showed a fluctuating increasing trend with a change rate of -0.14 to 0.13. The largest wetland area occurred in 2019, while the smallest occurred in 2009. Different wetland types showed varying area change trends: herbaceous marsh and bare patch areas decreased, while swamp meadow, permanent river, and inland salt marsh areas increased.

Wetland landscape patch numbers fluctuated and increased, with landscape fragmentation increasing and shapes simplifying. Fragmentation of permanent rivers and swamp meadows decreased, while fragmentation of other wetlands increased. Patches became more regular and evenly distributed, with wetland landscape distribution developing toward a more balanced direction.

Temperature and precipitation showed differentiated correlations with various wetland areas and landscape indices. Changes in temperature and precipitation were the main causes of area changes and fragmentation in Yanchi Bay alpine wetlands. In 2006, Yanchi Bay was upgraded to a national nature reserve. Implementation of wetland conservation projects, grazing withdrawal, and population migration to urban areas provided opportunities for wetland recovery, alleviating degradation trends, substantially increasing forage production and proportions of high-quality grass populations, and improving plant community structure. Reductions in human population, large livestock, and sheep numbers caused only minor changes to landscape patterns, strengthening the influence of natural factors on landscape patterns.

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Note: Figure translations are in progress. See original paper for figures.