

Spatial Coordinated Evolution and Pattern Analysis of Oases and Oasis Cities in Arid Regions During Urbanization: Postprint

Authors: Han Yuchen, Sun Qinke, Zhou Liang, Li Yuang

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Abstract

Oasis cities, as the core spatial units in oasis systems that carry population agglomeration, economic activities, and public service functions, are constrained by the oasis ecological pattern during their expansion process while also spatially driving the evolution of oases. Systematically identifying the evolution characteristics of oases and oasis cities constitutes a key foundation for achieving coordinated development of ecological protection and spatial development in arid regions. This study first identifies the spatial area distribution of oases and oasis cities in the arid regions of northwestern China from 2000 to 2023, analyzes their spatial evolution trends, then constructs the Oasis City Synergy Index (OCSI) to quantitatively evaluate the co-evolution characteristics between oases and oasis cities in the study area, and further explores the expansion patterns of oasis cities. The results indicate: (1) From 2000 to 2023, the area of oases and oasis cities in the study area continued to increase, but the number of oasis patches decreased, with oases exhibiting a trend toward “large-scale and centralized” development. (2) The classification of co-evolution trends and OCSI calculation results reveal that 8 regions are of the similar-trend type, 23 regions are of the opposite-trend type, and the synergy between oases and oasis cities gradually strengthened from 2000 to 2023. (3) Based on comprehensive evaluation results of co-evolution trends and OCSI, oasis cities with infill expansion and edge expansion patterns generally demonstrate higher synergy, while those with leapfrog expansion and riverine expansion patterns exhibit large OCSI fluctuations and lower synergy due to their dispersed expansion methods or linear spread along watercourses. The research findings identify and reveal the spatial evolution relationship between oases and oasis cities in the arid regions of northwestern China, which can provide theoretical basis and decision-making support for alleviating human-land contradictions in oasis areas of arid regions and promoting sustainable development.

Full Text

1.1 Study Area

The study area encompasses the arid regions of northwest China, located between 74°-115°E and 36°-49°N, covering four provincial-level administrative regions: Inner Mongolia, Gansu, Qinghai, and Xinjiang. The region is concentrated in the Hetao Plain, Hexi Corridor, Qaidam Basin, northern foothills of the Tianshan Mountains, and northern foothills of the Kunlun Mountains, with a total area of approximately 1.77×10^6 km². Characterized by typical arid and semi-arid climate conditions, the region receives average annual precipitation generally below 200 mm, while evaporation exceeds 2,000 mm. Oasis formation and maintenance primarily depend on meltwater from snow and ice in high mountain regions such as the Qilian, Altai, Tianshan, and Kunlun mountains, as well as water from the Yellow River. Particularly in the Hexi Corridor and Hetao Plain, irrigation systems not only ensure agricultural stability but also constitute the core support for regional economic development. This area serves as a crucial production base for grain, cotton, and fruits in China while fulfilling important ecological functions, sustaining oasis agriculture through complex irrigation networks. Given that cities represent the primary carriers of urbanization and oasis development in arid regions, this study selected 31 cities (including prefecture-level cities, county-level cities, and central cities of some prefectures and autonomous regions) within the study area as research subjects.

1.2 Data Sources

Research data include: (1) Land use data derived from the Annual China Land Cover Dataset, which employs spatiotemporal feature construction and random forest classification algorithms with a spatial resolution of 30 m. (2) Normalized Difference Vegetation Index (NDVI) data obtained from the National Earth System Science Data Center, with annual maximum values calculated for each pixel using the maximum value composition method, a spatial resolution of 30 m, and a temporal resolution of one year. (3) Evapotranspiration data sourced from the Loess Plateau Science Data Center of the National Earth System Science Data Center, with data for the study period processed through interpolation to a unified spatial resolution of 500 m. (4) Fundamental geographic information data from the National Geomatics Center of China. (5) OpenStreetMap (OSM) database. (6) Statistical yearbook data from the *China Statistical Yearbook* published by the National Bureau of Statistics.

1.3 Methods

1.3.1 Oasis Identification and Accuracy Assessment

This study delineates the spatial extent of oases based on the Aridity Index (AI), selecting regions with AI values between 0.05 and 0.65 to define potential oasis areas. A threshold segmentation method is applied regionally and annually

to determine optimal NDVI thresholds, refined using a bimodal segmentation approach to enhance the stability of oasis extraction. Visual interpretation incorporating actual geographic data and topographic information of the study area yields the distribution of oases from 2000 to 2023. According to the United Nations Convention to Combat Desertification classification, oases are extracted using an NDVI cutoff value of 0.24, with the reasonableness of this threshold verified. To validate the reliability of the oasis extraction method, accuracy assessment is performed using a confusion matrix (Table 1), with validation data drawn from the oasis spatiotemporal distribution dataset published by the National Cryosphere Desert Data Center. Results demonstrate producer and user accuracies exceeding 90% for both oasis and non-oasis regions, with an overall classification accuracy above 95% and Kappa coefficients exceeding 0.90, indicating high effectiveness and robustness of the extraction results for subsequent analysis.

1.3.2 Oasis-City Synergy Evolution Trend Classification System

This study employs the Oasis Expansion Rate (OER) to characterize interannual oasis dynamics, representing the degree of oasis expansion in a given year:

$$OER_{n,n+1} = \frac{O_{n+1} - O_n}{O_n} \times 100\%$$

where O_n and O_{n+1} represent oasis area in years n and $n + 1$, respectively. The Urban Expansion Rate (UER) measures urban interannual dynamics:

$$UER_{n,n+1} = \frac{U_{n+1} - U_n}{U_n} \times 100\%$$

where U_n and U_{n+1} represent urban area in years n and $n + 1$, respectively. A synergy evolution trend classification system is constructed based on the changing trends of these two metrics across three time periods. Trend segments are formed by connecting the magnitude of change between $OER_{n,n+1}$ and $UER_{n,n+1}$ across periods, with directions indicating increasing or decreasing trends. Trend-similar types refer to synchronized growth or contraction between oasis and urban expansion trends across multiple periods, subdivided into “increase-increase” (II) and “decrease-decrease” (DD) types. Trend-opposite types indicate directional divergence between oasis and urban trends in at least one period, classified as one-period opposite (OP) and two-period opposite (TP) types.

1.3.3 Oasis-City Synergy Index

Building upon the concept of the “Oasis Settlement Breeding Index,” this study proposes the “Oasis City Synergy Index” (OCSI) to analyze the synergy between

urban scale and oasis scale, establishing a feedback mechanism of oasis scale on urban evolution:

$$OCSI = \frac{UCA}{OCA}$$

where UCA is the total urban area within the oasis, and OCA is the total oasis area within the city's administrative boundary. To further characterize the intensity and stability of synergy between oasis and city, a "two-dimensional synergy evaluation system" is constructed. The mean value (μ_{OCSI}) of the Oasis City Synergy Index measures overall synergy intensity, with smaller values indicating stronger synergy. Synergy levels are classified as: high synergy ($OCSI \leq 1.10$), medium synergy ($1.10 < OCSI \leq 1.35$), and low synergy ($OCSI > 1.35$). The range value ($\Delta OCSI$) serves as an indicator of synergy stability, with smaller values indicating more stable relationships. Stability is classified as: high stability ($\Delta OCSI \leq 0.60$), medium stability ($0.60 < \Delta OCSI \leq 1.00$), and low stability ($\Delta OCSI > 1.00$). Comprehensive synergy levels are determined by integrating these classifications: high synergy requires high synergy-high stability or medium synergy-high stability combinations; medium synergy requires high synergy-medium stability or medium synergy-medium stability combinations; and low synergy is assigned when any indicator falls into the low level.

1.3.4 Oasis-City Expansion Pattern Classification

Based on visual interpretation and remote sensing image analysis, four typical expansion patterns are identified and summarized (Figure 3), reflecting different spatial configurations of oasis and city expansion: (1) **River-dependent expansion**: New urban patches are located on new oasis patches that exhibit linear expansion along rivers. (2) **Infilling expansion**: Urban expansion occurs primarily within existing oasis areas, filling previously non-urbanized oasis spaces. (3) **Edge expansion**: New urban patches concentrate at oasis margins, gradually expanding outward. (4) **Leapfrogging expansion**: New urban patches are distributed on new oasis patches that are disconnected from original oasis patches.

2.1 Spatial-Temporal Evolution Characteristics of Oasis and City

From 2000 to 2023, the spatial patterns of oases and cities in China's arid regions changed significantly, with both areas showing continuous expansion. Oasis area increased from 2.44×10^5 km² to 3.34×10^5 km², a growth of 0.90×10^5 km² representing a 36.89% increase. The highest growth rate occurred during 2010-2015 at 11.52%. Although oasis and city expansion occurred simultaneously, their rates varied considerably. Urban area expanded from 1.20×10^3 km² to 5.54×10^3 km², a growth of 4.34×10^3 km² representing a 361.60% increase, with an average annual expansion rate of

15.72%. The highest urban growth rate occurred during 2015-2020 at 75.04%. Regionally, Xinjiang Uygur Autonomous Region has the largest oasis area, while Inner Mongolia Autonomous Region has the smallest. Xinjiang's oasis area grew most significantly from $1.94 \times 10^5 \text{ km}^2$ to $2.67 \times 10^5 \text{ km}^2$, with the highest growth rate across all periods at 37.63%. Gansu Province's oasis area increased from $3.50 \times 10^4 \text{ km}^2$ to $4.34 \times 10^4 \text{ km}^2$, ranking second. Qinghai Province's oasis area grew from $2.32 \times 10^4 \text{ km}^2$ to $2.68 \times 10^4 \text{ km}^2$. Inner Mongolia's oasis area is the smallest, increasing from $5.50 \times 10^3 \text{ km}^2$ to $8.78 \times 10^3 \text{ km}^2$.

Based on existing oasis classification research, oases are categorized by size into micro ($<50 \text{ km}^2$), small ($50-100 \text{ km}^2$), medium ($100-300 \text{ km}^2$), large ($300-500 \text{ km}^2$), and giant ($>500 \text{ km}^2$). The number of oases in northwest China decreased from 135 to 101, indicating consolidation. This reduction primarily resulted from decreases in micro, small, and medium oases, which declined by 42.86%, 52.38%, and 41.86%, respectively. In contrast, large and giant oases remained relatively stable (Figure 4).

2.2.1 Classification Results of Oasis-City Synergy Evolution Trends

Based on the combination characteristics of expansion rate trends across three periods, results show that 23 cities (74.19%) exhibit trend-similar patterns, while 8 cities (25.81%) show trend-opposite patterns. Trend-similar cities include Hotan Prefecture, Kashgar Prefecture, Kizilsu Kirghiz Autonomous Prefecture (abbreviated as Kezhou), and others. Trend-opposite cities include Zhangye City, Jiuquan City, Shuanghe City, and Alxa League. Most cities demonstrate gradually strengthening synergy between oasis resources and urban expansion (Figure 5). Kunyu City shows the highest synergy, with OCSI values below 1.10 in most periods, indicating high synergy. However, Haixi Prefecture and Jiayuguan City exhibit OCSI values above 1.35, indicating significantly decreased synergy. The mean OCSI value further declined to 1.21 during 2015-2020, suggesting increasingly coordinated oasis-city expansion. Beitun City, Haixi Prefecture, Jiayuguan City, and Kezhou show noticeably low OCSI values, while Wujiaqu City also has OCSI exceeding 1.35, indicating the lowest synergy. Hotan Prefecture and Kunyu City maintain OCSI values below 1.10, reflecting high synergy.

2.2.2 Trend Analysis of Oasis-City Synergy Index

Oases nurture cities in arid regions, and investigating the synergistic development relationship between oasis and city scales is crucial for sustainable development. Quantitative analysis of 31 cities based on OCSI values reveals that the overall mean decreased from 2000 to 2023, indicating increasingly coordinated urban and oasis expansion. Eight cities have achieved synergistic development, with OCSI values below 1.10. Most other cities show significantly increased

OCSI values. To avoid extreme value impacts, Haixi Prefecture's OCSI values were excluded, reducing the mean to 1.21. Cities with OCSI values below 1.10 include Kunyu City, Wuwei City, Bortala Mongol Autonomous Prefecture, Bayingolin Mongol Autonomous Prefecture, Hami City, Tiemenguan City, Huyanghe City, Karamay City, Beitun City, Changji Hui Autonomous Prefecture, and Urumqi City. Cities with OCSI values between 1.10 and 1.35 include Yili Kazakh Autonomous Prefecture Directly-administered Counties (abbreviated as Yili Zhili), Tacheng Prefecture, Jiayuguan City, Turpan City, Aksu Prefecture, Tumushuke City, Jinchang City, Haixi Mongol and Tibetan Autonomous Prefecture (abbreviated as Haixi Prefecture), Shihezi City, Kokdala City, Altay Prefecture, and Wujiaqu City.

2.3 Analysis of Oasis-City Expansion Patterns and Synergy Relationships

Spatial expansion patterns of oases and cities in northwest China show significant regional variation. In-depth analysis of 12 typical cities reveals distinct synergy evolution characteristics across different city types (Figure 6; Table 2). River-dependent expansion cities such as Yili Zhili, Jinchang City, and Aksu Prefecture exhibit linear spread along water bodies. While oases primarily rely on nearby river water resources, the spatial synergy between oasis and city expansion is generally low, with large OCSI fluctuations and overall low synergy. Infilling expansion cities such as Zhangye City, Jiuquan City, and Turpan City expand primarily within oasis interiors. Because urban growth depends on land resources within oasis areas, the oasis landscape pattern becomes more homogeneous, fragmentation decreases, and OCSI mean values remain low with small fluctuations, indicating high synergy. Edge expansion cities such as Urumqi City and Karamay City expand toward oasis margins, resulting in high spatial overlap between oasis and city. Oasis boundaries change with urban expansion, leading to increased oasis area in some regions and high synergy. Leapfrogging expansion cities such as Alxa League exhibit discrete, non-continuous urban land distribution, with some new patches failing to connect effectively with original oasis patches, resulting in low spatial overlap and medium synergy.

3 Discussion

Urban development relies on the spatial foundation and resource carrying capacity provided by oasis ecosystems, while oasis patterns undergo spatial restructuring and boundary compression during urban expansion. The two form a potential two-way feedback mechanism through land use evolution processes. Research demonstrates that oasis-city synergy relationships exhibit significant spatial heterogeneity and temporal inconsistency. Among different expansion patterns, river-dependent expansion shows strong spatial orientation, with urban development unfolding along water bodies and linear coupling between oasis distribution and urban development. However, synergy levels vary considerably across such cities, possibly related to water resource distribution, though this

study does not empirically analyze relevant water resource or policy factors, leaving mechanistic aspects for future research.

Overall, diverse synergy evolution patterns exist between oases and cities, necessitating differentiated management strategies based on urban expansion patterns. River-dependent expansion cities should strengthen ecological protection of oases along river courses, designate ecological buffer zones, and prioritize water allocation for oasis ecosystems. Infilling expansion cities can promote urban renewal while ensuring ecological protection, improving land use efficiency and green development. Edge expansion cities require strengthened guidance for land use at oasis margins to avoid interference from interleaved expansion, ensuring sustainable ecological buffer functions. Leapfrogging expansion cities should limit non-continuous expansion, enhance oasis spatial connectivity, and improve resource utilization efficiency.

4 Conclusions

This study reveals that from 2000 to 2023, oases and cities in China's arid regions exhibited overall expansion, though with significant differences in speed and pattern. Oasis area increased substantially while patch numbers decreased markedly, showing a trend toward concentration and large-scale development, with edge and leapfrogging as primary expansion modes. Urban area expanded by 361.60%, significantly outpacing oasis growth, with expansion patterns including infilling, edge expansion, leapfrogging, and river-dependent expansion. Synergy trends between oases and cities show phased fluctuations, with overall OCSI mean values declining, indicating increasingly coordinated expansion. However, significant regional and structural differences exist across the 31 cities. Different urban expansion patterns correspond to varying synergy levels, with spatial layout directly influencing oasis-city synergy. Cities dominated by infilling and edge expansion, which rely on oasis space, show reduced oasis fragmentation and high synergy, while leapfrogging and river-dependent expansion cities exhibit lower synergy.

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