Three decades of oasis transition and its driving factors of Turpan-Hami Basin in Xinjiang, China: a complex network approach

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Abstract

Oasis, as a predominant and distinctive resource in arid regions, plays an important role in maintaining land stability, human production and living activities. The research on oasis transition dynamics and driving factors owns vital significance in supporting arid regions sustainable development. As a typical mountain-desert-oasis landscape, Turpan-Hami (Tuha) Basin in Xinjiang of China, exhibits sophisticated interactions among different land types. In this study, we inspected the spatio-temporal patterns and transition processes of the oasis using a complex network during 1990 and 2020 in Tuha Basin. In the oasis transition network, degree value, betweenness centrality, and average path length were calculated to express the transition relationship, key oasis type, and oasis structural stability, corresponding. Six factors were selected to investigate the driving forces for oasis transition behind climate change and human activities. Our results showed that the oasis area of Tuha Basin, including natural oasis and artificial oasis, all grew from 1990 to 2020, with the natural oasis expanding more than the artificial oasis. The transitions between oasis types became more frequent as the number of the nodes increased throughout the study period. Grassland acted as the most important oasis type in the network with the highest betweenness centrality, but its importance declined due to the increasing complexity in the oasis transition network from 1990 to 2020. The transitions between oasis types became simpler and the oasis structural stability were increasingly unstable. Through the driving analysis, the oasis changes showed positive correlation with temperature (P-value < 0.05, $r = 0.88$), and urbanization and industrialization factors prompted the transitions of built-up and cropland from grassland and shrubland. Totally, preventing the degraded grassland and excessive reclamation of land cover, protecting the shrubland and water resources are suggested in this study to conduct a harmonious symbiotic relationship between natural environment and human activities, and promote the oasis sustainable development.

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Abstract: Oasis, as a predominant and distinctive resource in arid regions, plays an important role in maintaining land stability, human production and living activities. The research on oasis transition dynamics and driving factors owns vital significance in supporting arid regions sustainable development. As a typical mountain-desert-oasis landscape, Turpan-Hami (Tuha) Basin in Xinjiang of China, exhibits sophisticated interactions among different land types. In this study, we inspected the spatio-temporal patterns and transition processes of the oasis using a complex network during 1990 and 2020 in Tuha Basin. In the oasis transition network, degree value, betweenness centrality, and average path length were calculated to express the transition relationship, key oasis type, and oasis structural stability, corresponding. Six factors were selected to investigate the driving forces for oasis transition behind climate change and human activities. Our results showed that the oasis area of Tuha Basin, including natural oasis and artificial oasis, all grew from 1990 to 2020, with the natural oasis expanding more than the artificial oasis. The transitions between oasis types became more frequent as the number of the nodes increased throughout the study period. Grassland acted as the most important oasis type in the network with the highest betweenness centrality, but its importance declined due to the increasing complexity in the oasis transition network from 1990 to 2020. The transitions between oasis types became simpler and the oasis structural stability were increasingly unstable. Through the driving analysis, the oasis changes showed positive correlation with temperature (P -value < 0.05, $r = 0.88$), and urbanization and industrialization factors prompted the transitions of built-up and cropland from grassland and shrubland. Totally, preventing the degraded grassland and excessive reclamation of land cover, protecting the shrubland and water resources are suggested in this study to conduct a harmonious symbiotic relationship between natural environment and human activities, and promote the oasis sustainable development.

Keywords: Turpan-Hami Basin, complex network, oasis transition, oasis structural stability, driving force, oasis sustainable development

Introduction

Oases are the most productive, dynamic, and vulnerable systems in drylands that supply stable water resource, basic resources and conditions for human survival and living environments (Bie & Xie, 2020; Chen *et al.* , 2022; Xue *et al.* , 2015, 2019). Oases are also crucial ecological barriers in drylands defeating desertification (Abuzaid & Abdelatif, 2022), salinization (Li *et al.* , 2021), and sandy weather (An *et al.* , 2022). Since the 1950s, artificial oases had expanded due to the land reclamation and agriculture in northwest China (Wang, 2010), which contributed to sufficient and stable food production and economic growth (Zhou *et al.* , 2017), and caused series of eco-environment problems. Because of the extremely drought weather and limited water supply, oases had experienced groundwater reduction, desertification expansion, and grass degradation (Luo *et al.* , 2020; Ma *et al.* , 2022; Xue *et al.* , 2019; Yan *et al.* , 2021), which deeply influenced the stability of oasis systems. Therefore, it is necessary to quantify the oasis spatio-temporal patterns and its driving factors under natural and human impacts.

Previous studies have explored the spatio-temporal oasis patterns and the interactions between oasis and various factors (e.g., natural and human factors). Land use dynamic model and landscape pattern index were the common methods to quantify and forecast the oasis dynamic changes (Lü *et al.* , 2020; Xiao *et al.* , 2019; Chen *et al.* , 2023; Liu *et al.* , 2021). For examples, Amuti & Luo (2014) analyzed Hotan oasis temporal changes using land use/land cover (LULC) data and the main driving factors of oasis changes during 1990 and 2008, which found that intensified human activities reduced the desert-oasis ecotone. Tan et al. (2020) analyzed the oasis changes of Zhangye city from 1980 to 2015, and simulated the future oasis changes in 2030 applying future land use simulation model (FLUS), LULC data, geography and socioeconomic data; the authors found that main transfers of oasis transition existed in cropland, built up, waterbody and desert from 2015 to 2030. These methods mainly described oasis transitions from a specific land type to another in terms of type and quantity, ignoring the changing processes in the entire oasis transition system (Zhang*et al.* , 2021). Moreover, the identification of key land type mostly relies on the amount of the changed area and rate, which could not express the interactions among different oasis types, oasis and non-oasis types, even the oasis structural stability.

Therefore, the complex network model was introduced in this paper to analyze the dynamic processes within oasis types. As a theoretical method, a complex network is composed of a large number of interconnected nodes, performing substantial non-trivial topological features of the target system and quantifying the interactions among the sub-systems (Newman, 2003; Zhang *et al.* , 2020). It has demonstrated that the complex network is an effective tool in modeling and analyzing the land use change processes (e.g., urbanization, afforestation / deforestation) and identifying the key land types during those processes. Xu et al. (2023) studied the complex relationship in the procession of LULC using complex network, which concluded that key land types were more vulnerable to change and had greater impacts on land ecosystems. Zhang et al. (2020) constructed the complex network of landscape index and patch type index, and evaluated the stability of landscape and network in Pingshuo opencast mining area in China during 1986 and 2015. The authors found that the landscape heterogeneity tended to be unstable, and the network length became shorter, demonstrating more human activities in mining areas during the study period. So far, the applications of complex network in investigating oases transition and stability were scarce, especially on the long-term large scale.

In this study, we conducted oasis transition processes and structural stability investigation using the constructed oasis transition network and analyzed driving factors over Tuha Basin during 1990 and 2020. Our research aims to (1) find out the spatio-temporal patterns for different oasis types, (2) simulate the oasis transition processes and identify the key oasis types, and (3) discover the main driving factors for natural and artificial oasis.

Study area and datasets

2.1 Study area

Tuha Basin is the abbreviation of Turpan and Hami Basin and located in eastern Xinjiang of China (86044'55"-96025'0"E, 40049'13"-4503'21"N, Figure 1), which comprises two districts (Gaochang and Yizhou) and four counties (Tuokexun, Shanshan, Balikun, and Yiwu). With the average elevation of 800 m and elevation drop beyond 5000 m, Tuha Basin shows high mountain in the north and low basin in the south.

Tuha Basin has uneven distribution of precipitation and temperature. Rainfall occurs primarily in the mountain areas between April and September annually. Annual precipitation is usually less than 20 mm, while evaporation can reach 3000 mm, causing typical arid climate, with the water resource mostly relying on the snow meltwater from the mountains. The annual average temperature is around 15 0C. The maximum temperature exceeds 500C in plain areas, whereas in the mountain areas, it only reaches 27 0C.

In this study, we categorized oasis into natural and artificial oasis according to the oasis features and function (Guo *et al.* , 2016; Wang *et al.* , 2021). Natural oasis was defined as the basic ecological environment, including forest, shrubland, grassland and waterbody. Artificial oasis is formed by the combination of natural disturbances and human interventions, and predominant by cropland and built-up in Tuha Basin.

Other land types (bare land, permanent ice and snow) were classified into non-oasis type. Generally, oases are situated in the plain area of Tuha Basin, with the elevation range of −50 to 300 m. There is a small percentage of oases embedded in river basins formed by the meltwater from snow mountains.

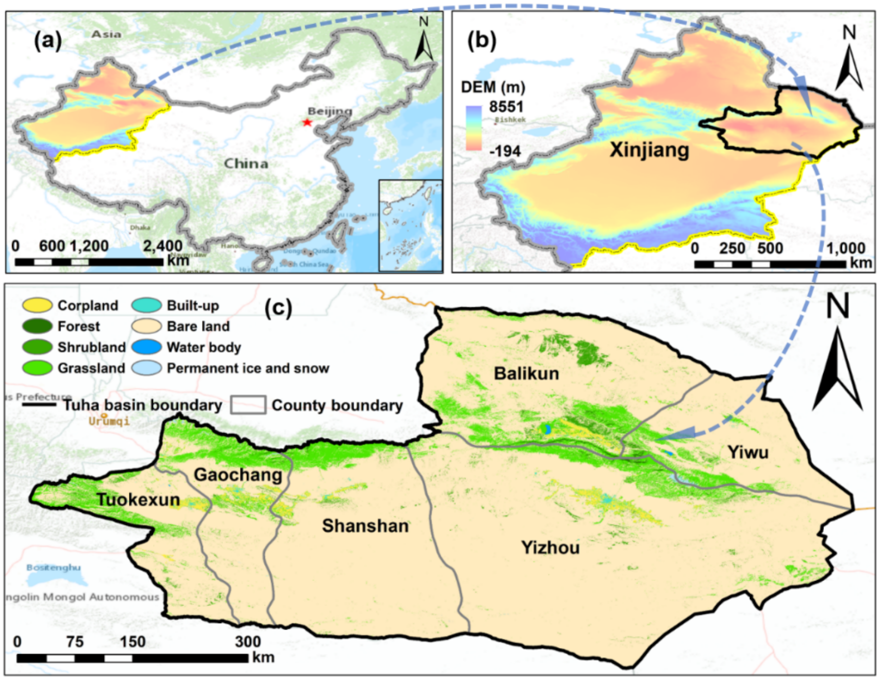

Figure.1 The geographical location of (a) Xinjiang, (b) Tuha Basin, and (c) land cover map of Tuha Basin in 2020.

2.2 Datasets

Oasis data are extracted from GLC_FCS30 in Earth System Science Data (https://doi.org/10.5194/essd-13-2753-2021/), with 30 m spatial resolution and 5-year interval from 1990 to 2020. GLC_FCS30 data classified land types into cropland, forest, shrubland, grassland, wetlands, built-up, bare land, water body, and permanent ice and snow. Because of the tiny coverage in Tuha Basin, wetland was merged into water body. Compared with the apparent vertical zonality of mountainous areas, oasis owns intrazonal characteristics (Zhang *et al.* , 2021; Zhou *et al.* , 2010). Therefore, in this study, the areas with the elevation higher than 2500 m and between 500 m and 2500 m with the slope greater than 250 were regarded as mountainous areas and masked out (Kapos *et al.* , 2000; Körner *et al.* , 2017, 2021).

Oasis dynamics are mainly affected by natural and human factors (Chen*et al.* , 2023). Natural factors are characterized by wide ranges and long duration, but they have minor short-term effects on oases dynamics (Zhang *et al.* , 2021; Zhou *et al.* , 2017). Two natural factors, precipitation and temperature, were collected from National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn) with 1 km spatial resolution throughout the growing seasons (from May to July). Human factors had further impacts on oasis dynamics, but they were limited in local ranges (Amuti & Luo, 2014; Xiao *et al.* , 2019). Four human factors, total power of agricultural machinery, total output value of the plantation industry, production of raw coal, and population were acquired from the Xinjiang statistic yearbook, which were collected during the same periods as LULC data.

3. Methodology

3.1 Complex network

Complex networks are intricate structures composed of multiple interconnected sub-systems with interaction occurring among them (Newman, 2003; Xu *et al.* , 2023). The complexity of these networks is affected by the number of sub-systems involved and the nature of their interactions (Wen & Jiang, 2019). In this study, oasis types are denoted as nodes, and their interactions are represented as the edges. This model quantifies the relationship among nodes and facilitates the analysis of the whole network system (Ramirez-Arellano *et al.* , 2021).

The flowchart of the oasis transition network construction in this study was shown in Figure 2. The entire oasis transition process was viewed as a complex network, and land types played the roles of sub-systems. Transformation relations between land types were regarded as the network edges. Depending on the edge direction, a complex network can be categorized into directional and non-directional networks, as well as weighted and non-weighted network based on the edge attributes. According to the land use transition matrix in Tuha Basin, six directional and weighted oasis transition network phases were created. The oasis transition process, key land types and oasis structural stability were then evaluated using three metrics: degree value, betweenness centrality, and average path length.

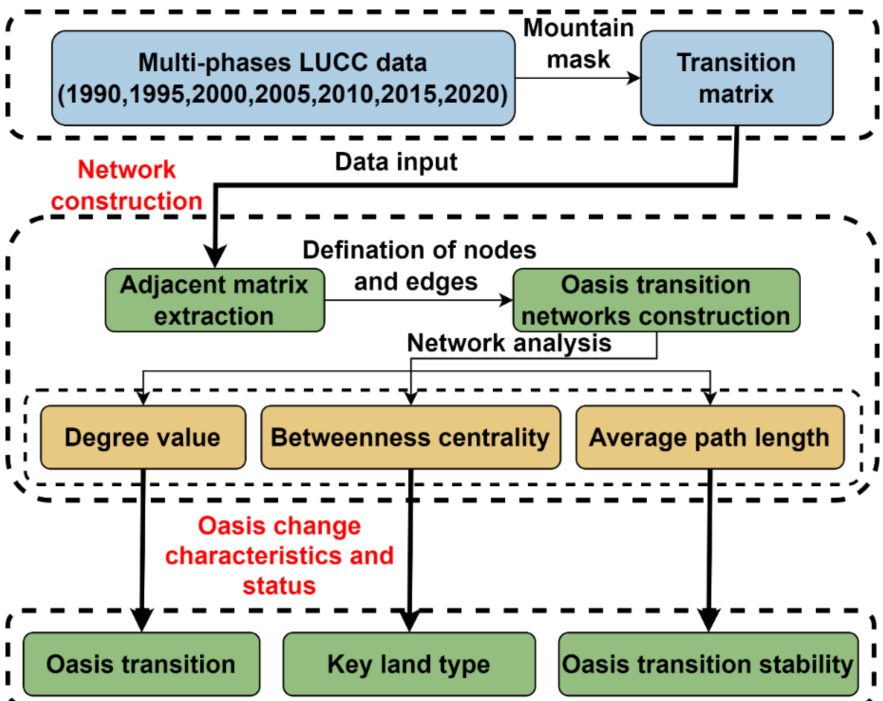

Figure.2 Flowchart of oasis transition network construction

3.1.1 Oasis transition analysis

In oasis transition network, the degree value of one oasis type node refers to its edge number. The higher the degree value, the more connections the node has with other nodes (Li & Xiao, 2017). The direction and intensity of the node interactions are important indicators in a directional and weighted network. The weighted in-degree and out-degree are defined based on the direction and weight from the edges. Here, in-degree and out-degree represent the transfer-in and transfer-out areas of oasis types, respectively. Weight refers to the converted areas between two land types. The ratio of weighted out-degree to weighted in-degree (named ratio) is employed to determine whether a land type is a transfer-in or transfer-out type. If the ratio greater than 1, the land type is defined as a transfer-out type; otherwise, it is a transfer-in type. In-degree and out-degree can be calculated as:

where is adjacency matrix of the network. If there are any connections between th node and th node, ; else, , here , *N, n* represent the number of nodes in a network, and when , . is the transition matrix. is the element in , if represent the weighted out-degree from th node to th node, else represent the weighted in-degree from th node to th node. The number of , when equal to the out-degree of th node else equal to the in-degree of th node.

3.1.2 Identification of key land type

In the complex network, betweenness centrality is used to identify the key node in oasis transition network, which refers to the ratio of the shortest paths that pass through this node to all the shortest paths in the network. The shortest path refers to the node sequence with shortest weighted sum between two nodes, and its length is considered as the smallest weighted sum between two nodes (Lambiotte *et al.* , 2019; Sporns, 2018). In the oasis transition network, a land type with higher betweenness centrality would have more control over the whole network, because of more information passing through that node. The key land type plays a vital role in affecting the interactions of land types and the oasis transition network vitality. Betweenness centrality can be calculated as:

where is the th node betweenness centrality, is the number of shortest path passing the th node, and is the number of shortest path in whole network.

3.1.3 Oasis structural stability

Oasis type transition possibility demonstrates the oasis structural stability in the complex network and the path length usually represents the transition possibility of two types. Average path length are employed to express the possibility of two types in this study (Zhang*et al.* , 2019). Here, the path length refers to the number of edges in a sequence that connects two nodes in a network, and the corresponding sequence with the shortest length between two nodes is called the shortest path. The average length of the shortest path in a network is the average path length. The shorter average path length, the higher transfer efficiency is among the oasis types but a more unstable oasis structure. The average path length was calculated as:

where is the average path length in the network. refers to the number of nodes in the network. represents the length of the shortest path between node and .

3.2 Driving forces for Oasis transition

Oasis transition driving forces were explored from natural and human aspects. Pearson's correlation coefficient (r) is used to express the linear correlation between two variables (Cui *et al.* , 2023). In this study, we quantified the driving forces between driving factors and oasis changes using r -value. r -value can be expressed as:

where and represent oasis type and the area at the th year. is the number of samples; and represent the mean value vectors of and , respectively. is the correlation coefficient between and .

4. Results

4.1 Oasis changes in areas

The area and proportion of oasis area in Tuha Basin for different oasis types were counted from LULC data during1990 and 2020 in Tuha Basin. As shown in Figure 3, the oasis in Tuha Basin expanded between 1990 and 2020, with the area increasing from 14346.43 km^2 to 19977.09 km^2. Natural oasis expanded the most, with the area increasing from 11219.26 km^2 to 15922.68 km^2, the proportion increasing from 78.21% to 79.71%. Shrubland contributed the most expansion in natural oasis, with the area and proportion increasing from 1121.93 km^2 to 4756.68 km^2 and from 2.01% to 23.81%, respectively. Grassland was the largest oasis type, and averagely accounting for 3.91% of Tuha Basin for seven periods.

Artificial oasis also had a slight rising trend, with the area increasing from 3127.17 km^2 to 4054.41 km^2, the proportion decreasing from 21.79% to 20.29% during 1990 and 2020. Explicitly, cropland accounted the greatest number of artificial oasis, the area changing from 2914.63 km^2 to 3597.91 km^2, and the proportion decreasing by 18.01% in 2020 than that in 1990 with 20.31%. Artificial oasis expansion was mainly attributed to the increment of built-up, with the area from 213.53 km^2 increasing to 456.50 km^2, the proportion increasing from 1.48% to 2.28%.

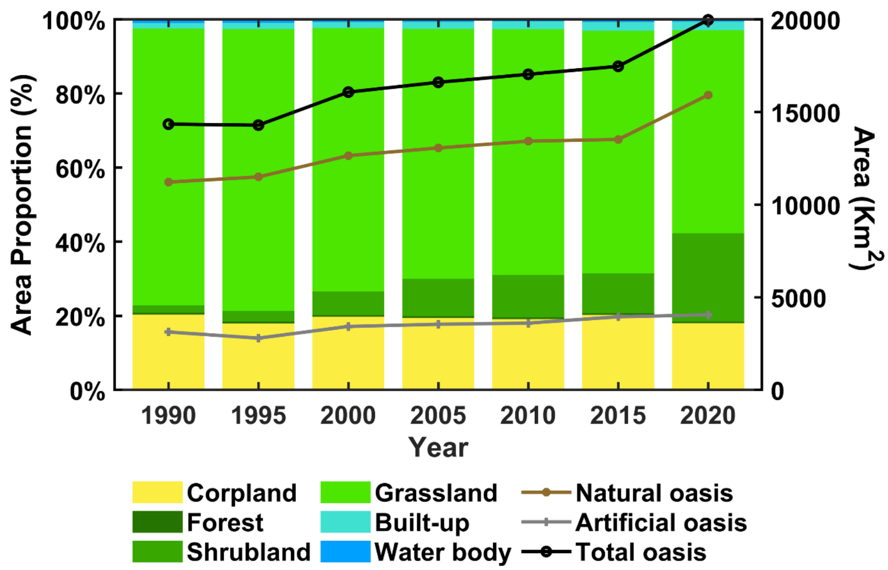

Figure. 3 Oasis area and proportion variations in Tuha Basin from 1990 to 2020.

4.2 Oasis transition process analysis

Oasis transition process was reflected in Figure 4 through nodes and edges in the oasis transition network. The width of the edges in the subgraphs referred to the converted areas from one node to another. The complexity of the network was decided by the numbers of nodes and edges. Generally, the interactions among all the land types became more frequent from 1990 to 2020, with more edges connecting the nodes. Grassland owned the most edges, proving the most active node in the oasis transition network. The interaction between cropland and shrubland was dramatic during the first three periods from 1990 to 2005, and kept steady in the last three periods. There was no transfer-out of built-up to other land types from 1990 to 2000, and the edge of the transfer-in type was substantially wider than the transfer-out one throughout the whole study period.

To reduce the redundancy of the network, principal component analysis was conducted by calculating the main components nodes and edges that had the edge weights with above-average values in the oasis transition network (Figure 5). The primary conversions occurred among grassland, cropland, shrubland, and Bare land. The interaction between grassland and bare land dominated in the oasis transition network throughout the whole study period; the transition between bare land and shrubland was predominant after 1995. The weight of cropland gradually decreased until it was below the average weight, at which point it was eliminated as a primary component in the oasis transition network in the period of 2015-2020.

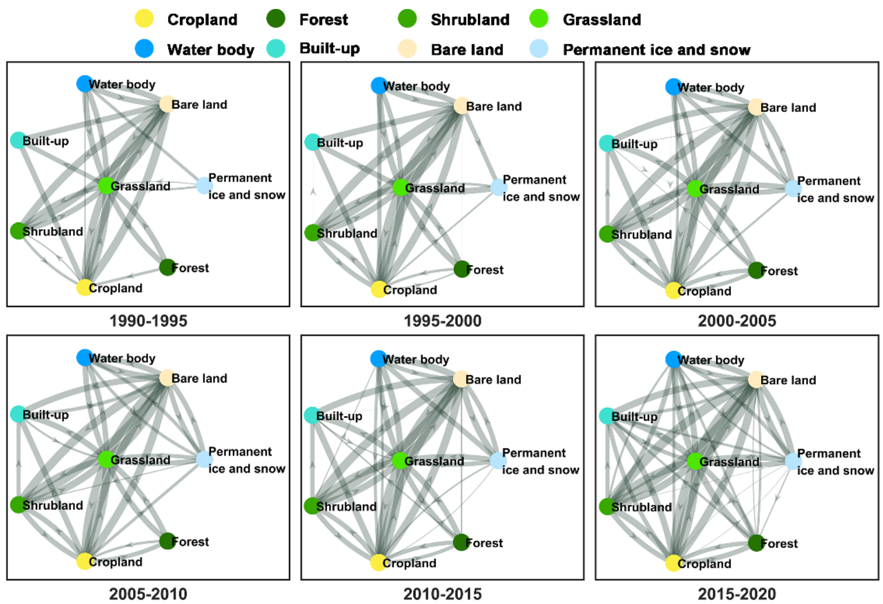

Figure.4 Oasis transition networks in different periods

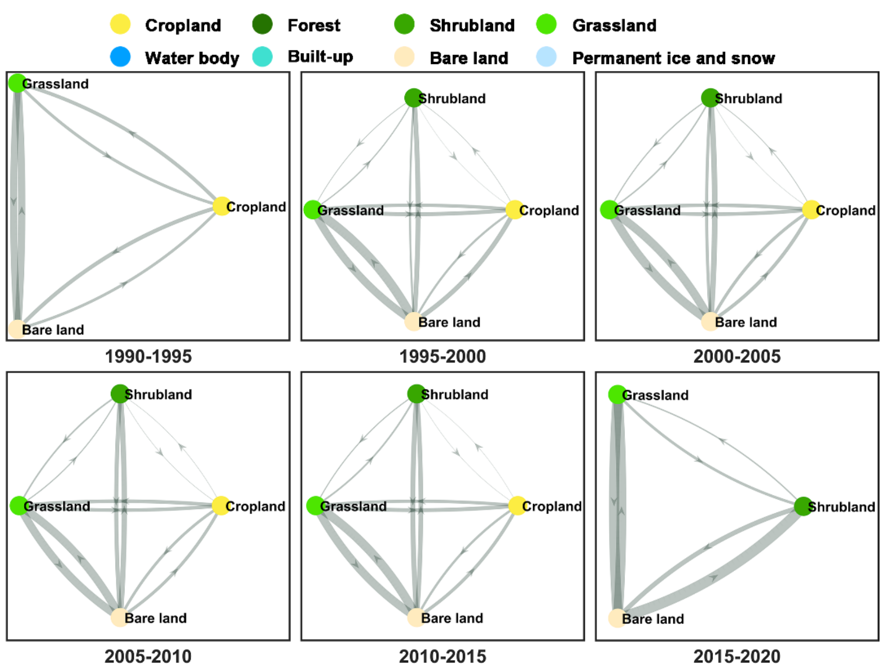

Figure.5 Oasis transition network principal components in different periods

Table 1 showed the results of node ratios, out-degree and in-degree from the oasis transition network to quantify the conversions among various oasis types. A ratio less than 1 indicated a transfer-in oasis type in the sub-period; if the ratio declined during 1990 and 2020, the transfer-in area of the oasis type accelerated. A ratio greater than 1 showed a transfer-out oasis type; if the ratio grew during 1990 and 2020, the transfer-out area of the oasis type sped up.

Natural oasis and artificial oasis were expressed as transfer-in types from 1990 to 2020, with ratios of 0.46 and 0.52, respectively. Throughout the study periods, grassland had the highest out-degree and in-degree values and the ratios were steadily round 1, implying the most active land type in the oasis transition network. Shrubland had a low ratio and increasing tendency in out-degree and in-degree throughout the study period. The ratio of shrubland dramatically dropped from 1.10 to 0.19 from 2015 to 2020, indicating the shift from transfer-out to transfer-in. The ratio of forest varied during the study period and it peaked at 0.23 during 2015 to 2020. Generally, water body was a transfer-out type, and the ratio fluctuated during 1990 and 2020. The ratio of cropland was a transfer-in type with the ratio smaller than 1 after 1995. The out-degree and in-degree maintained in a high level and changed slightly from 1990 to 2020. Built-up had the lowest ratio (0.00-0.02), suggesting that the area of built-up was fixed, and it was difficult to be converted into other land types.

Tab.1 Node ratio, out-degree and in-degree in oasis transition network

Land type	1990-1995 (Ratio, out-degree, in-degree)	1995-2000 (Ratio, out-degree, in-degree)	2000-2005 (Ratio, out-degree, in-degree)	2005-2010 (Ratio, out-degree, in-degree)	2010-2015 (Ratio, out-degree, in-degree)	2015-2020 (Ratio, out-degree, in-degree)
Cropland	1.75, 5, 4	0.44, 6, 5	0.92, 7, 5	0.96, 6, 4	0.62, 7, 6	0.92, 7, 6
Built-up	0.00, 0, 3	0.00, 0, 4	0.00, 2, 5	0.01, 2, 4	0.00, 2, 5	0.02, 3, 6
Forest	1.35, 2, 1	0.57, 3, 2	1.65, 3, 2	0.74, 2, 2	1.64, 3, 3	0.23, 4, 5
Shrubland	0.32, 3, 3	0.17, 4, 3	0.32, 4, 3	0.68, 4, 4	1.10, 5, 3	0.19, 6, 4
Grassland	**0.91, 7, 6**	**0.80, 7, 6**	**1.09, 7, 7**	**0.95, 7, 7**	**0.95, 7, 7**	**1.15, 7, 7**
Water body	1.33, 2, 4	3.73, 3, 2	3.51, 4, 3	2.39, 3, 3	0.17, 3, 5	1.34, 5, 5
Permanent ice and snow	4.50, 2, 1	0.00, 1, 3	1.92, 2, 4	0.60, 4, 4	0.48, 4, 3	1.22, 6, 5
Bare land	0.97, 5, 4	1.91, 6, 5	1.19, 6, 6	1.17, 6, 6	1.16, 7, 6	1.65, 7, 7

The oasis transition during 1990 and 2020 was exhibited in Figure 6, which illustrated the distribution features of various oasis types in Tuha Basin. Totally, the area of oasis converted to non-oasis was 3940.70 km^2; and 9570.38 km^2 of non-oasis converted to oasis, which demonstrated the oasis expansion in Figure 3. Specifically, as an almost transfer-in type, the converted area from non-oasis to artificial oasis was 1418.18 km^2, distributing in the southeast of Gaochang district, surrounding of Yizhou district and northern Balikun county. Natural oasis converted 3520.84 km^2 to non-oasis, mainly occurred in northern and eastern Balikun; as an important transfer-in oasis, non-oasis converted 8152.20 km^2 to natural oasis, mainly concentrating in northern part of Balikun county.

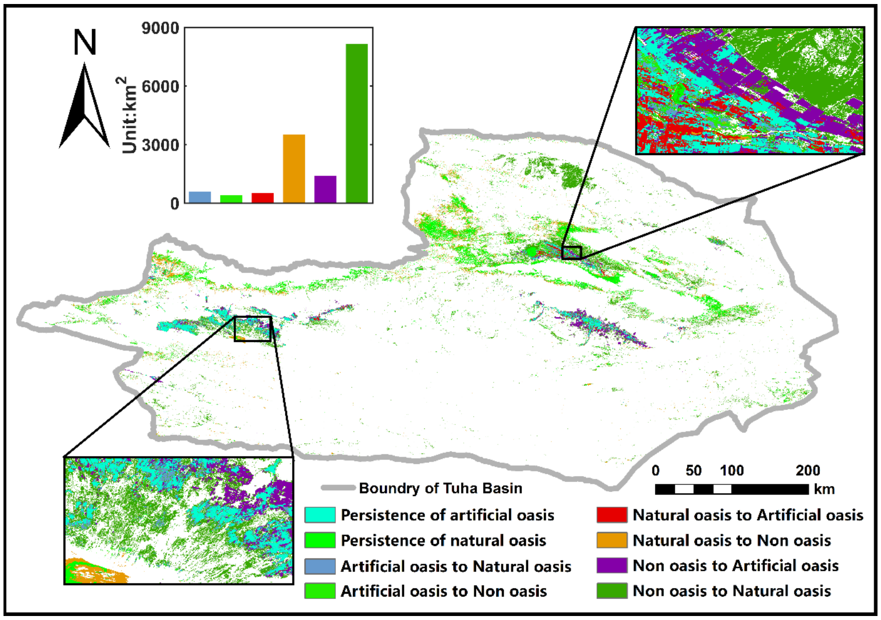

Figure.6 Transition of different oasis types in Tuha Basin during 1990 and 2020 (a), and area of oasis transition statistic (b)

4.3 Identification of key land type

Betweenness centrality was calculated for all nodes in the oasis transition network (Figure 7) to reveal the importance of nodes and identify the key land types in the oasis transition network. During the six sub-periods, grassland had the highest betweenness centrality with value 17.67, 11.33, 10.67, 12.17, 7.33, and 3.18, respectively, proving the most important type in the oasis transition process. Grassland was transferred in mostly from cropland and bare land, and transferred out to shrubland. However, the betweenness centrality showed descend tendency as the oasis expansion and more complicated topological relationship among the land types. The second highest betweenness centrality was cropland, with the values of 2.67, 3.83, 4.67, 3.33, 4.83 and 2.78, respectively during the six sub-periods. Betweenness centrality of cropland was close to grassland in 2015-2020, becoming the key land types in oasis transition network. Furthermore, the betweenness centrality of bare land was 5.50 in 2015-2020, revealing that it was also a key land type.

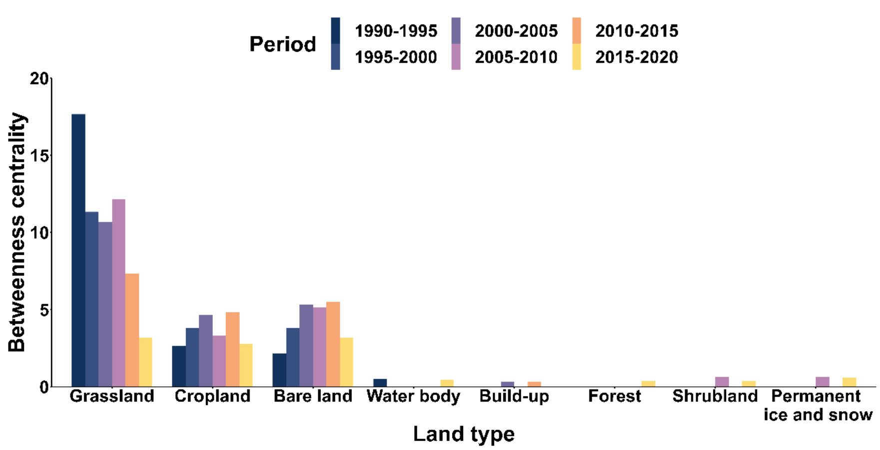

Figure.7 Betweenness centrality of nodes in oasis transition network during various periods

4.4 Oasis structural stability analysis

The oasis structural stability was assessed by the average path length for all the sub-periods in the oasis transition network. If the average path length was longer, the transition between the oasis types was more difficult, and the oasis had a stronger structural stability. In Table 2, the average path length of the oasis transition networks was all shorter than 1.5 in the seven sub-periods, implying an unstable structure of the oasis system. Additionally, the average path length of the oasis transition network descended from 1.47 to 1.20 in 1990-2020, which demonstrated the oasis system became increasingly unstable.

The average path length decreased by 5.44% between 1190-1995 and 1995-2000, and kept stable during 1995-2010. In this period, cropland areas expanded significantly, and many efforts like planting. However, the average path length decreased to 1.20 during 2010-2020, which indicated transitions among different land types were easier and oasis transition network was more complex.

Tab.2 Average path length of oasis transition complex network

Periods	1990-1995	1995-2000	2000-2005	2005-2010	2010-2015	2015-2020
Average path length	1.47	1.39	1.38	1.39	1.32	1.20

4.5 Driving factors for oasis changes

The inter-annual variations of driving factors during 1990 and 2020 were displayed in Figure 8. the average monthly temperature in growing season ranged from 15.64 0C and 22 0C to 20.15 0C and 25.79 0C. The mean temperature in growing season ranged from 19.22 0C to 23.07 0C, with a slight upward tendency. Precipitation decreased obviously from 1990 to 2020, and the variations in growing season ranged from 1.44 mm and 16.99 mm to that of between 2.77 mm and 6.24 mm. In growing season, precipitation expressed as significant decreased tendency. The four human driving factors- population, total power of agricultural machinery, production of raw coal and total output value of plantation industry, all showed upward tendency over the study period. The production of raw coal and the total output value of the plantation industry were increased dramatically after 2005.

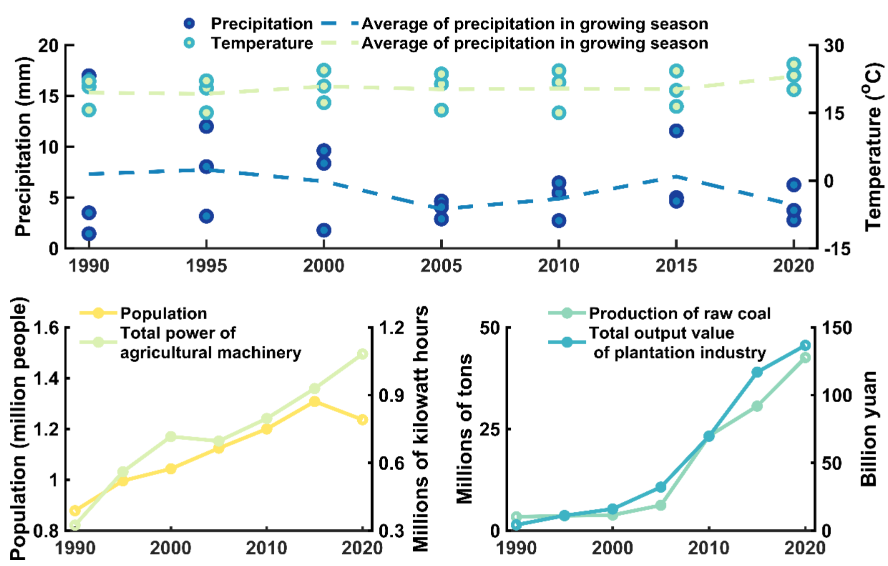

Figure.8 Annual variations of different driving factors

Pearson's coefficient and t -test were utilized to express the relevance between oasis transitions and driving factors in Figure 9. Among the natural driving factors, oasis transitions showed positive correlation with temperature (P -value < 0.05, $r = 0.88$) and insignificant correlation with precipitation. Temperature was positively related to forest (P -value $< 0.01, r = 0.94$) and shrubland changes (P -value $< 0.01, r = 0.95$). Notably, precipitation had negative effects (P -value < 0.05) on shrubland changes. It indicated that the most natural oasis changes in Tuha Basin was highly sensitive to temperature, and scarcely affected by precipitation due to the extremely low precipitation and its downward trend during 1990 and 2020 over Tuha Basin. Generally, natural factors mainly affected natural oasis with the average coefficient of 0.92 (P -value < 0.01), and had insignificant effects on artificial oasis.

All the human driving factors, population, total power of agricultural machinery, raw coal production, and total agricultural output showed positive correlations with the oasis changes, with the coefficients of 0.83, 0.94, 0.90 and 0.91 (P -value < 0.05), respectively. Cropland, shrubland and built-up changes were mainly controlled by human activities, and built-up had the most positive response to population, total agricultural machinery power, raw coal production, and agricultural output, with the coefficients of 0.93, 0.94, 0.96 and 0.98 (P -value < 0.01), respectively. Shrubland changes were influenced significantly by the total power of agricultural machinery, raw coal production, and agricultural output value, with the coefficients of 0.87, 0.89, and 0.87, respectively (P -value < 0.05). With the same coefficient of 0.89, human activities had obvious driving forces on both natural oasis and artificial oasis. Human activities mainly affected shrubland in natural oasis; the four human factors showed significant positive correlations on artificial oasis, with the coefficients of 0.86, 0.86, 0.85 and 0.89, respectively (P -value < 0.05). The spatial allocation of water resources improved with the development of agriculture and industry of Tuha Basin. Moreover, the policies supporting the shrub planting and growth were encouraged to combat desertification and reinforce sand.

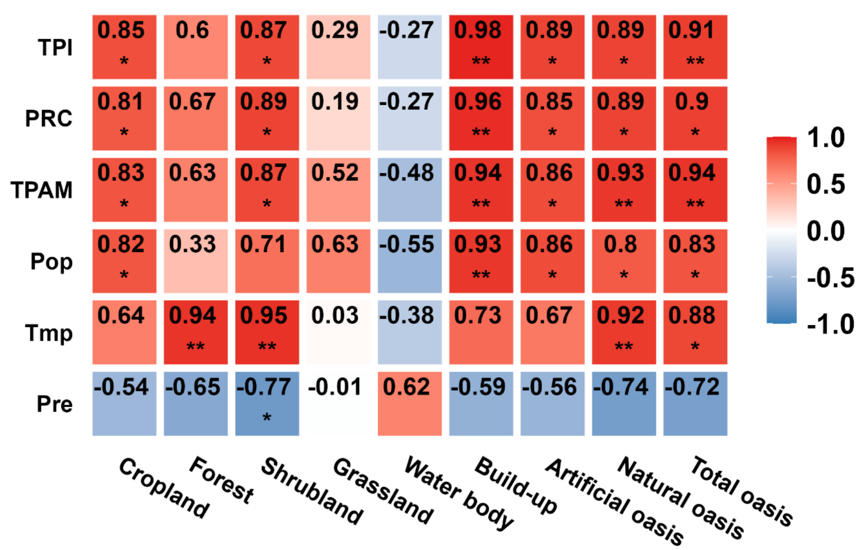

Figure.9 Coefficients matrix between oasis changes and driving factors during 1990-2020 (Pre: Precipitation, Tmp: Temperature, Pop: Population, TPAM: Total power of agricultural machinery, PRC: Production of raw coal, TPI: Total output value of plantation industry; * represents P -value < 0.05, and ** represents P -value < 0.01)

5. Discussion

In this study, we constructed a directed and weighted complex network, naming the oasis transition network, which was used to express the transition patterns between different oasis types, identify the key land type and quantify the oasis structural stability. Compared with traditional transition analysis, the complex network described the dynamic process and the influences of different oasis types in the oasis system. Between centrality was used to identify the key land type, which was explained the possibility the land type being the transitional type. The findings of the oasis transition network indicated that the oasis transitions were increasingly complicated from 1990 to 2020. Grassland was the key oasis type in the oasis transition process, and the importance decreased during 1990 and 2020. Bare land had the highest betweenness centrality in 2015-2020 and cropland ranked third among all the land types, indicating the important roles and the changes of key land type in the transition network. According to the relevant report and statistic year book published by the beau of statistic in Turpan and Hami region, through the thirteenth 'five-year' plan, greening construction projects like returning farmland to grassland, afforestation, combating and controlling desertification and three north protective forests have gained significant effectiveness (Lyu *et al.* , 2020). During that period, grassland was not the most important transitional land type due to the efforts of planting and reclamation of the bare land.

Notably, in the oasis transition network, the land types with low proportion of coverage also contacted with other land types frequently. For example, shrubland expressed high degree values and was one of the principal components in the oasis transition network and the interactions with bare land dominated during the sub-periods of 1995-2000, 2000-2005, 2005-2010, 2010-2015 and 2015-2020. According to the local statistic yearbook, a large proportion of shrubland were planted artificially to combat wind and sand at the edge of the oasis and against land degradation in the inner oasis, like shuttle and camel thorn; the area of shrubland showed a distinct increasing trend in 2015-2020. We were inspired those human forces dominated in the oasis transition process for most sub-periods.

Oasis structural stability was quantified using average path length in the oasis transition network, which was a crucial index to express the oasis sustainability in dryland. So far, few studies had investigated the structural stability of the entire oasis system in dryland. In this study, we applied the average path length to reveal the difficulty of the interactions among the oasis types. With the results of more unstable oasis structural stability, we concluded that there were easier transitions among different land types recent years than before. Therefore, we suggest that more attentions on key land types (e.g. grassland) should be paid for the dryland sustainable development.

Even though the correlations between oasis and precipitation were insignificant, water resource was one of the most important restraint factors in dryland development (Yang *et al.* , 2021). The surface water in Tuha Basin is obviously shrinking recent years partly because of the increasing temperature and intense evaporation (Rodell *et al.* , 2018; Wang *et al.* , 2023) in Tuha Basin. Additionally, water resources were over-exploited and underground water level had continuously dropped for agricultural irrigation and mining (Hu *et al.* , 2019; Wang *et al.* , 2022; Cheng *et al.* , 2023). A more adaptive strategy for regulating cropland areas and water resource allocation is needed. From the driving factors analysis, population played a key role in oasis expansion, for example, to meet the requirements of the fast-growing population, the urbanization including artificial reclamation and construction speeded up, making built-up a most transfer-in type in the oasis transition network. Human factors including policy factors, economic factor and cultural factors were all important in the maintaining of the entire oasis system and land optimization in drylands. Therefore, further survey and analysis for the oasis driving should be deep considered.

6. Conclusion

In this study, oasis spatial-temporal variations in Tuha Basin were first analyzed for the further transition investigation over the past 30 years. All the oasis types increased from 1990 to 2020, and the natural oasis expanded the most. Oasis transition processes, key land type and oasis structural stability were then depicted using the constructed oasis transition network. We concluded that the oasis transition relationship among different oasis types became more complicated in 2020 than that was in 1990. Grassland, shrubland, forest and cropland changed the most during the study period, and grassland was viewed as the key land type due to the high out-degree, in-degree values and betweenness centrality. The oasis structural stability calculated from the network showing declining trend from 1990 to 2020. To explore the driving forces of oasis changes, correlation analysis between the natural and human factors and oasis changes was conducted using the Pearson coefficient. Among the natural driving factors, temperature correlated positively with natural oasis changes, and had insignificant effects on artificial oasis. In human driving factors, population, the total power of agricultural machinery, raw coal production, and the total agricultural output improved the growth of shrubland and the artificial oasis; built-up showed the most positive response to human driving factors. The study clarified the oasis transition pattern and process, and provided scientific reference for future oasis study and management.

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Conflict of Interest

The authors declare no conflict of Interest.

Reference:

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