Land Use Intensity Changes and Their Impact on Evapotranspiration in the Aksu River Basin, 2000–2020: Postprint

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Abstract

Thoroughly investigating information on internal conversion processes within land use types, quantifying the impact of land use change intensity on evapotranspiration, and accurately assessing the spatiotemporal variation patterns of actual evapotranspiration hold significant importance for scientific management and efficient utilization of watershed water resources. Based on the intensity analysis model, this study reveals the characteristics of intensity changes in land use types at different hierarchical levels in the Aksu River Basin from 2000 to 2020 and their impacts on basin-scale actual evapotranspiration. The results demonstrate that: (1) At the temporal interval level, the intensity of land use change in the basin exhibited a trend of initially increasing and subsequently decreasing, with the most active changes occurring during 2000–2005. At the land category level, area changes in cultivated land, construction land, water bodies, and forest land displayed relatively active behavior. At the transition level, increases in cultivated land area primarily originated from grassland (accounting for 54.31%) and unused land (accounting for 26.26%); (2) The multi-year average evapotranspiration of the basin is 166.56 mm, characterized by substantial interannual fluctuations and an overall increasing trend with an annual growth rate of 3.68 $\mathrm{mm \cdot a^{-1}}$. Evapotranspiration from April to October accounts for 71.76% of the annual total. High values of actual evapotranspiration are distributed across mountainous forest areas and cultivated land in plain regions, while low-value areas are located in piedmont desert zones and the transition belt between oasis and desert; (3) Principal component analysis results indicate that the driving forces of actual evapotranspiration variation in the Aksu River Basin are the conversion intensities of grassland, cultivated land, and unused land. The correlation coefficient between land use change intensity and actual evapotranspiration is 0.87, demonstrating a strong correlation between the two.

Full Text

Abstract

It is of great significance for scientific management and efficient utilization of water resources in the basin to deeply explore the information of internal conversion processes of land use types, measure the impact of land use change intensity on evapotranspiration, and accurately evaluate the temporal and spatial variation patterns of actual evapotranspiration. Based on the intensity analysis model, this study reveals the intensity change characteristics of land use types at different levels in the Aksu River Basin from 2000 to 2020 and their impact on the basin's actual evapotranspiration. The results show that: (1) At the time interval level, the intensity of land use change in the basin increased first and then decreased, with the most active changes occurring from 2000 to 2005. At the land category level, the increase and decrease of cultivated land, construction land, water area, and forest land area were relatively active. At the transition level, the increase in cultivated land area mainly came from grassland (accounting for 54.31%) and unused land (accounting for 26.26%). (2) The multi-year average evapotranspiration of the basin is 166.56 mm, with large interannual fluctuations and an overall increasing trend at a rate of 3.68 $\mathrm{mm \cdot a^{-1}}$. Evapotranspiration from April to October accounts for 71.76% of the annual evapotranspiration. High actual evapotranspiration values are distributed in mountainous forest land and plain cultivated land, while low values are distributed in piedmont desert areas and the oasis-desert transition zone. (3) Principal component analysis results indicate that the driving forces of actual evapotranspiration change in the Aksu River Basin are the conversion intensities of grassland, cultivated land, and unused land. The correlation coefficient between land use change intensity and actual evapotranspiration is 0.87, indicating a strong correlation between the two.

Keywords: land use change; intensity analysis; actual evapotranspiration; Aksu River Basin

Introduction

Land Use/Cover Change (LUCC) is an important cause of global environmental change. Simultaneously, land use changes (such as oasis expansion and urbanization) alter evapotranspiration processes, thereby affecting water resource allocation and exacerbating water supply-demand imbalances. The impact of land use change on actual evapotranspiration is currently an urgent problem to be solved.

Intensity analysis is a theoretical framework based on transition matrices, encompassing three levels: time interval, land category, and transition. Compared with transition matrices and traditional land use dynamic degree analysis methods, this analytical framework can fully exploit the information contained in transition matrices and quantitatively analyze the internal conversion status during land use dynamic change processes. Aldwaik and Pontius considered the impact of regional structure on conversion areas between land categories, depicting internal conversion of land use change from interval, category, and transition levels. This framework first appeared in China in Huang et al.'s study analyzing land use patterns in the Jiulong River Basin of Fujian Province. Subsequently, Yang Jianxin et al. further improved the intensity analysis model by applying a specific conversion model cross-tabulation that can quickly and intuitively display the stability and systematic characteristics of land use. Additionally, Tian Lixin et al. in the southern Laizhou Bay coastal zone, Sun Yunhua et al. in Kunming City, and Tan Xuejing et al. in Beijing have applied the intensity analysis model framework for land use dynamic change analysis. Existing research results demonstrate that intensity analysis models have certain advantages in deeply analyzing the internal structural conversion relationships between land categories. Meanwhile, most existing studies on the impact of land use change on actual evapotranspiration are based on comparing actual evapotranspiration amounts corresponding to land use in different periods, with fewer studies considering the impact of internal conversion intensity of land use on actual evapotranspiration. Therefore, this paper uses the intensity analysis model to compensate for the shortcomings of existing LUCC model analyses, deeply explores internal transition matrix information, and investigates the response relationship between land use intensity and actual evapotranspiration.

The Aksu River Basin is a key component of the "four sources and one trunk" water system pattern of the Tarim River Basin, with an average annual inflow to the Tarim River of over 80%. Changes in the hydrological cycle and water resources of the Aksu River Basin directly affect the ecological security and regional security of the Tarim River Basin and the entire southern Xinjiang region. ET is a key expenditure item in the basin's water cycle. Especially in recent decades, with the development and utilization of water and land resources in the basin, desert artificial oases represented by farmland irrigation areas have been the most frequent in land use type conversion. Large-scale analysis of the impact of land use change intensity on ET is of great significance for efficient water resource utilization and ecological environment protection and restoration in the basin. Based on this, this study adopts land use data from 2000 to 2020 in the Aksu River Basin, analyzes land use change intensity at different levels based on the intensity analysis model, and combines MOD16A2 data from the same period to explore the impact of LUCC change on ET, aiming to provide scientific guidance for optimizing land resource management policies and efficient water resource utilization and rational allocation in the Aksu River Basin.

1. Materials and Methods

1.1 Study Area Overview

The Aksu River Basin is located in the western part of the middle Tianshan Mountains' southern slope, on the northwestern edge of the Tarim Basin, at 40°00 ~42°27 N, 75°35 ~82°00 E. The terrain is dominated by mountains and plains, with elevation gradually decreasing from north to south and from west to east. The basin area is approximately 4.8$×10^{4}$ km^2. The Aksu River Basin has a warm temperate arid climate with prominent continental climate characteristics. The multi-year average temperature is around 10°C, and the multi-year average precipitation is 137.7 mm. Atmospheric precipitation and glacier meltwater are the main sources of runoff recharge in the basin.

1.2 Data Sources and Processing

Land use data (2000, 2005, 2010, 2015, and 2020) were obtained from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences. Meteorological data were sourced from the China Meteorological Data Service Center. MOD16A2 data were obtained from NASA. The data selection included actual evapotranspiration (ET) and potential evapotranspiration (PET) from 2000 to 2020, with h23v04 and h24v04 selected. First, the MODIS Reprojection Tool was used to project and resample the MODIS format data. Second, ArcGIS software was used to remove invalid data, followed by vector clipping to obtain ET and PET data for the study area at 500 m resolution. Finally, the data and land use data were resampled to unify the spatial resolution to 500 m.

1.3 Methods

1.3.1 Intensity Analysis Model The intensity analysis model can provide the change intensity of different land use types within different time periods, including time interval, land category, and transition levels.

(1) Time interval level. The purpose of time interval level intensity analysis is to determine whether the change speed of land types in a given period is fast or slow by studying the relationship between the average change intensity in each time period (St) and the average change intensity of the entire study period (U). If St = U, the land type is absolutely stable; if St > U, the change is fast; conversely, it is slow. The calculation formula is:

$$St = \frac{\sum_{i=1}^{J}\sum_{j=1}^{J} C_{tij}}{\sum_{i=1}^{J}\sum_{j=1}^{J} C_{tij} + \sum_{i=1}^{J} C_{tii}} \times 100\%$$

$$U = \frac{\sum_{t=1}^{T-1}\sum_{i=1}^{J}\sum_{j=1}^{J} C_{tij}}{\sum_{t=1}^{T-1}\left(\sum_{i=1}^{J}\sum_{j=1}^{J} C_{tij} + \sum_{i=1}^{J} C_{tii}\right)} \times 100\%$$

where: i is the initial land category in time interval t; j is the final land category in time interval t; J is the number of land categories; T is the number of time nodes; t is the time interval identifier, ranging from 1 to T-1; Yt is the year of time point t; and Ctij is the amount of land converted from category i to category j during time interval t.

(2) Land category level. The intensity analysis at the land category level determines whether the change intensity of a land category is active or stable by comparing the average annual change intensity in each time period (St) with the change intensity of each category's increase or decrease area. If greater than St, the change intensity is active; conversely, it is stable. If a specific land category shows an active or stable trend in each time period, it indicates that during the entire study period, the increase or decrease of that category presents a stable pattern. The calculation formulas are:

$$G_{tj} = \frac{\sum_{i=1}^{J} C_{tij} - C_{tjj}}{\sum_{i=1}^{J} C_{tij} + \sum_{i=1}^{J} C_{tii}} \times 100\%$$

$$L_{ti} = \frac{\sum_{j=1}^{J} C_{tij} - C_{tii}}{\sum_{j=1}^{J} C_{tij} + \sum_{j=1}^{J} C_{tjj}} \times 100\%$$

where: Gtj is the average annual increase intensity of category j during time interval t; Lti is the average annual loss intensity of category i during time interval t; Ctii is the area of category i that remains unchanged during time interval t; and Ctjj is the area of category j that remains unchanged during time interval t.

(3) Transition level. Transition level intensity analysis mainly reveals the transfer-in and transfer-out intensities of specific land categories in different periods and compares them with the average change intensity of land categories to show the change tendency between categories. The calculation formulas are:

$$R_{tin} = \frac{C_{tin}}{\sum_{i=1}^{J} C_{tin} - C_{tnn}} \times 100\%$$

$$W_{tn} = \frac{\sum_{i=1}^{J} C_{tin} - C_{tnn}}{\sum_{i=1}^{J} C_{tin} + \sum_{i=1}^{J} C_{tii}} \times 100\%$$

where: Rtin is the transfer intensity of land category i to category n during time interval t (i $\neq$ n); Wtn is the average intensity of all categories transferring to category n during time interval t; and Ctnn is the area of category n that remains unchanged during time interval t.

If Rtin > Wtn, category n tends to transfer in from category i. Conversely, category n does not transfer in from category i. Similarly, if Qtmj > Vtm, category m may transform into category j; otherwise, category m will not transfer out to category j.

1.3.2 Principal Component Analysis Principal Component Analysis (PCA) is a statistical method for random variables that, with minimal information loss, combines original variables through linear combination into a few new variables that are uncorrelated with each other, replacing the original variables in data modeling. This paper uses PCA to explore the driving factors of ET changes caused by land use type conversion.

2. Results and Analysis

2.1 Land Use Change Characteristics

The most important land use types in the basin are grassland and unused land, accounting for 71.76% of the total area. Grassland is mainly distributed in the northern mountainous area of the basin, while unused land is widely distributed in the piedmont desert area and the oasis-desert transition zone. The area of each land use type in descending order is: unused land > grassland > cultivated land > forest land > water area > construction land.

Table 1 shows the area changes and land use dynamics of each category in the study area from 2000 to 2020. Cultivated land and construction land area showed a continuous increasing trend throughout the study period; forest land area gradually decreased; grassland and unused land area slightly increased; and water area first decreased then increased. Among these, cultivated land area increased the most in 2000-2005, with an increase of 805.31 km^2 and a dynamic degree reaching its peak at 3.47%. Forest land area decreased the most in 2010-2015, with a dynamic degree of -1.29%. Water area decreased the most in 2000-2005, with a dynamic degree of -1.10%. Unused land area remained relatively stable during the study period.

2.2 Intensity Analysis Results

2.2.1 Time Interval Level Analysis Figure 3 shows the land use change area and intensity analysis results at the time interval level in the Aksu River Basin from 2000 to 2020. The left panel shows that the proportion of change area in the 2000-2005 period was the largest at 3.96%. The right panel shows that St in the 2000-2005 period was much greater than U, indicating that land use change was rapid, while St in the other three time periods was less than U, indicating relatively slow change. Overall, the average change area and change intensity of land categories in the Aksu River Basin from 2000 to 2020 showed a consistent trend of first increasing significantly and then slowly decreasing.

2.2.2 Land Category Level Analysis Figure 4 shows the land use change intensity analysis results at the land category level in the Aksu River Basin from 2000 to 2020. It can be seen that from 2000 to 2020, forest land, water area, and grassland showed an overall decreasing trend, while the other categories increased. Among these, cultivated land had the largest net increase, while grassland had the largest net decrease. The average annual change intensity was most active for cultivated land, with the largest average change intensity.

From 2000 to 2005, the increase intensity of cultivated land, construction land, and water area was higher than the average intensity, while the decrease intensity was lower than the average intensity, indicating that the increase of these three categories was active while the decrease was stable. In contrast, the decrease intensity of forest land was higher than the average intensity, while the increase intensity was lower than the average intensity. The increase and decrease intensities of unused land and grassland were both lower than the average intensity, indicating that the decrease of forest land was active, while the increase and decrease of grassland and unused land were relatively stable.

From 2005 to 2010, the increase and decrease of construction land, forest land, and water area were all higher than the average change intensity, showing an active state, while the increase and decrease of cultivated land, grassland, and unused land were all lower than the average change intensity, indicating that the changes of these three categories tended to be relatively stable during this time interval.

From 2010 to 2015, the increase and decrease of construction land, forest land, and water area all showed active change trends. The increase intensity of cultivated land was greater than the average intensity, showing an active state. From 2015 to 2020, the increase and decrease of cultivated land, construction land, forest land, and water area were all higher than the average change intensity, showing an active state, while the changes of grassland and unused land were relatively stable. Overall, from 2000 to 2020, the area changes of cultivated land, construction land, water area, and forest land were relatively active, while grassland and unused land changes were relatively stable.

2.2.3 Transition Level Analysis Figure 5 shows the analysis results of cultivated land transfer in the Aksu River Basin from 2000 to 2020. The increase in cultivated land mainly came from grassland and unused land. In 2000-2005, 64.28% of the cultivated land increase came from grassland transfer, and 25.88% came from unused land transfer. In 2005-2010, 47.94% of the cultivated land increase came from grassland and 23.58% from unused land. In 2010-2015, 79.04% of the cultivated land increase came from grassland and 14.26% from unused land. In 2015-2020, 54.31% of the cultivated land increase came from grassland and 29.32% from unused land. Throughout the study period, the conversion from grassland to cultivated land showed a stable systematic conversion pattern, while the conversion of other categories was unstable over time.

The increase in cultivated land area mainly came from grassland, forest land, and unused land in the early stage, and later mainly occupied construction land, showing a stable systematic conversion pattern. Although the area of cultivated land occupying construction land was small, its change intensity was much higher than the average change intensity, indicating that the spatial distribution relationship between cultivated land and construction land is relatively close and has certain synergy in spatial distribution. Comparing the proportion of transfer area shows that categories with small transfer area do not necessarily show a stable avoidance systematic pattern, and categories with large transfer area do not necessarily show a stable systematic pattern.

Figure 6 shows the analysis results of grassland conversion to other categories in the Aksu River Basin from 2000 to 2020. The left panel shows that grassland mainly converted to cultivated land and unused land, with proportions far higher than other categories. From 2000 to 2005, grassland converted to cultivated land accounted for 73.34% of the total transferred area, and converted to unused land accounted for 20.58%. From 2005 to 2010, grassland converted to cultivated land and unused land accounted for 93.92% of the total transferred area. From 2010 to 2015, the total transferred area of grassland decreased, with the proportion transferred to forest land increasing to 32.47%. From 2015 to 2020, grassland converted to cultivated land accounted for 51.74% and to unused land accounted for 22.97%.

The right panel shows that from 2000 to 2005, grassland conversion to cultivated land showed a stable systematic conversion pattern. In the 2005-2010 and 2010-2015 periods, the transfer intensity of grassland to forest land and water area increased significantly. From 2015 to 2020, the change intensity of grassland to construction land was greater than the average intensity, indicating that construction land intensified its encroachment on grassland. Overall, grassland area mainly converted to cultivated land and unused land, but its change intensity was unstable over time. Although grassland area decreased significantly, its large area proportion remained relatively stable.

2.3 Actual Evapotranspiration Dynamics

2.3.1 Accuracy Verification The Aksu River Basin is located in arid and semi-arid regions. Pan evaporation and PET both represent the maximum possible evaporation under sufficient water supply conditions. This paper uses correlation analysis between pan evaporation and potential evapotranspiration for applicability testing. First, daily pan evaporation data were processed into annual values. Second, PET data were processed to the annual scale to ensure temporal consistency between the two datasets. Finally, correlation analysis was conducted between pan evaporation data and PET data at the station scale (Figure 7). The results show good correlation between meteorological station pan evaporation and PET, with a correlation coefficient reaching 0.87. Previous studies have confirmed that MOD16A2 data can be used for basin or large-scale surface evapotranspiration research, and MOD16A2 data has good applicability in the Aksu River Basin.

2.3.2 Temporal Variation of Actual Evapotranspiration Figure 8 shows the interannual and monthly variation characteristics of evapotranspiration in the Aksu River Basin. From 2000 to 2020, the basin's annual evapotranspiration fluctuated between 122.45~200.14 mm, with a multi-year average of 166.56 mm. From an interannual perspective, the basin's actual evapotranspiration showed large fluctuations but an overall increasing trend, with an annual growth rate of 3.68 $\mathrm{mm \cdot a^{-1}}$. From a monthly perspective, the evapotranspiration showed a significant single-peak pattern, continuously increasing from April, reaching a maximum in July, then gradually decreasing, and reaching a minimum in December. Overall, April to October is the concentrated period of basin evapotranspiration, accounting for 71.76% of the annual evapotranspiration.

Figure 9 shows the spatial distribution characteristics of multi-year average ET in the Aksu River Basin from 2000 to 2020. The basin's evapotranspiration shows significant spatial distribution differences. High ET values are mainly distributed in mountainous forest land and plain cultivated land, where abundant precipitation in mountainous forest land and irrigation in cultivated land provide sufficient water supply, and high vegetation coverage leads to strong vegetation transpiration, resulting in higher ET values. Low ET areas are mainly distributed in piedmont desert areas and oasis-desert transition zones, where precipitation is scarce, vegetation is sparse, and ET values are low.

2.4 Actual Evapotranspiration Characteristics of Different Land Use Types

Land use changes cause fluctuations in evapotranspiration. This paper extracts the annual average ET of different land categories based on five-period land use data and MOD16A2 data, and analyzes their spatiotemporal characteristics. Due to missing ET values on water bodies and construction land, these two categories were ignored when calculating ET values for each land category to avoid statistical errors.

Figure 10 shows that there are significant differences in annual average ET among land categories. Grassland has the highest annual average ET value at 179.21 $\mathrm{mm \cdot a^{-1}}$, while unused land has the lowest at 104.27 $\mathrm{mm \cdot a^{-1}}$. Combined with the land use type map (Figure 2), grassland and unused land are the main land use types in the basin. Grassland and forest land are distributed in mountainous areas and river valleys with relatively sufficient soil moisture, resulting in larger ET values. Unused land is distributed in piedmont desert areas and oasis-desert transition zones with sparse vegetation and lower ET values.

2.5 Relationship Between Land Use Change Intensity and Actual Evapotranspiration

To explore the relationship between land use intensity change and ET in the basin, this paper uses the conversion intensity at the land category level of six land use types as driving factors and employs principal component analysis to quantitatively analyze the impact of land use type changes on ET. The results (Table 2) show that the cumulative variance contribution rate of the first two principal components exceeds 85%, with the first principal component having the largest contribution rate. According to the principal component load values of driving factors (Table 3), except for cultivated land and water area, other driving factors have correlations higher than 0.7 with the first principal component, with grassland and unused land having the highest correlations. The factors closely related to the second principal component are cultivated land and construction land. Therefore, the driving forces of ET change in the Aksu River Basin are the conversion intensities of grassland, cultivated land, and unused land.

To further clarify the impact of land use change intensity on ET, this paper selects cultivated land, which showed active increase at the land category level, and conducts linear regression analysis between cultivated land increase intensity and annual average evapotranspiration in four time intervals in the Aksu River Basin (Figure 11). The results show a strong correlation between land use change intensity and ET, with a correlation coefficient of 0.87.

3. Discussion

In recent years, many scholars have used single or comprehensive land use dynamic degree methods to explore land use dynamic change characteristics in the Yellow River Basin, Dianchi Lake Basin, Fen River Basin, and the southern margin of the Tarim Basin. The results truly reflect the land use dynamic change characteristics of each study area. Therefore, this study compares the results obtained from single and comprehensive land use dynamic degrees (Figure 12) with those from the intensity analysis model. The analysis found that the change in cultivated land area in the Aksu River Basin directly affects the surface evapotranspiration process, which is similar to the conclusion obtained from the principal component analysis that the driving forces of ET change in the Aksu River Basin are the conversion intensities of grassland, cultivated land, and unused land.

The land use transition matrix can intuitively reflect the transfer area and direction of each category in the study area during each period, but cannot determine the internal conversion patterns between categories. To compare differences between methods, this study compares the land use transfer chord diagram based on the transition matrix (Figure 13) with the intensity analysis results. Grassland and unused land have large transfer areas but relatively stable change degrees; forest land, water area, and construction land have small transfer areas but active change degrees.

From 2000 to 2005, grassland had the largest transfer area to cultivated land, but its transfer intensity was less than the average change intensity. Construction land had a small transfer-in area, but its transfer intensity was much greater than the average intensity. This is consistent with the conclusions of Niu Lele and Li Shuaicheng that there is no obvious correlation between the magnitude of area or quantity and transfer intensity. Land categories with small transfer areas do not necessarily show stable avoidance systematic patterns, and those with large transfer areas do not necessarily show stable systematic patterns.

This paper uses the intensity analysis model to conduct an in-depth analysis of the conversion of land use types in the Aksu River Basin from 2000 to 2020 from three perspectives: time interval, land category, and transition level, combined with MOD16A2 data and correlation analysis methods to explore the impact on basin ET. The surface evapotranspiration process is extremely complex and affected by sensors, clouds, etc. Using MOD16A2 data for basin evapotranspiration analysis may have certain biases. Future research will link land use change with natural and socio-economic factors to explore the driving mechanisms of land use change. Meanwhile, multi-source data and various evapotranspiration estimation methods will be integrated to improve evapotranspiration estimation accuracy, and combined with climate and human activity factors to explore the influencing factors of actual evapotranspiration change in the basin.

4. Conclusions

Based on the intensity analysis framework, this paper systematically analyzed the land use change process and pattern in the Aksu River Basin from 2000 to 2020, revealing the intensity change characteristics of land use types at different levels and their impact on basin actual evapotranspiration. The main conclusions are as follows:

(1) At the time interval level, the intensity of land use change in the Aksu River Basin from 2000 to 2020 first increased and then decreased, with the most active change intensity from 2000 to 2005. At the land category level, the increase and decrease of cultivated land, construction land, water area, and forest land area were relatively active, while grassland and unused land changes were relatively stable. At the transition level, the increase in cultivated land area mainly came from grassland (accounting for 54.31%) and unused land (accounting for 26.26%).

(2) The multi-year average evapotranspiration of the basin is 166.56 mm, with large interannual fluctuations and an overall increasing trend at a rate of 3.68 $\mathrm{mm \cdot a^{-1}}$. Evapotranspiration from April to October accounts for 71.76% of the annual evapotranspiration. Evapotranspiration shows significant spatial distribution differences, with high ET values mainly distributed in mountainous forest land and plain cultivated land, and low ET values mainly distributed in piedmont desert areas and oasis-desert transition zones.

(3) Principal component analysis results show that the driving forces of ET change in the Aksu River Basin are the conversion intensities of grassland, cultivated land, and unused land. According to the principal component load values of driving factors, except for cultivated land and water area, other driving factors have correlations higher than 0.7 with the first principal component, with grassland and unused land having the highest cor-

relations. The factors closely related to the second principal component are cultivated land and construction land. There is a strong correlation between land use change intensity and actual evapotranspiration, with a correlation coefficient of 0.87.

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