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Analysis of land cover change and its driving forces in a desert oasis landscape of southern Xinjiang, China

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Abstract

The combined effects of drought, warming and the changes in land cover have caused severe land degradation for several decades in the extremely arid desert oases of Southern Xinjiang, Northwest China. This study examined land cover changes during 1990–2008 to characterize and quantify the transformations in the typical oasis of Hotan. Land cover classifications of these images were performed based on the supervised classification scheme integrated with conventional vegetation and soil indexes. Change-detection techniques in remote sensing (RS) and a geographic information system (GIS) were applied to quantify temporal and spatial dynamics of land cover changes. The overall accuracies, Kappa coefficients, and average annual increase rate or decrease rate of land cover classes were calculated to assess classification results and changing rate of land cover. The analysis revealed that major trends of the land cover changes were the notable growth of the oasis and the reduction of the desert–oasis ecotone, which led to accelerated soil salinization and plant deterioration within the oasis. These changes were mainly attributed to the intensified human activities. The results indicated that the newly created agricultural land along the margins of the Hotan oasis could result in more potential areas of land degradation. If no effective measures are taken against the deterioration of the oasis environment, soil erosion caused by land cover change may proceed. The trend of desert moving further inward and the shrinking of the ecotone may lead to potential risks to the eco-environment of the Hotan oasis over the next decades.

1 Introduction

Land use and land cover changes are among the most important human-induced alterations of the Earth's land surface (Dickenson, 1995; Lambin et al., 2000). The change of land use and land cover is not only closely related to the ecosystem services but also has influences on the climate, biodiversity and evolution of the ecological envi-

SED
6, 1907–1947, 2014

ronment (Kalluri, 2002; Wang et al., 2006; Qi et al., 2007). In arid environments, soils suffer from high erosion rates due to wind, drought, sparse vegetation cover and the pressure of human activities (Lambin et al., 2001; Ziadat and Taimeh, 2013). In these environments, soil loss and vegetation deterioration has increasingly been accelerated by improper use of land and water resources (Geist and Lambin, 2002; Ma et al., 2002; Lei et al., 2006; Wei et al., 2008; Zhao et al., 2013). The conversion of natural vegetation to cropland and overgrazing will therefore affect the storage of soil organic matter and soil nutrients (Li et al., 2005; Yu et al., 2012; Bruun et al., 2013). During the last few decades, land degradation associated with land use/cover changes in dryland ecosystems have been the focus of the study of land/vegetation processes and climatic change (Reid et al., 2000; Masoud and Koike, 2006; Reynolds et al., 2007; John et al., 2009; Bakr et al., 2010; Tsegaye et al., 2010; Schulz et al., 2010).

China is one of the countries most severely impacted by desertification (approximately encompasses 34.6 % of the total land territory), among which the desertified land located in the intrazonal landscape oases surrounded by deserts accounts for a significant proportion of the arid and semi-arid regions in China (Zhang et al., 2003; Wang et al., 2012). The desertification in these areas is mainly caused by wind erosion, water erosion, soil salinization and degradation by human factors. The oases located in the Xinjiang Uyghur Autonomous Region of northwest China, as the areas experiencing severe drought and sandy desertification, have undergone remarkable changes in land cover with increasing human activities over the last decades, largely reflecting the general trend of oasis expansion into the transitional zone between oasis and desert (Hu et al., 2001; Dittrich et al., 2010). Under the disturbance of the arid climate and improper human intervention, the desert–oasis ecotone, being the most sensitive area to change (Neilson, 1993), has encountered vital depletion of natural vegetation in the process of both oasification and desertification (Han and Meng, 1999; Wang et al., 2006; Li and Tiyip, 2008). The stability of oasis ecosystems is affected by both desertification in the oases-desert ecotone and salinization in the interior of the oasis (Hamid et al., 2002). These changes have led to drought, desertification and, consequently, have hindered the development of sustainable agriculture, resulting in an urgent need to understand the oasis–desert interaction and processes (Liu et al., 2007). Despite various attempts to rehabilitate the degraded land and ensure the ecological balance of the oases, the sandy desertification and salinization of the land are the most serious environmental problems occurring widely in these rangelands (Jia et al., 2004; Yang et al., 2005; Zhou et al., 2010), thus threatening the stability and sustainable development of the entire region.

Previous studies on the land use/cover changes of oases in Xinjiang have mainly focused on farmland expansion, land use change, vegetation cover, soil properties, land desertification as well as their environmental impacts (Li et al., 2004; Wang, 2004; Cheng et al., 2006; Tang et al., 2007; Wang et al., 2009; Luo et al., 2010; Liu et al., 2010), including the description of severe reductions of desert–oasis ecotons due to desertification and the loss of natural vegetation (Ding et al., 2006; Sun et al., 2007). These studies have generally described the processes and trends of land use/cover changes in desert oasis landscapes. However, they have not provided detailed information on quantitative changes of land cover temporally and spatially, and few attempts have been made to identify changing patterns and trajectories of ecotones between oases and deserts. There has been little research acknowledge the ecological importance of the desert–oasis ecotones and the significance of links between the mechanism of special zones and the environmental evolution of oases. The ethnic eco-cultural aspects of local farmers driving land cover changes in these regions are also mostly neglected. It is therefore necessary to determine the magnitude of land cover changes and examine the causes of such changes in these regions. This would allow us to identify how humans have changed land cover and the ways oases, deserts and ecotones interact under the current climate and human forces. To better interpret the temporal and spatial patterns of land cover change in desert oasis landscapes, the oasis of the Hotan river basin at the fringe of the Taklimakan desert in southern Xinjiang was selected as a case study. This area represents a typical irrigation and agriculture oasis in extreme arid regions of northwest China.

To gain a systematic understanding of the processes of land cover changes in the study area, an integrated method of remote sensing (RS) with a geographic information system (GIS) was used. The main benefit of this method is to enable researchers and resource managers to obtain reliable and up-to-date information for policy and decision making by analyzing and monitoring the complex environment (Alphan, 2012). The method includes supervised classification and post-classification comparison techniques in RS, and GIS spatial analysis, which have been widely used to clarify the magnitude, location and patterns of land cover changes (Lambin et al., 2003; Coppin et al., 2004; Lu, 2004; Serra et al., 2008).

The main purposes of this study are as follows: (1) to detect land cover changes in the Hotan oasis during 1990–2008 using remote sensing image analysis and geospatial techniques, (2) to evaluate the temporal and spatial patterns of land cover changes associated with the dynamics of the desert–oasis ecotone, (3) to identify the rates, drivers and consequences of such changes within the study area. This study can help to understand land cover dynamics and human-environment interactions in desert oasis landscapes, which is crucial for land managers to establish long-term soil conservation and restoration practices.

2 Materials and methods

2.1 Study area and data

2.1.1 Study area

Hotan oasis, which includes three counties and one city, is located in the Hotan river basin at the south of the Tarim river in southern Xinjiang between latitudes 36°52′–38°02′ N and longitudes 79°26′–80°35′ E. It is an extreme arid area characterized by the alluvial plain interleaved by the Gobi desert in the middle. The exceptions are the Taklimakan desert, which dominates in the north, and the Kunlun Mountains bordered

SED
6, 1907–1947, 2014

by Tibet in the south, where droughts, sandstorms and salt-alkalization are severe, as well as the utilization of soil and water is very low. The Hotan river, including the Yorungkash and Karakash rivers, crosses the oasis and winds its way through the Taklimakan Desert for 319.0 km before flowing into the Tarim river (Fig. 1).

The Hotan oasis falls within the category of a continental warm temperate monsoon climate with distinct seasons. The average annual temperature is between 10 °C and 20 °C, and the annual average precipitation is 13.1–48.2 mm; however, the potential evapotranspiration is 2159–3137 mm. The major soils support crops and forests in the Hotan River Basin are fluvisols, gleysols, solonchaks, arenosols, and anthrosols (FAO, 2006). Sand and dust storms are very common in the region during the spring and summer, which greatly influence the vegetation photosynthesis and growth. The natural vegetation is mainly distributed in the desert–oasis ecotone, which can be seen as part of the oasis, and is characterized by low diversity, sparse cover, and dominance by perennial species, such as *Populus euphratica*, *Tamarix ramosissima*, *Alhagi sparsifolia* and *Phragmites australis*.

2.1.2 Data

The data used to extract land cover information in this study consisted of three available Landsat TM, ETM cloud-free images acquired on 5 October 1990, 24 October 2000 and 28 September 2008, with 28.5 m × 28.5 m and 30 m × 30 m spatial resolutions (path/row 146/34), respectively. A topographic map and a land use map at a scale of 1 : 50 000 produced in 1990 with positional accuracy of ±2.5 m and ±5.6 m, respectively, were used as reference data to assist accuracy assessment for the classification of 1990 image. For 2000 image classification assessment, a multispectral 4 m resolution IKONOS image acquired in September 2000, which covered the whole study area, was used as reference data. High spatial resolution imagery (QuickBird operated by DigitalGlobe) in Google Earth (GE) at 0.6 m resolution was used as visual interpretation tool for classification and validation of land cover imagery in 2008. Images of vegetation and soil indexes were also derived from three Landsat images and used as reference data. In addition, socio-economic data and hydro-climatic data were used to better explain the driving forces of land cover changes in the study area.

2.2 Methods

2.2.1 Data pre-processing

The pre-processing of each Landsat image was image enhancement, geo-registration, radiometric correction using ENVI 4.7 image processing software. Each Landsat image was enhanced using linear contrast stretching and histogram equalization to better identify ground control points in geo-registration. The multi-dated images were geo-referenced to a common Universal Transverse Mercator coordinate system (UTM/WGS84, Zone 44) based on high resolution IKONOS image and the 1 : 50 000 scale topographic map with 26 ground control points (GCPs). The resultant root mean square error (RMSE) of rectification was less than half a pixel (15 m). To make the classified land cover images comparable, the Landsat images were re-sampled to a pixel size of 30 m × 30 m using the nearest neighbor method. Radiometric correction (Chen et al., 2005) was then implemented on these images to reduce the influences of errors due to sensor differences, Earth–Sun distance, solar zenith angle and atmospheric condition, which are important in multi-temporal analysis of vegetation indexes.

Radiometric correction was performed by two-step process. Firstly, the 8-bit digital numbers (DN) of sensor measurements were converted to spectral radiance measured by satellite sensors using Eq. (1):

$$L_\lambda = \mathrm{DN} \times \mathrm{Gain} + \mathrm{Bias} \tag{1}$$

where L_λ is spectral radiance ($\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}}$) measured over spectral bandwidth of a channel; DN is digital number value recorded; Gain is band specific gain, and Bias is band specific bias values ($\mathrm{m^2\,sr\,\mu m\,W^{-1}}$). DN values of Landsat-7 images were converted to spectral radiance using Eq. (2):

$$L_\lambda = ((\mathrm{LMAX}_\lambda - \mathrm{LMIN}_\lambda)/(\mathrm{DNMAX} - \mathrm{DNMIN})) \times (\mathrm{DN} - \mathrm{DNMIN}) + \mathrm{LMIN}_\lambda \tag{2}$$

SED
6, 1907–1947, 2014

where $LMAX_\lambda$ is band specific spectral radiance scaled to DNMAX ($W\,m^{-2}\,sr^{-1}\,\mu m^{-1}$), $LMIN_\lambda$ is band specific spectral radiance scaled to DNMIN ($W\,m^{-2}\,sr^{-1}\,\mu m^{-1}$), DNMAX is maximum quantized calibrated pixel value (typically = 255), and DNMIN is minimum quantized calibrated pixel value (typically = 1).

Secondly, the spectral radiance was converted into top of atmosphere (TOA) reflectance using Eq. (3):

$$R_\lambda = \pi \times L_\lambda \times d^2 / \mathrm{ESUN}_\lambda \times \cos\theta_s \tag{3}$$

where R_λ is unitless planetary reflectance or albedo; L_λ is spectral reflectance (calculated from the first step); d is Earth–Sun distance in astronomical units; ESUN_λ is mean solar exoatmospheric irradiances; θ_s is solar zenith angle in degrees. Calibration parameters can be obtained from the image header files and the Landsat Calibration page at the USGS.

2.2.2 Vegetation and soil indexes

To better discriminate different land cover types and minimize land cover classification errors, the normalized difference vegetation index (NDVI), the soil-adjusted vegetation index (SAVI) and the normalized difference salinity index (NDSI) were extracted from each geometrically and radiometrically corrected image and used as reference data. These indexes improve the accuracy of the land cover classification under the spatial heterogeneity of vegetation and soil properties.

NDVI (Rouse et al., 1973) is the ratio between near infrared and red reflectance (Eq. 4) and provides an indication of vegetation growth to estimate the amount or cover of vegetation (Shippert et al., 1995; Masek et al., 2000). It was calculated as:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}} \tag{4}$$

SAVI (Huete, 1988; Stefanov et al., 2001) was developed as a modification of the normalized difference vegetation index to correct for the influence of soil brightness when

SED
6, 1907–1947, 2014

vegetative cover is low. SAVI can be created from Landsat TM and ETM images using the following band combination:

$$\mathrm{SAVI} = \left(\frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red} + 1}\right) \cdot (1 + L) \tag{5}$$

L is a constant (generally set at 0.5) used to compensate for the high soil reflectance values observed in desert areas with sparse vegetation.

NDSI (Khan et al., 2005), shown in the form of Eq. (6), is another effective method for extracting salinized soil information (salt affected areas) in degraded lands that are mostly distributed in the arid ecotones.

$$\mathrm{NDSI} = \frac{\mathrm{Red} - \mathrm{NIR}}{\mathrm{Red} + \mathrm{NIR}} \tag{6}$$

2.2.3 Land cover classification

In this study, supervised classification method using the maximum likelihood classifier (MLC) (Richards and Jia, 1999), which is based on the probability that a pixel belongs to a particular class, was adopted to classify the individual Landsat images. MLC takes the variability of classes into account by using the covariance matrix. Therefore, it requires sufficient number of representative training samples for each class to accurately estimate the mean vector and covariance matrix needed by the classification algorithm (Hubert-Moy et al., 2001; Chen et al., 2004). A total of 200 training sample plots with at least 15 plots for each training class were randomly selected. The training sample dataset were collected based on visual interpretation on the false-color composite (bands 4, 3, and 2), and vegetation and soil index of each Landsat image by means of on-screen selection of polygonal training data method to cover the whole study area. These training samples were used to create spectral signatures of the selected land cover classes to efficiently implement decision rules in the supervised classification scheme. Training sets initially represented seven specific land cover classes, which namely are agricultural land, forest, high-coverage grassland, medium-coverage grassland, low-coverage grassland, built up area, water and desert.

After a preliminary classification, some land cover types were merged into one major land cover category to minimize misclassification and mainly analyze alternative changes between the major landscape types (oasis, desert and ecotone). Consequently, the final classification results included four main categories of land cover: "Oasis", "Ecotone", "Desert" and "Water", which simplified the classification procedure. Oasis was described as the major area where human activities concentrated, including agricultural land, forest, high-coverage grassland, medium-coverage grassland and built up area. Ecotone was defined as the transitional zone between oasis and desert where low-coverage grassland dominated. Description of major land cover types in this classification, as well as the initial land cover classes grouped into which were described in Table 1.

The post-classification modification was applied to improve the accuracy of the classification, so that the misclassified pixels were corrected to their true classes. The isolated pixels that occurred at the class boundaries due to spectral mixing were removed based on their surroundings using a majority filter (3×3 pixel window).

2.2.4 Accuracy assessment

Accuracy assessment is often required for evaluating the quality of land cover classification results derived from remotely sensed data by means of confusion matrix (Congalton and Green, 1993). Validations of the 1990 TM, 2000 ETM+ and 2008 ETM+ land cover maps were accomplished based on a stratified random sample of 291, 245 and 166 independent points, which were distributed on the whole study area. For the 1990 land cover map, the digitized and geo-referenced topographic map and land use map in 1990 used to identify ground verification points. IKONOS image in 2000 and high-resolution imagery (QuickBird) obtained from Google Earth in 2008 were used as reference data to assist accuracy assessment of land cover classifications for 2000 and 2008 ETM+ images, respectively. Producer's accuracy (a measure of omission error) and user's accuracy (a measure of commission error) for each class, as well as overall accuracy and Cohen's Kappa coefficient were calculated for each classification.

2.2.5 Detection of land cover change

A post-classification comparison approach was employed to detect the nature, rate and location of changes between 1990–2000 and 2000–2008 within the study area. The GIS overlay operation was carried out using ArcGIS 9.3 software to obtain conversions between the land cover types. The overlay analysis describes the spatial distribution and attributes of changes in land cover during the different study periods. The cross-tabulated matrices between classifications were generated to quantify the conversions from a particular land cover type to other land cover categories and the corresponding changes in area were calculated as proposed by Pontius et al. (2004). The change occurrence map of land cover types and the temporal trajectories of land cover changes were generated based on the three resulting maps in 1990, 2000 and 2008. The change occurrence map could help better identify areas with high probabilities of change and the human impacts causing such changes within whole study period (Zhou et al., 2008). The temporal trajectories of changes among land cover types not only reflect the patterns of land cover types but also help deliver the developing trend of the changes.

The annual change rate and average annual transition probabilities of each land cover class were calculated to interpret and assess the land cover change processes.

The annual rate of change for each land cover class was calculated as (FAO, 1995):

$$r = (A_2/A_1)^{1/(t_2-t_1)} - 1 \quad (7)$$

where r is the annual change rate, and A_2 and A_1 are the land cover class areas at time t_2 and t_1, respectively.

The average annual transition probabilities (Mertens and Lambin, 2000) between the ecotone and the other land cover types were computed as:

$$p_{ij} = \frac{a_{ij}}{N} \Big/ \sum_j a_{ij} \quad (8)$$

where a_{ij} is the area of land cover i at the initial period that was converted to land cover j at the subsequent period, and N is the number of years of the observed study period.

3 Results

3.1 Land cover classification

For each date, four main land cover classes (oasis, ecotone, desert and water) were examined in the Hotan oasis of arid desert landscape of northwest China. The use of NDVI, SAVI and NDSI data derived from spectral images significantly improved the classification accuracy for the present data set compared to using spectral data (TM or ETM) only. The land cover classification results and the percentage of land cover class areas for the 1990, 2000 and 2008 images are shown in Fig. 2. Overall accuracies for the three set of classified images were 95.99, 95.96, 98.65, while Kappa coefficients were 92.36, 94.17, 97.83, respectively (shown in Table 2), which meet the demand for land cover change detection in this study. The classification results show that desert was the dominant land cover type within the study area over the whole study period. The next dominant land cover type was the oasis surrounded by sparsely vegetated ecotone and deserts. It can be found that a large area of sandy desert covered more than 60 %, while the oasis, ecotone and water only covered more than 30 % of the total area. Table 5 shows the quantitative results of the land cover classification, and explains the area coverage for each land cover class by hectare (ha) across the three dates.

SED
6, 1907–1947, 2014

3.2 Land cover change

Tables 3 and 4 show the cross-tabulation matrix for the areas changed from one land cover class to another and their percentage comparison to total area during 1990–2000 and 2000–2008. The results show that all land cover types changed during the whole study period. Overall, desert declined at an annual rate of −0.2 %, from 65.8 % of the study area in 1990 to 63.48 % in 2008. Desert–oasis ecotone showed the largest decline in relation to its area, with only about 68 % of its extent in 1990 remaining in 2008, and an annual decline of −2.11 %. The amount of water areas declined slightly at an annual rate of −0.24 %, with around 95.7 % of the 1990 extent remaining in 2008. However, oasis experienced an overall expansion during 1990–2008, which increased annually by 1.7 % and expanded to 135 % of the area occupied in 1990. The ecotone and desert mainly contributed to the extended oasis, forming an artificial oasis. Figure 3 shows the spatial distribution of thematic land cover changes for the two different periods.

Between 1990 and 2000, the oasis and desert had significant gains, while the desert–oasis ecotone and water experienced strong losses. However, the oasis and water areas spread sharply from 2000 to 2008, while there was shrinkage in the areas of ecotone and desert. In the first period, about 2.8 % of the oasis was converted to ecotone while about 14 % of ecotone was developed to oasis. In addition, around 25 % of ecotone was transformed to desert mainly due to being desertified by wind erosion, water deficiency and overgrazing. There was shrinkage in the water area from 1990 to 2000 mainly by changing (about 29.8 % and 15.5 % of its area) to oasis and desert, respectively. During the period of 1990–2000, areas of no-change represented about 90.7 %, and the changed area represented 9.3 %. During 2000–2008, about 5.4 % of the oasis was changed to water due to construction of artificial reservoirs and ponds. Significant changes also occurred in ecotone, and 44.9 % of its area was converted to oasis. During the same period, a total of 6.2 % of desert area was altered to ecotone due to land reclamation practices in the desert regions. About 17.9 % and 12.8 % of

SED
6, 1907–1947, 2014

water areas were altered to oasis and desert although it showed increase in this period. Thus, from 2000 to 2008 the unchanged and changed areas represented 87.2 % and 12.8 %, respectively.

Land cover changes did not occur at equal rates during the two time intervals. Between 1990 and 2000, ecotone experienced a strong loss at annual rate of −2.93 %. This annual rate declined to −1.13 % for the 2000–2008 period. Overall, ecotone losses during the two study periods were offset by about one third by ecotone gains. During the period of highest ecotone loss (1990–2000), oasis and desert cover increased at annual rate of 0.34 % and 1 %, respectively. However, the desert decreased at annual rate of −0.87 % from 2000 to 2008, while oasis continued increasing at an annual rate of 2.51 %. The area of water decreased at annual rate of −3.2 % during the 1990–2000 period, but increased at annual rate of 3.46 % during the 2000–2008 period. Thus, the total changes occurred in water areas coincided with the trends of increasing water demands for the oasis expansion.

3.3 Land cover change patterns

From Table 6 it can be shown that the ecotone continued to shrink throughout the two study periods. The average annual transition probability from ecotone to oasis increased by 6.72 % while the annual transition probability from desert to ecotone increased by 5.81 % between the two study periods due to the accelerated oasification process and desertified land reclamation in the desert–oasis ecotone. Thus, the ecotone loss was partly offset by the newly developed grasslands and forests along the outer edges of the ecotone.

The spatial distribution of the intensity of land cover changes is shown in Fig. 4, in which the change frequency among the land cover types indicated the areas where human activities are more intense. It was found that 12.97 % of the study area was subject to only one change, 3.76 % was subject to two changes, and 83.27 % remained unchanged during the entire study period. The land cover changes mostly have occurred at the fringe of the oasis in the northwest and northeast, and in the north along the Yorungkash and Karakash rivers, as these areas were clear priorities for urban and agricultural developments. The temporal trajectory of land cover changes explained the patterns and trends of land cover changes in the Hotan oasis (Fig. 5). It can be found that the major contributions to net change were the conversion of ecotone to oasis and desert during 1990–2000, while the major changes were the conversions of ecotone to oasis and desert to ecotone between 2000 and 2008.

4 Discussion

In spite of the methodological challenges related to image data quality and subtle nature of the land cover change, it proved possible to estimate the area of land cover classes and their rate of change in the typical arid desert oasis landscape of Hotan in northwest China. In this study, visual interpretation, land cover classification and change detection of multi-temporal images was shown to provide a practical way for mapping and quantifying land cover dynamics in the Hotan oasis. In contrast to former land cover change research in northwest China, this study put particular emphasis on the dynamics of desert–oasis ecotone.

The radiometric rectification nearly eliminated the effects of varying atmospheric conditions on multi-date images. Incorporation of vegetation and soil indexes into the classification process showed positive effects on the classification of land cover types with different surface vegetation covers, indicating strong interdependences between these indexes and land cover. Combination of some initial land cover types (agricultural land, forest, high-coverage grassland, medium-coverage grassland and built-up area) within the oasis to observe the alternative changes and dynamics between the major land cover categories (oasis, ecotone and desert) greatly improved the accuracy of classification. It may yet be oversimplified to conduct categorical analysis on the complex dynamics inherent in the desert–oasis landscape, particularly for the human-disturbed landscape. However, such simplifications make it easier to understand human interactions with dryland oasis ecosystem, but also provide general trends in dynamics of

SED
6, 1907–1947, 2014

desert–oasis ecotone that are useful for arid oasis landscape planning and serve as a basis for analyzing drivers of land cover change.

Ground truth data were obtained from the existent topographic map, IKONOS image and high-resolution image from Google Earth for 1990, 2000 and 2008, respectively, to perform classifications of Landsat TM (ETM+) images. However, misinterpretation of land cover types may occur due to the uncertainty of the ground truth data. Further classification improvements can be made by collecting ground truth data by field investigations and historical ground-based photographs in the areas where are class boundaries, as these have proven to cause misclassification.

The results of land cover change in the Hotan oasis between 1990 and 2008 revealed a general trend of a continuous expansion in oasis and consistent loss in desert–oasis ecotone as a consequence of the conversions from ecotone to desert and intensive land uses (e.g., agricultural land) in the oasis. Due to the frequent gains and losses, desert–oasis ecotone is identified as the most dynamic and striking land cover type compared with other land cover types within the study area. The continuing oasification and land reclamation usually results with land abandonment due to deteriorating soil conditions, which aggravates the land degradation in the entire region. The frequent conversions between land cover types may lead to more soil salinization and further decline in soil fertility if no appropriate measures are taken to stop this process. From the overall land cover change patterns and dynamics it can be inferred that the oasis has expanded into ecotone while ecotone has extended into desert, resulting in gradually shifting of the desert–oasis ecotone into the adjacent desert. Under the pressure from the continuous expansion of artificial oases and human-caused habitat destruction, the general trends of vegetation dynamics in the ecotone exhibited potential uncertainty to the at-risk eco-environment of the Hotan oasis. Such uncertainty could result in the instability of the desert–oasis ecotone as well as over the oasis interior. Therefore, the changes in desert–oasis ecotone can be used as an indicator of land degradation in the arid oasis ecosystems due to its vulnerability to the effects of climatic variability and human activities. In order to effectively prevent land degradation/salinization within

SED
6, 1907–1947, 2014

the oasis, effective effort is needed toward the ecological security in the oasis and protection of natural vegetation in the desert–oasis ecotone.

5 Driving forces: implications for arid oasis landscape planning and management

5.1 Natural forces

The influence of climate variability on land cover changes seems to be important for the Hotan oasis' evolution. The observed hydrological and meteorological data showed that (Figs. 6 and 7) during the last few decades the mean annual temperature and precipitation in the Hotan oasis had an increasing trend, whereas the average annual runoff of the Hotan river showed decreasing tendency due to its main recharging source from glacial meltwater in the Kunlun mountains area. Glaciers account for 64.9 % and 54.1 % of the Yorungkash river and the Karakash river runoff, creating a potential flooding hazards in the study area. This may be the reason for the anti-correlation between precipitation and the Hotan river runoff. Above discussed seems to approve the fact that the climate of the Hotan oasis became warmer and wetter, which was favorable to vegetation growth and agricultural development. However, because of the high evaporation rate salt concentrates at the soil surface, easily leading to soil salinization. Moreover, flooding of Hotan river in 1994, 1999 and 2005 had serious damages on the soils and plants across the basin. Thus, the annual variations in hydro-climate reflected the urgency of environmental optimization and water management in the study area.

5.2 Human forces

Although the land use/cover changes and degradation of the oasis environment are driven by the combined impacts of climate and human factors, in the arid areas these changes are mainly resulted from human activities (Hao et al., 2008). Eco-environmental issues derived from population growth, economic policy, improper use of land and water resources, as well as various eco-cultural practices were mostly attributed to human forces. Therefore, it is important to understand how human activities influenced the land cover changes in this study.

5.2.1 Population growth

Population growth is the most important factor in the land cover changes of the Hotan oasis, creating increasing urbanization and agricultural intensification. The rapid migration of cultivators and herders into the marginal sites of the Hotan oasis resulted in rising population densities. In 1990, a total of 0.85 million people lived in the Hotan oasis; and in 2000 the population was 1.07 million. During the 10 years, population increased 0.22 million people with growth rate of 20.15 %. In 2008, the total population of the Hotan oasis reached up to 1.25 million. It increased 17.5 % compared with that in 1990, and the growth rate was 14.9 % (Fig. 8). Along with the increasing population, land utilization degree has increased. Accordingly, a significant proportion of grasslands and paddy fields in the study area have been lost for other uses (e.g., residential areas, fruit farming, and other traditional industries). Overexploitation of land resources and deforestation due to the need of growing population put severe pressure on the environment and resulted in high level of soil erosions, land desertification and salinization within the entire oasis.

5.2.2 Economic policy

The reform of economic structure and transition to the market economy played a significant role in land cover changes of the Hotan oasis. The economic growth based on the agricultural and industrial production accelerated since 1990. From Fig. 8 it can be found that the gross domestic product (GDP) of Hotan was only 683 million in 1990, which increased to 1812 million in 2000 and 4960 million in 2008 at an annual increasing rate of 16.5 % and 21.7 % during the two study periods. Under the market economy, a large proportion of non-agricultural land, especially desert–oasis ecotone has been

SED
6, 1907–1947, 2014

converted into farmland and built-up land, which is one of the major features of the land cover changes in the study area. The cultivated land in the Hotan oasis expanded from 50 000 ha in 1990 to 130 000 ha in 2000 with an annual increasing rate of 16 % with over-intensification of agriculture. Due to the rapid urbanization and industrialization, the built-up area within the oasis sharply expanded from 22 687 ha 1990 to 50 130 ha in 2008. Large areas of plantation of economic crops, such as cotton, were conducted in the region, which greatly influenced the actual water consumption and reallocated water resources by changing areas and structures of crop plantation. Thus, the volume of water consumption had a sharp increase in the Hotan oasis during the whole study period (Fig. 7). Consequently, the agricultural land, natural grassland and shrub land in the desert–oasis ecotone has been desertified because of its typical geographical conditions together with the excessive exploitation of surface water and groundwater. Responding to a wide range of land degradation, the "Conversion of Cropland to Forest and Grassland Program (CCFGP)" was initiated in 1999 in many dryland oases of the northwest China to minimize soil erosion and vegetation degradation, as well as to improve utilization of water resources. The program helped prevent the further expansion of farmland and helped rehabilitate degraded desert vegetation landscapes. The area of cultivated land was 175 000 ha in 2008 and the annual increasing rate decreased to 4.3 % during 2000–2008 (Fig. 7). Therefore, the stability of the internal oasis was promoted, and the pressure from water demand and the tensions among agriculture, forestry and animal husbandry activities was alleviated to a certain extent. However, the oasis area continued to extend into the ecotone plantation of shelter forests and grasses. Although the speed of desertification expansion has slowed down, the expanding trend remains unchanged. Hence, there is an urgent need to consider the fragility of the ecological environment under land development in the desert oasis due to the water scarcity and lack of watershed management.

5.2.3 Unsustainable land use

Unsustainable land use, such as overexploitation of surface and groundwater, overgrazing and firewood collection, was another driver for the land cover change in the Hotan oasis. The area of artificial reservoir increased from 9856 ha to 14 135 ha during 1990–2008 to provide water for human and livestock consumption as well as for supplementary irrigation in dry-season. The dramatic increase in the use of water from the reservoir in the oasis indicated that the level of the groundwater table and groundwater mineralization increased significantly, causing the higher rate of soil salinization. Consequently, the agricultural fields at marginal sites of the oasis were abandoned after several years of cultivation due to deteriorating soil condition. The livestock population of grazing animals were also far beyond the carrying capacity in the Hotan oasis, which increased from 1 737 200 to 2 573 200 during the whole study period (Fig. 8). The already fragile vegetation in the desert–oasis ecotone has been severely destroyed by overgrazing on the grasslands and cutting of *Populus*, *Tamarix* and shrubs for fuel wood, leading to the vegetation degradation around the oasis fringe. Due to the removal of the grasses and woody plants that protect soils from wind and water erosion, the Hotan river basin has experienced more frequent floods and sandy storms. Therefore, effective effort is needed toward the ecological security in the oasis and protection of natural vegetation in the desert–oasis ecotone.

5.2.4 Socio-cultural factors

Hotan was a crucial hub in the ancient Silk Road, where the combination of the community economy and the unique culture was prominent. Traditional agriculture, animal husbandry and various agro-forestry in the oasis, as the basis of subsistence, provided different goods and services. The cultural ecosystem services of aesthetics had a rising trend in the Hotan oasis (increased 4×10^8 Yuan ha^{-1}) during the period of 1990–2008. The economic activities centered on cultural industries, such as fruit farming and Uyghur medicine, improved the development of the economy in the oasis. However,

SED
6, 1907–1947, 2014

these resource-processing practices have influenced the decisions regarding land use and environmental change in the process of shifting toward the intensive irrigation agriculture in the study area. The traditional cultural beliefs and lack of education of rural farmers regarding land use regulations lead to misuse of the new agricultural technologies and management systems, which accelerated the loss or depletion of land, plant and water resources. Therefore, it is important to build an adaptive application policy of integrating the useful traditional practices into the new land use and water management systems with specific focus on raising awareness local communities concerning the urgency of desertification control in the Hotan river basin.

6 Conclusions

This study examined the spatial and temporal dynamics of land cover changes in the desert oasis landscape of the Hotan river basin during 1990–2008 using GIS, RS and ancillary data. Conventional vegetation and soil indexes were integrated to better distinguish heterogeneous classes and boundaries, especially the ecotone areas between the desert and oasis. The land cover change detection techniques were used to estimate the temporal and spatial changes of land cover types. Causes and consequences of these changes were analyzed in the light of from-to change information and the ancillary data. The analysis revealed that the oasis areas continuously increased, while the ecotone areas decreased during 1990–2008. The main pattern of land cover changes in the Hotan oasis was the exchanges between the oasis and ecotone and between the desert and ecotone. These changes were mainly caused by intensified human activities in the last few decades. Continued land cover change, coupled with soil salinization, has greatly affected people's livelihoods and put the crop production system under increasing threat. Therefore, it is necessary to investigate the complex dynamics in the oasis using more detailed analyses of the causes and processes of land cover changes. The results of the present study not only elucidate the changes in land cover and the impact on soil salinization in the arid desert oasis of Hotan, but also represent a lesson to be learned for integrated land management in similar ecotones in arid zones.

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SED
6, 1907–1947, 2014

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Table 1. Description of major land cover types defined in this study.

Classes name	Description
Oasis	Agricultural land, forest, high-coverage grassland with vegetation cover > 50 %, medium-coverage grassland with vegetation cover 20–50 % and urban or built-up area
Water	Lake, river, pond, reservoir and wetland
Ecotone	Transitional zone between the desert and oasis with 5–20 % of sparse or low vegetation cover
Desert	Saline and alkaline lands, sandy land and Gobi desert

SED
6, 1907–1947, 2014

Table 2. Accuracies of land cover classifications for 1990, 2000 and 2008 (units: %).

Land cover	1990		2000		2008	
type	PA	UA	PA	UA	PA	UA
Oasis	98.65	95.31	100.00	97.89	96.37	99.93
Ecotone	97.47	88.17	86.47	91.46	100.00	88.19
Desert	95.01	99.74	97.00	95.11	98.72	100.00
Water	97.75	85.00	98.00	99.38	99.93	100.00
	OA: 95.99,	OK: 92.36	OA: 95.96,	OK: 94.17	OA: 98.65,	OK: 97.83

OA: overall accuracy, OK: overall Kappa, PA: producer's accuracy, UA: user's accuracy.

SED
6, 1907–1947, 2014

Table 3. The conversion matrix of land cover change from 1990 to 2000.

		1990				
2000		Oasis	Ecotone	Desert	Water	Total (2000)
Oasis	(ha)	217 812	21 968	2064	14 197	256 041
	(%)	17.10	1.72	0.16	1.11	20.10
Ecotone	(ha)	6465	94 000	15 044	1125	116 634
	(%)	0.51	7.38	1.18	0.09	9.16
Desert	(ha)	1122	39031	819 045	7308	866 506
	(%)	0.09	3.06	64.30	0.57	68.03
Water	(ha)	6236	1393	1951	24 949	34 529
	(%)	0.49	0.11	0.15	1.96	2.71
Total (1990)	(ha)	231 635	156 392	838 104	47 579	1 273 710
	(%)	18.19	12.28	65.80	3.74	100.00

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SED

6, 1907–1947, 2014

Analysis of land cover change and its driving forces in a desert oasis landscape of China

T. Amuti and G. Luo

Table 4. The conversion matrix of land cover change from 2000 to 2008.

		2000				
2008		Oasis	Ecotone	Desert	Water	Total (2008)
Oasis	(ha)	240 703	52 438	13 744	6194	313 079
	(%)	18.90	4.12	1.08	0.49	24.58
Ecotone	(ha)	156	52 646	53 720	31	106 553
	(%)	0.01	4.13	4.22	0.00	8.37
Desert	(ha)	1223	9635	793 262	4415	808 535
	(%)	0.10	0.76	62.28	0.35	63.48
Water	(ha)	13 959	1915	5780	23 889	45 543
	(%)	1.10	0.15	0.45	1.88	3.58
Total (2000)	(ha)	256 041	116 634	866 506	34 529	1 273 710
	(%)	20.10	9.16	68.03	2.71	100.00

SED
6, 1907–1947, 2014

Table 5. Amounts of changes by land cover classification during 1990–2008 (ha).

Land cover types	1990	2000	2008	1990–2000	2000–2008	1990–2008
Oasis	231 635	256 041	313 079	+24 406	+57 038	+81 444
Ecotone	156 392	116 634	106 553	−39 758	−10 081	−49 839
Desert	838 104	866 506	808 535	+28 402	−57 971	−29 569
Water	47 579	34 529	45 543	−13 050	+11 014	−2036

SED
6, 1907–1947, 2014

Table 6. The average annual transition probabilities between ecotone and other land cover types (units: %).

	1990–2000			2000–2008		
	Oasis	Desert	Water	Oasis	Desert	Water
From ecotone to other land cover types	3.52	6.26	0.22	10.24	1.88	0.37
From other land cover types to ecotone	2.86	6.65	0.50	0.04	12.46	0.007

SED
6, 1907–1947, 2014

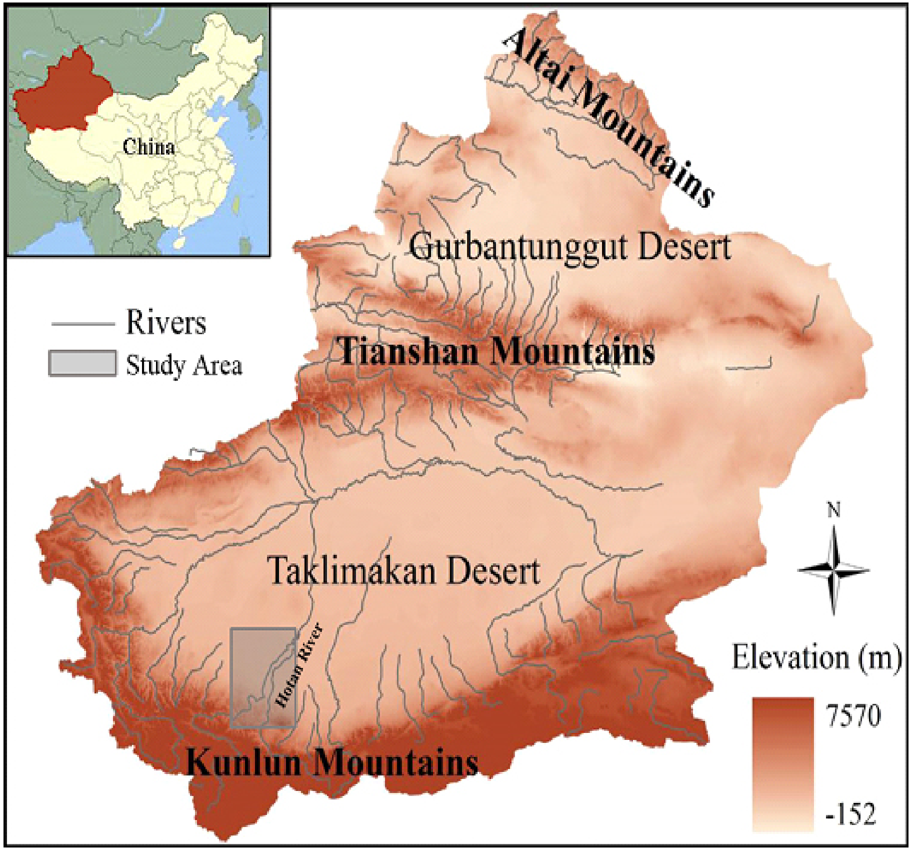

Figure 1. Sketch map of the study area.

SED
6, 1907–1947, 2014

Analysis of land cover change and its driving forces in a desert oasis landscape of China

T. Amuti and G. Luo

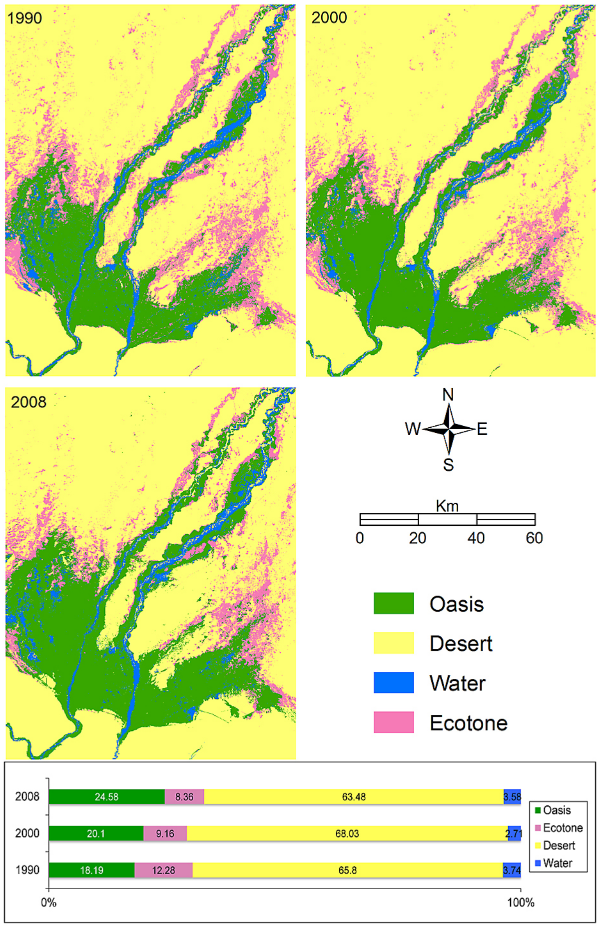

Figure 2. Land cover maps of the Hotan Oasis for the years 1990, 2000 and 2008 and the respective extents of land cover classes by percentage (study area = 1273710 ha).

SED
6, 1907–1947, 2014

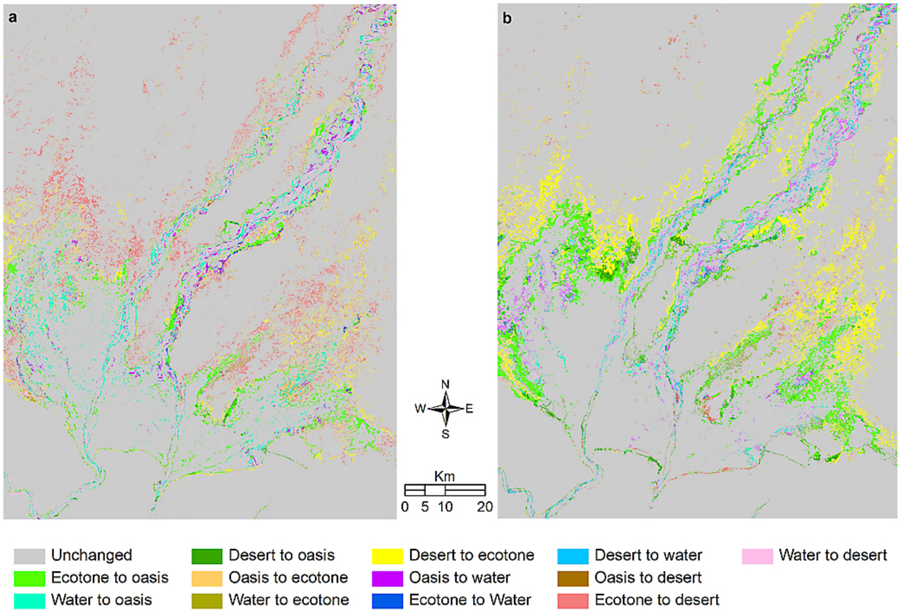

Figure 3. Land cover change maps of the Hotan Oasis: **(a)** 1990–2000 **(b)** 2000–2008.

SED
6, 1907–1947, 2014

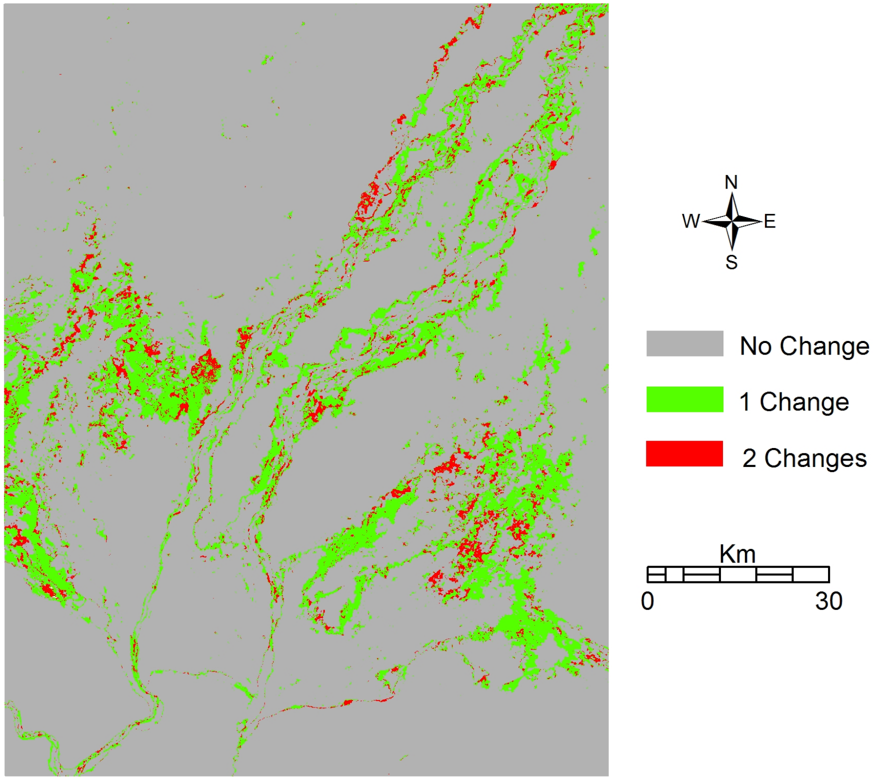

Figure 4. Distribution of areas showing change occurrence among land cover types across the two periods from 1990 to 2008.

SED
6, 1907–1947, 2014
Analysis of land cover change and its driving forces in a desert oasis landscape of China
T. Amuti and G. Luo

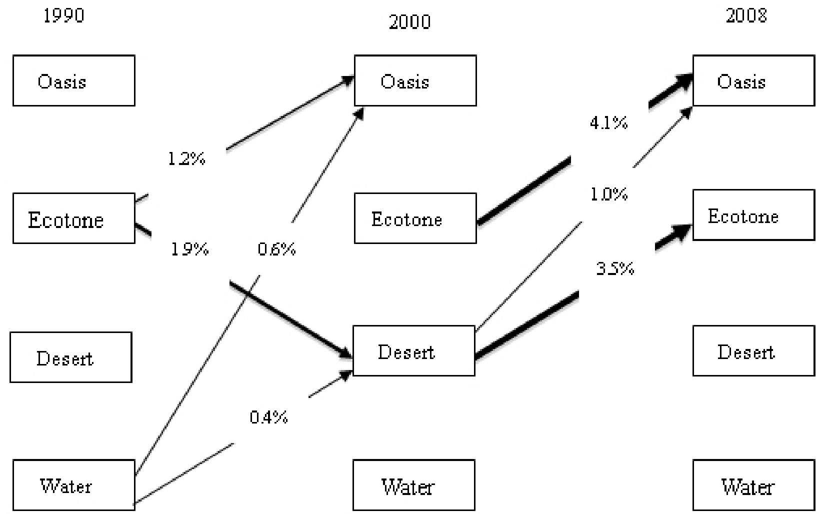

Figure 5. Major change trajectories and their contributions to net change in percentage of the study area (thick lines correspond to net change > 3.5 %, intermediate lines correspond to net changes between 1.8 % and 3.5 %, and thin lines correspond to net change < 1.8 %; only net contributions to change > 5000 ha or 0.4 % of the study area are represented).

SED
6, 1907–1947, 2014

Analysis of land cover change and its driving forces in a desert oasis landscape of China

T. Amuti and G. Luo

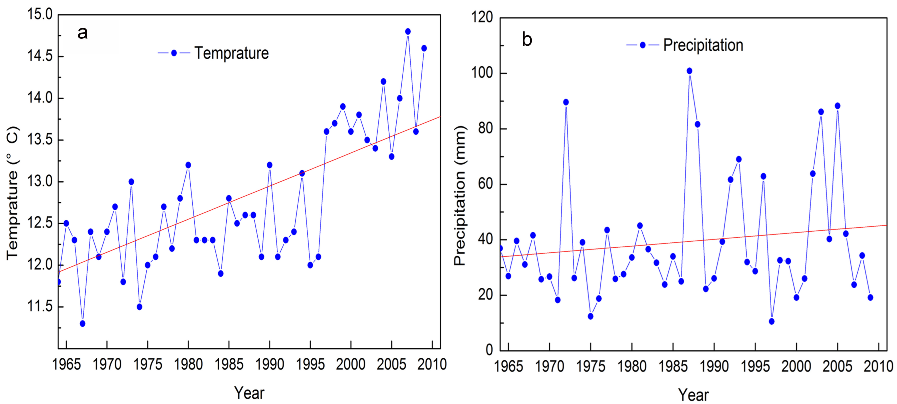

Figure 6. Average annual temperature **(a)** and precipitation **(b)** in the Hotan oasis.

SED
6, 1907–1947, 2014

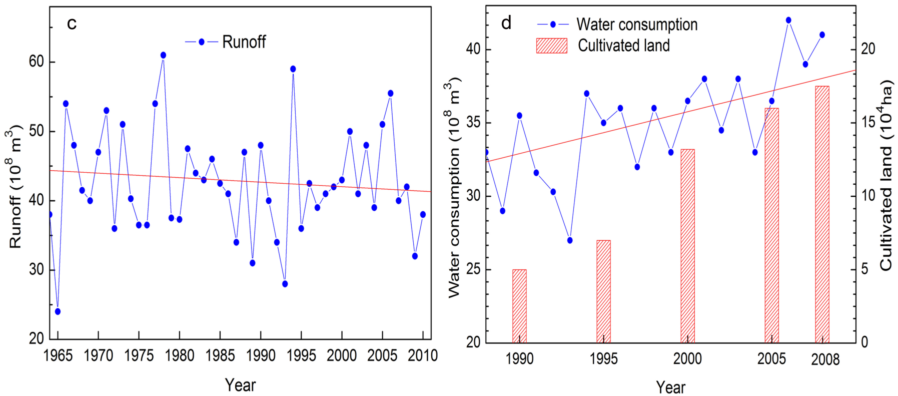

Figure 7. Runoff of Hotan river **(c)**, water consumption and area change of cultivated land in the Hotan oasis **(d)**.

SED
6, 1907–1947, 2014

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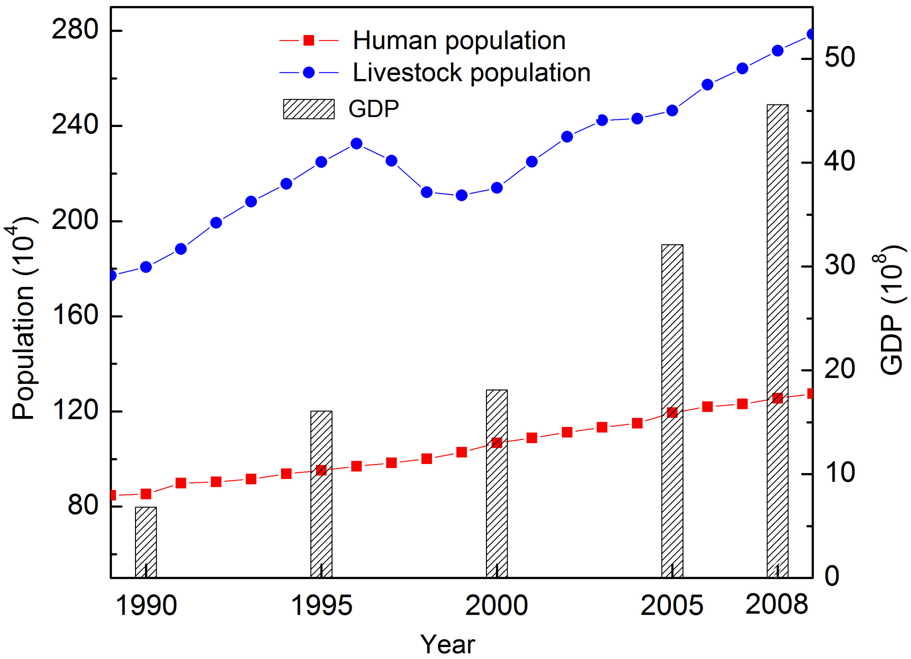

Figure 8. Population, livestock and GDP in the Hotan oasis.

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6, 1907–1947, 2014