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Author(s): Qiming Zhou, Baolin Li and Yumin Chen
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REPORT

Remote Sensing Change Detection and Process Analysis of Long-Term Land Use Change and Human Impacts

Qiming Zhou, Baolin Li, Yumin Chen

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Abstract This study investigates environmental change over a 30-year period and attempts to gain a better understanding of human impacts on an arid environment and their consequences for regional development. Multi-temporal remotely sensed imagery was acquired and integrated to establish the basis for change detection and process analysis. Land cover changes were investigated in two categories, namely categorical change using image classification and quantitative change using a vegetation index. The results show that human-induced land cover changes have been minor in this remote area. However, the pace of growth of human-induced change has been accelerating since the early 1990s. The analysis of the multi-temporal vegetation index also shows no overall trend of rangeland deterioration, although local change of vegetation cover caused by human activities was noticeable. The results suggest that the current trend of rapid growth may not be sustainable and that the implementation of effective counter-measures for environmentally sound development is a rather urgent matter.

Keywords Remote sensing · Land use change · Change detection · Human impact assessment · Arid zone

INTRODUCTION

Land use/land cover change is widely recognized as an important aspect of global environmental change, which plays a pivotal role in regional socio-economic development (Chen 2002). To ensure a sustainable management of natural resources, it is necessary to understand and quantify the processes of landscape change (Petit et al. 2001). It is also necessary to develop a better understanding of the causes of land use change so that efficient counter-measures can be undertaken.

In the vast area of China's arid zone, land use/land cover change has been identified as one important indicator for environmental changes that have taken place in the recent decades, as a result of rapidly increasing human impacts on the environment (Chen et al. 2009). The fast population and economic growth have had a great impact on the fragile ecosystem and have broken the delicate man–environment balance that was maintained in the past centuries (Zhou 1998).

Numerous research projects have been reported that deal with land cover change, accelerated environmental degradation, and significant human–environment conflicts (e.g., Xia and Dregne 1995; Wang 1996; Mao 1998; Jiao et al. 2000; Tian et al. 1999). Specific methodologies have also been developed to detect and model the land cover change in arid zones (e.g., Lambin and Ehrlich 1997; Zhou et al. 1998; Zhou and Robson 2001; Maldonado et al. 2002; Li and Zhou 2009b).

This study aims to analyze human impacts on the arid environment of China by detecting and modeling land use change using remotely sensed imagery over the past 30 years. The objective of this study is to clarify the land use change in the past 30 years and assess and model human impacts such as cultivation and dam construction on the environment.

MATERIALS AND METHODS

Study Area and Data

The study area is located in the west of Yuli County, Xinjiang Uygur Autonomous Region of China. The 64 km^2

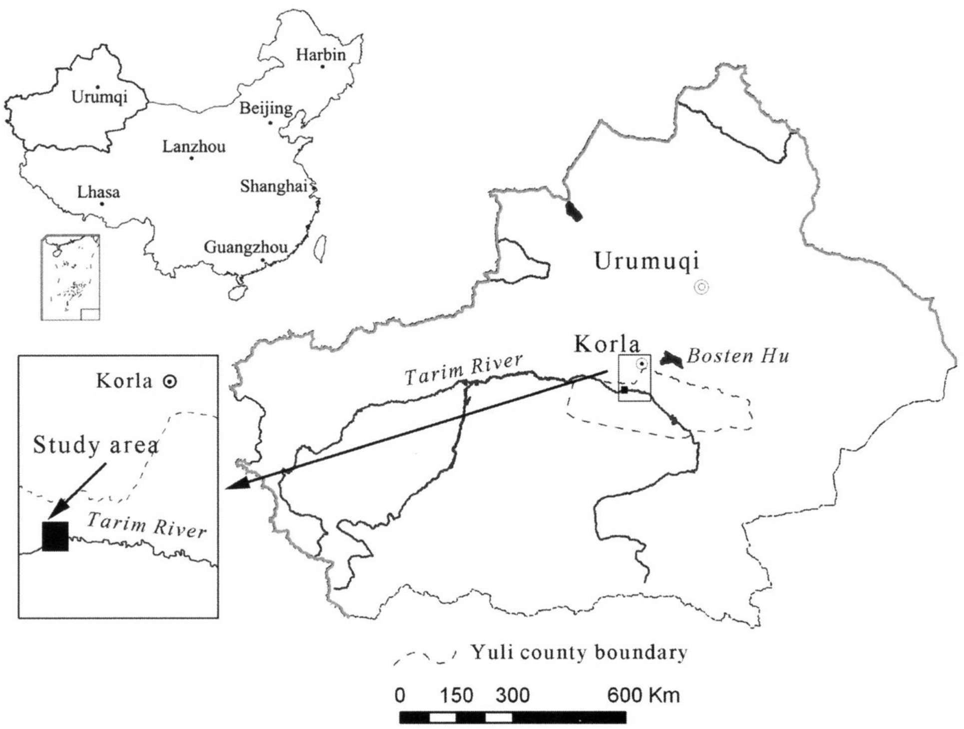

Fig. 1 Location of the study area

study area is centered at about 41°5′N and 85°43′E and located in the middle reach of the Tarim River, the longest inland river of China (Fig. 1). At the fringe of the Taklimakan Desert, the "green corridor" of the Tarim Basin is one of the most important habitation areas in the arid zone of China. The landscape is generally characterized as a dry and harsh environment, represented by typical desert vegetation and soils. The area is dominated by a floodplain with elevations ranging from 900 to 910 m.

Natural vegetation consists of trees, shrubs, and herbage. *Tree species* includes *Populus euphratica,* shrubs include *Tamarix spp*., *Nitraria sibirica,* and *Halimodendron halodendron* (*Tamarix ramosissima*, *Tamarix hispida*, and *Tamarix elongata* are dominant species), and herbage includes *Phragmites communis*, *Poacynum hendersonii*, *Alhagi sparisifolia*, *Glyzyrrhiza inflata,* and *Karelinia caspica*, etc. The main crop is cotton, which is planted in April and harvested at the end of September. With increasing land development in recent decades, the fragile environment has experienced quite remarkable change, largely reflecting the general development trend and temporal effects of government policies and administrative measures.

Five multi-temporal remotely sensed images were acquired for change detection in this study, namely, Landsat MSS (3/7/1973, 12/10/1976), TM (25/9/1994), ETM+ (17/9/2000), and SPOT HRV (20/7/1986) multispectral images. All five images were used for the analysis of categorical changes to establish the categorical change trajectories of land cover types, but only three of them (1973, 1986, and 2000) were used for the quantitative analysis of vegetation condition change to avoid potential systematic biases in computing vegetation indices. In addition, a multispectral 4 m resolution IKONOS image acquired in September 2000, which covered the whole study area, was also used to assist field investigation and accuracy assessment of image classification. The IKONOS data were registered to the geo-referenced aerial photo on the scale of 1:10,000. This geo-coded IKONOS image was then taken as the master and the other remote sensing data were rectified by image to image, with an average registration error of less than half a pixel. To make the classified land cover images comparable, the Landsat images were resampled to 20 m, which is the resolution common to all of the images, using the nearest neighbor method.

A reference data set of 790 sample points was obtained. We chose a stratified random sampling scheme based on a 2000 ETM+ classified image, which had the most detailed land cover pattern. We collected the reference data of 2000 ETM+ directly based on the 2000 IKONOS image and fieldwork. For the images acquired on the other four dates, we used the IKONOS image as the basis to locate sample points. Comparison was then made with satellite images acquired on other dates for each of the sample points. By this means, obvious land cover changes such as grasslands to water and bare ground to cropland could be reliably detected by image interpretation. Field visits and interviews of elderly locals were also conducted for sample points where a clear relationship between the present and historical images could not be established.

Land Use Change

In arid zones, land use change can be characterized as two kinds: categorical or quantitative changes, which can also be further classified as reversible or irreversible changes. Irreversible change means that land use features have changed into other types and generally cannot change back (e.g., dam construction causing grassland to be permanently flooded). Reversible change, on the other hand, means that the changes have not reached the "no return" stage so that the original status of the land cover can be restored (e.g., vegetative cover change due to weather conditions or seasonal flooding).

Categorical Change

For the analysis of categorical change, the approach of change trajectory analysis (Miller et al. 1998; Larsson 2002; Yang and Lo 2002, Zhang et al. 2002; Zhou et al. 2008a, b; Li and Zhou 2009a) was used. Supervised classification was employed to classify individual images independently, using a unified land cover classification scheme to ensure that the classifications of the multi-scale, multi-temporal images are compatible with each other. The land cover was grouped into five categories including cropland (mostly irrigated cotton fields with a full green vegetation cover in the summer), grass and woodland (mostly native pastures with a sparse vegetation cover typically less than 50%), salty grass (salt-tolerant vegetation types at the fringe of water bodies or abandoned croplands), bare ground (e.g. sand dunes), and water bodies. The classified images were then combined in a GIS to establish the categorical change trajectories, e.g., grass and woodland (1973), grass and woodland (1976), grass and woodland (1986), cropland (1995), and cropland (2000). The identified land use trajectories were then grouped into three generic categories, namely, unchanged, human-induced, and naturally changed (Zhou et al. 2008a). Under this classification system, we considered the human-induced change as irreversible. In contrast, the natural changes were considered reversible, i.e., the original status of the land cover can be restored when conditions permit.

The *unchanged* class indicated that the same land cover type was found on the sample point over the past 30 years. The *human-induced* change class included decisive changes due to human activities such as the building of a dam/reservoir and cultivation. Old cultivation indicated that land cover had changed to cropland prior to 1994 and has since remained as cropland. New cultivation indicated that land cover changed to cropland at some time between 1994 and 2000, and in 2000 remained as cropland. Reservoirs/ponds indicated that land cover changed to and remained as water bodies since 1986. These changes were often irreversible so that they represent the major human impact on the environment. The *natural* change class included those indecisive changes due to the natural processes or minor human activities such as light grazing. For example, grassland may be flooded during summer and subsequently dried out as salty grassland because of strong evapotranspiration. Grass/woodland indicated that land cover changed periodically between grass/woodland and salty grassland. The flooded category indicated that land cover had changed periodically between water and other land cover types. Bare ground indicated that land cover changed periodically between bare ground and other land cover types.

Quantitative Change

Quantitative change evaluated the conditions of vegetation that resulted from temporary natural factors and that allowed the original status to be restored. Naturally, the irreversible changes (i.e., the human-induced change category as specified above) were excluded from this quantitative change analysis. The Normalized Difference Vegetation Index (NDVI) was used to compare and analyze the quantitative change of vegetation. NDVI is sensitive to the presence, density, and condition of vegetation and was correlated with absorbed Photosynthetically Active Radiation (PAR) and vegetation primary production (Herrmann et al. 2005). In spite of the impact of the vegetation phenology, the moisture conditions, the sun zenith angle or sensor view angle, and the differing wavelengths of different sensors, NDVI was well suited to the study of vegetation greenness in arid zones (Olsson et al. 2005).

In this study, to avoid uncontrollable systematic bias in computing NDVI, only three of the five available images (1973, 1986, and 2000) were used because they were all acquired in the summer season without substantial temporary effects (such as flooding). The 1976 image was excluded because of its late acquisition date (in the autumn when the vegetation phenology significantly varied from that in the summer) and the 1994 image was not used due to the extensive cover of flood water.

(1) Normalization of Remote Sensing Data

In order to make a quantitative comparison between digital images, radiometric normalization was undertaken to eliminate the radiometric and atmospheric effects on the images. Two approaches to radiometric correction are possible, namely, absolute and relative methods. The absolute approach requires the use of ground measurements at the time of data acquisition for atmospheric correction and sensor calibration. This is not only costly but also impractical when archival satellite image data are used for change analysis (Hall et al. 1991). The relative approach (Yang and Lo 2000), which does not require simultaneous ground data acquisition, is therefore, preferred. Various methods are available for the relative approach to radiometric normalization (RRN), such as robust regression (Olsson 1993) or the use of invariant target sets (Eckhardt et al. 1990; Jensen et al. 1995; Michener and Houhoulis 1997), pseudo-invariant features (Schott et al. 1988; Henebry and Su 1993; Yang and Lo 2000), or a Radiometric Control Set (RCS) (Hall et al. 1991).

In this study, the RCS method was used. Two sets of extreme features with nearly invariant reflectivity and identifiable on both image scenes were collected as targets, which should be independent from seasonal or biological cycles (Schott et al. 1988; Hall et al. 1991). The water body and bare ground were selected to represent the dark and bright control sets, respectively. The mean of the pixel digital numbers (DNs) was then derived for each of the normalization spectral bands to derive parameters used in linear regression as:

$$Y_k' = m_k X_k + b_k \tag{1}$$

where X_k was the DN of band k in image X on subject image, Y_k' is the DN of band k on normalized image, m_k is the slope and b_k is the intercept. The parameters m_k, b_k could be calculated as:

$$m_k = \frac{B_{rk} - D_{rk}}{B_{sk} - D_{sk}}, \text{ and } b_k = \frac{D_{rk}B_{sk} - D_{sk}B_{rk}}{B_{sk} - D_{sk}}$$

where B_{rk} was the mean DN for the bright control set of the reference images, B_{sk} was the mean DN for the bright control set of the subject image, D_{rk} was the mean DN for the dark control set of the reference image, D_{sk} was the mean DN for the dark control set of the subject image, and k is the band number.

The control sets were determined by intersecting post classification images instead of the Kauth–Thomas (KT) scattergram isolation method that was used by Hall et al. (1991). All five epoch images were classified using ISODATA with 15 classes and 500 iterations. After labeling the bare ground and deep water and intersecting the five epoch images, the common area of target samples of water and bare sand were 300 and 5,452 pixels, respectively. The SPOT HRV image of 1986, which was the median of the time-series of the multi-temporal images, was used as the reference data. The normalization parameters and adjustment on derived vegetation indices were as shown in Table 1.

(2) Vegetation Coverage Change

Vegetation Index (VI) is commonly used for evaluating vegetation condition. In this study, we employed the Normalized Difference Vegetation Index (NDVI) for this:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

Because of the availability of remote sensing data, the 1973 Landsat MSS, 1986 SPOT HRV, and 2000 Landsat ETM+ images were used to analyze vegetation conditions over the study period. The NDVI was calculated using Bands 5 and 7 of Landsat MSS, Bands 2 and 3 of SPOT HRV, and Bands 3 and 4 of Landsat ETM+ as red and near-infrared bands, respectively. The resulting NDVI images were then compared and thresholds were used to categorize the vegetation change.

In this study, the plant condition changes were taken into account. The high NDVI means better vegetation

Table 1 The normalization parameters and NDVI adjustment

	MSS (1973)		ETM (2000)	
The normalization parameters for SPOT (1986)				
Slope				
RED	1.83		1.14	
NIR	2.75		1.19	
Intercept				
RED	−41.38		−16.59	
NIR	−42.44		−11.78	
The comparison between NDVI derived from the original and normalized images				
	Original	Normalized	Original	Normalized
Mean	0.047	0.119	−0.168	0.034
Median	0.062	0.139	−0.163	0.043
Standard deviation	0.116	0.151	0.053	0.088

conditions. Where NDVI is less than or equal to zero (NDVI ≤ 0), the land cover types are most likely bare ground without vegetation such as sand dunes and water bodies, so that they are excluded from the quantitative analysis. Moreover, the area of human-induced categorical change was also excluded.

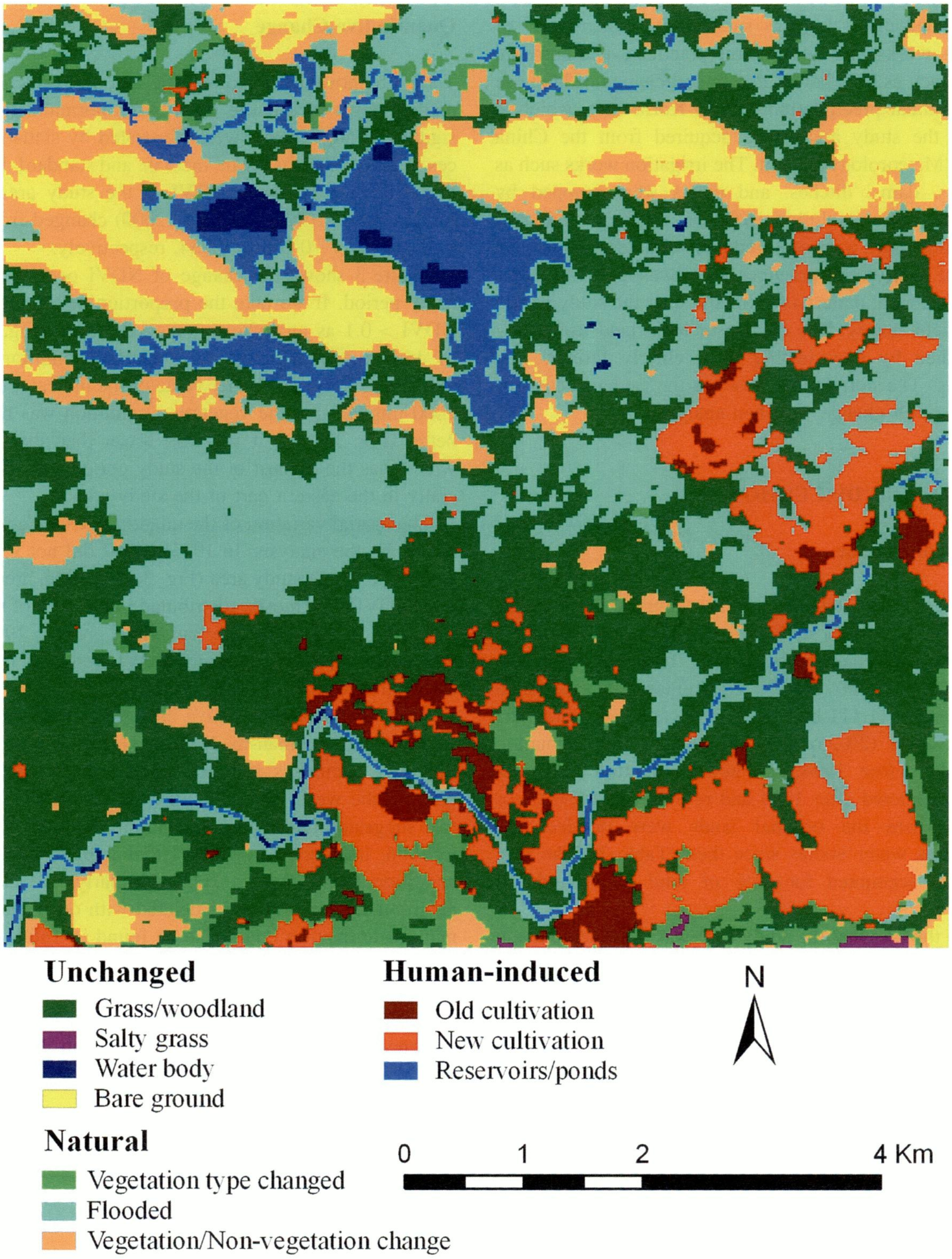

Fig. 2 The trajectories of landuse change in the past 30 years

Human Factors

Climatic, land use, and socio-economic data were collected for the investigation of the effects of natural and human factors on land cover change. In the arid zone, precipitation was the most critical natural limitation, while human factors included direct impacts such as the construction of irrigation works and agricultural practices, and intrinsic impacts such as population growth and change of land use policy. Annual precipitation data in Korla City, which is close to the study area, were acquired from the China National Meteorology Bureau. The irrigation works such as reservoirs, dams, ditches, and dykes were mapped by interpreting high-resolution IKONOS imagery, and their construction dates were acquired by field investigation. The pattern of agricultural practices was investigated by comparing the spatial pattern of farmland over the study period and by field survey. The change of local land use policy was studied by interviewing local elderly farmers and governors. The correlation between the human activities and land cover change was then analyzed.

RESULTS AND DISCUSSION

Categorical Change

According to the statistics of the temporal trajectories, 42% (2,710 ha) of the study area did not change and 40% (2,515 ha) was changed by natural forces between the years 1973 and 2000 (Fig. 2). The human-induced change occupied 18% (1,111 ha) of the total area, including the old cultivation (2%, or 124 ha) where the reclamation was made before 1994, the new cultivation (11%, or 675 ha) reclaimed after 1994 and reservoir/ponds (5%, or 312 ha) where the original lands were flooded and remained as water bodies since then (Table 2). The new cultivation accounted for 61% of total human-induced changes.

Given the fact that the study area was quite remote and human activities appeared to be quite limited, it was understandable that most of the environmental change was caused by natural forces (e.g., flooding). However, it should also be noted that since the early 1990s, human activities started to play an important role in environmental change, by altering the natural courses of water and surface materials. Although the total area of categorical change was still relatively small, its pace of growth is alarming.

Quantitative Change

Table 1b showed the radiometric and atmospheric effects on the images used in this study. After normalization, some significant adjustments were illustrated by statistical indices of NDVI such as mean, median, and standard deviation. For example, the mean NDVI in the study area for the images MSS (1973) and ETM (2000) changed from 0.047 to 0.119, and −0.168 to 0.034, respectively.

Figure 3 shows the change of NDVI over the 30-year study period. If we take the proportion of the area where NDVI > 0.1 as an indicator, the year 1986 (Fig. 3b) had the lowest value meaning the vegetation condition was the worst. Similarly, the higher value of the indicator shown in 2000 implied that the vegetation condition was becoming better (Fig. 3c), but it was still lower than that in 1973, which was the highest of the study period (Fig. 3a), especially in the eastern part of the study area.

The spatial variation of the quantitative change was also shown by the analysis. In 1973, NDVI did not vary much across the whole study area (Fig. 3a). In 1986, areas with a high NDVI were mostly distributed in the west of the study area (Fig. 3b). In 2000, the low NDVI areas in 1986 in the east were replaced by high NDVI patches, mostly in association with cultivation (Fig. 3c, d).

Table 3 shows quantitative changes in association with some natural and man-made features (presented in Fig. 3). Site “a” comprises samples along a large (abandoned) ditch in the west, which showed increasing NDVI values that suggested improving vegetation condition from 1973 to 1986, but decreasing NDVI that implied deteriorating condition from 1986 to 2000. Similarly, the change of environmental condition associated with other natural and man-made features could also be found in Table 3.

The quantitative changes of NDVI do not allow a firm conclusion as to whether the overall vegetation condition in the region was improving or deteriorating, and there was no evidence for land degradation by human impacts. The

Table 2 Human-induced categorical land use changes

Change types	Area (ha)	% Total area	% Human-induced change area
Old cultivation	124	2.0	11.2
New cultivation	675	10.7	60.8
Reservoirs/ponds	312	4.9	28.0
Total	1,111	17.5	100

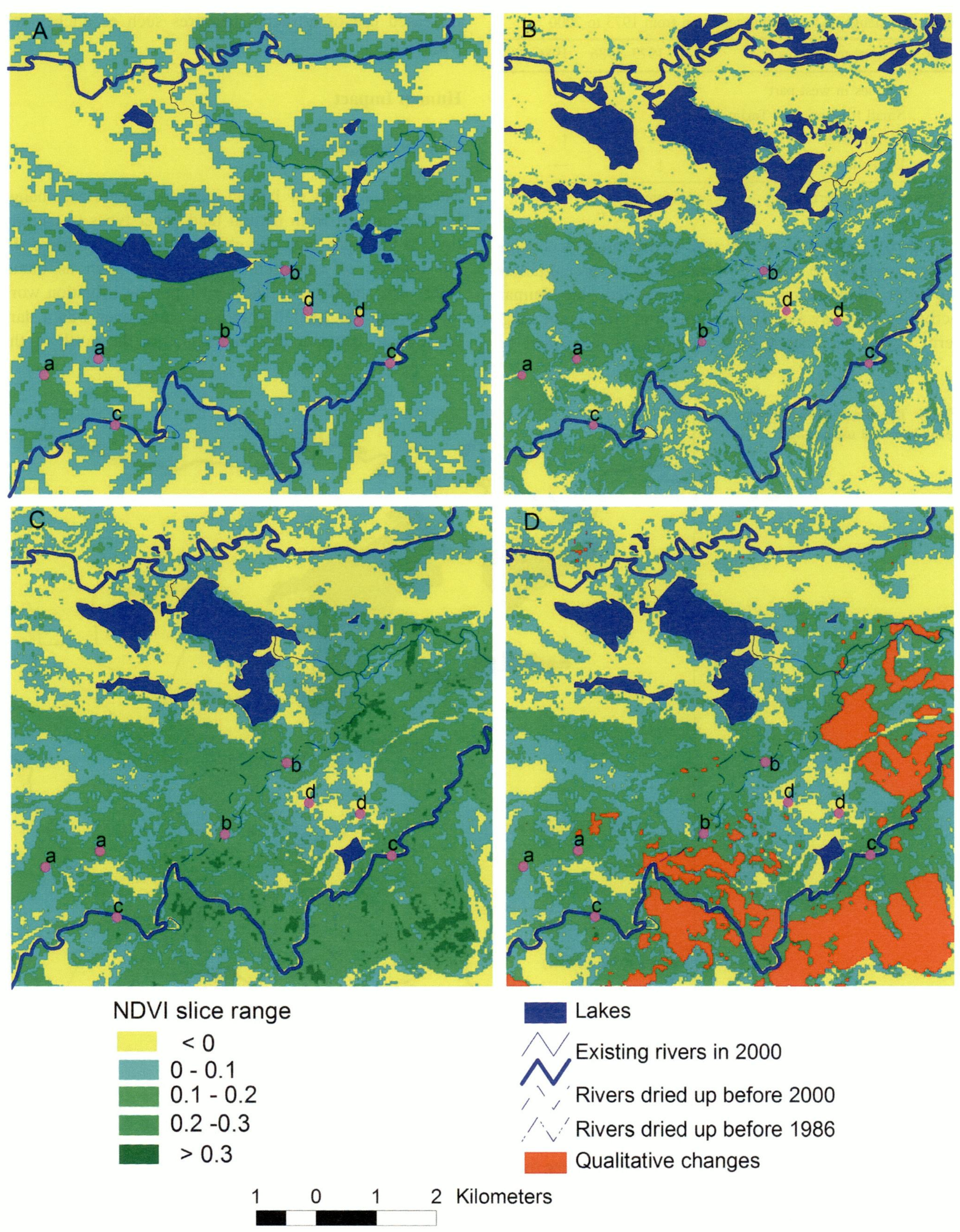

Fig. 3 The change of NDVI (**a** 1973, **b** 1986, **c** 2000, **d** 2000 excluding categorical change areas)

Table 3 Change of vegetation condition from 1973 to 2000

Sites	Related to features	1973–1986	1986–2000
a	Ditches in west part	↑	↓
b	Small tributaries of Tarim River	↑	↓
c	Tarim River	→	↑
d	Dunes in south part	↓	→

↑ Improving, ↓ deteriorating, → no significant change

growth of vegetation in the arid environment was more directly related to natural factors such as precipitation. However, the spatial variation suggested that human activities may play a much more important role in the long-term vegetation change if it were to be intensified by increased use of artificial measures such as ditches and irrigation.

Human Impact

Categorical Changes

The general trend of human-induced categorical change involved a shift from natural land cover types to cultivation. In the study area, the changes typically followed the construction of irrigation infrastructure, such as dams, reservoirs, and ditches. The first important irrigation work that altered the spatial pattern of land cover was a dam constructed between the sand dunes in the north of the

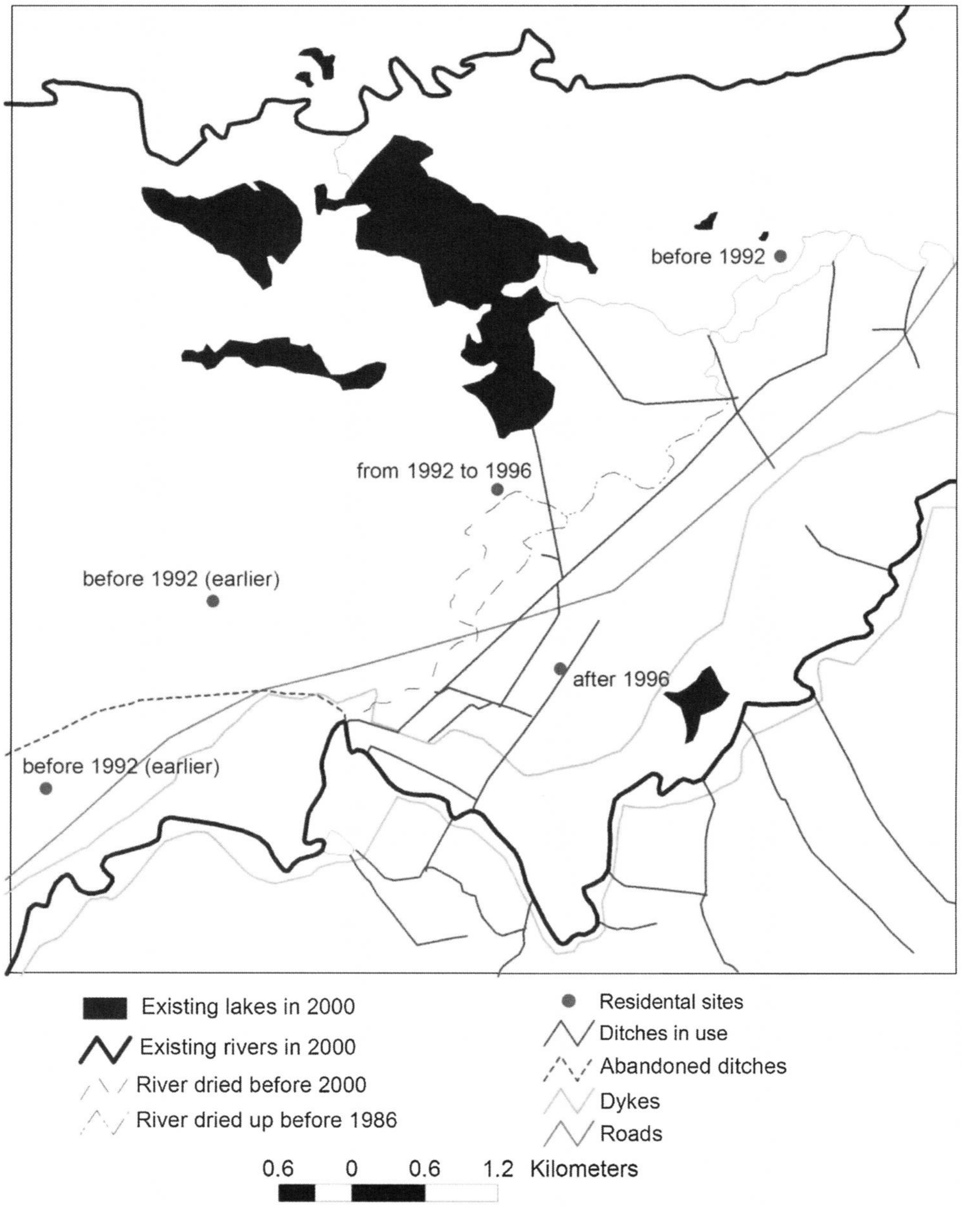

Fig. 4 The construction works related to land use change

study area in the mid-1980s, which formed a reservoir shown as a perennial water body that replaced original grassland (change trajectory classes "reservoirs/ponds"). The second significant work was construction of irrigation ditches in the east and south along the Tarim River in the early 1990s (Fig. 4), which triggered reclamation of natural grass and woodland for cultivation (change trajectory classes "old cultivation" and "new cultivation"). The third large impact was the construction of dykes along the Tarim River in 1998 and 1999. Under the shelter of the dykes, the probability of flood hazards has decreased greatly, and large areas of original grassland and salty grass along the river bed were reclaimed for large-scale commercial agriculture. In general, it was clear that the impact of human activities in the arid zone was mostly caused by altering water resources through the construction of irrigation infrastructure.

Quantitative Change

The general vegetation condition reflects precipitation controls. Figure 5 shows the annual precipitation and precipitation in the summer months for the area. The year 1973 had the highest precipitation of 55.9 mm among the three assessment dates, especially in June (33.4 mm) just before the MSS image acquisition date (3rd of July). The year 1986 had the lowest (29.9 mm) annual precipitation, especially in June (5.3 mm) and July (1.1 mm) before the SPOT image date (20th of July). This matched the above findings that the best vegetation condition, indicated by the highest NDVI of the three image dates, was in 1973 while the worst (indicated by the lowest NDVI) was in 1986.

Local variation in vegetation conditions were largely related to the change of irrigation works. Small ditches were dug by the local shepherds to irrigate the grassland with water from rivers. In the late 1970s, a large ditch (the "abandoned ditches" shown in Fig. 4) was constructed to form the basis for an irrigation network in the west. The impact of this irrigation work was shown by the fact that the vegetation condition in the west (site "a" in Fig. 3 and Table 3) was better in 1986 compared to that in 1973, even though the annual precipitation was lower in 1986. Since the early 1990s, the water supply from the upper reach of the Tarim River decreased, causing flow to cease in natural tributaries and the large ditch in the west. This forced local residents to move toward the east of the region (Fig. 4) and abandon irrigation works in the west. As a consequence, the vegetation condition deteriorated in the west but improved along the major river bed where new dykes were constructed to provide a more stable water supply (site "c" in Fig. 3 and Table 3).

Intrinsic Driving Forces and Potential Environmental Problems

Intrinsic Driving Forces

The history of land use change indicates that there was very limited farmland cultivation before the 1990s. The farmlands were so negligible that they could not be discriminated from natural land cover types on the historical images. Large-scale reclamation began in the early 1990s and accelerated in the mid-1990s (Fig. 6a). Meanwhile, local population growth, particularly the rural population

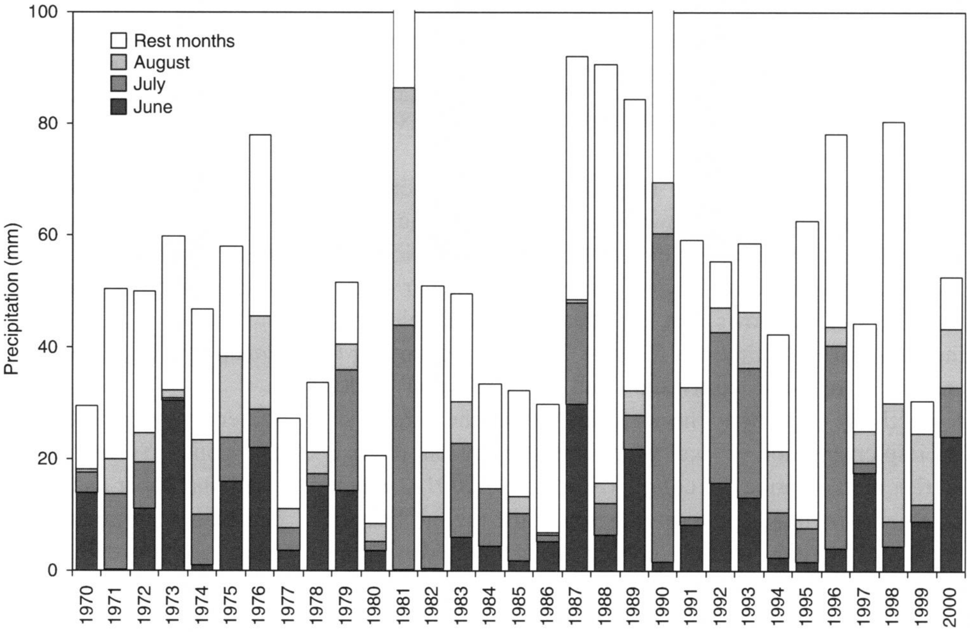

Fig. 5 Precipitation in Korla (1970–2000). (Data source: China National Meteorology Bureau)

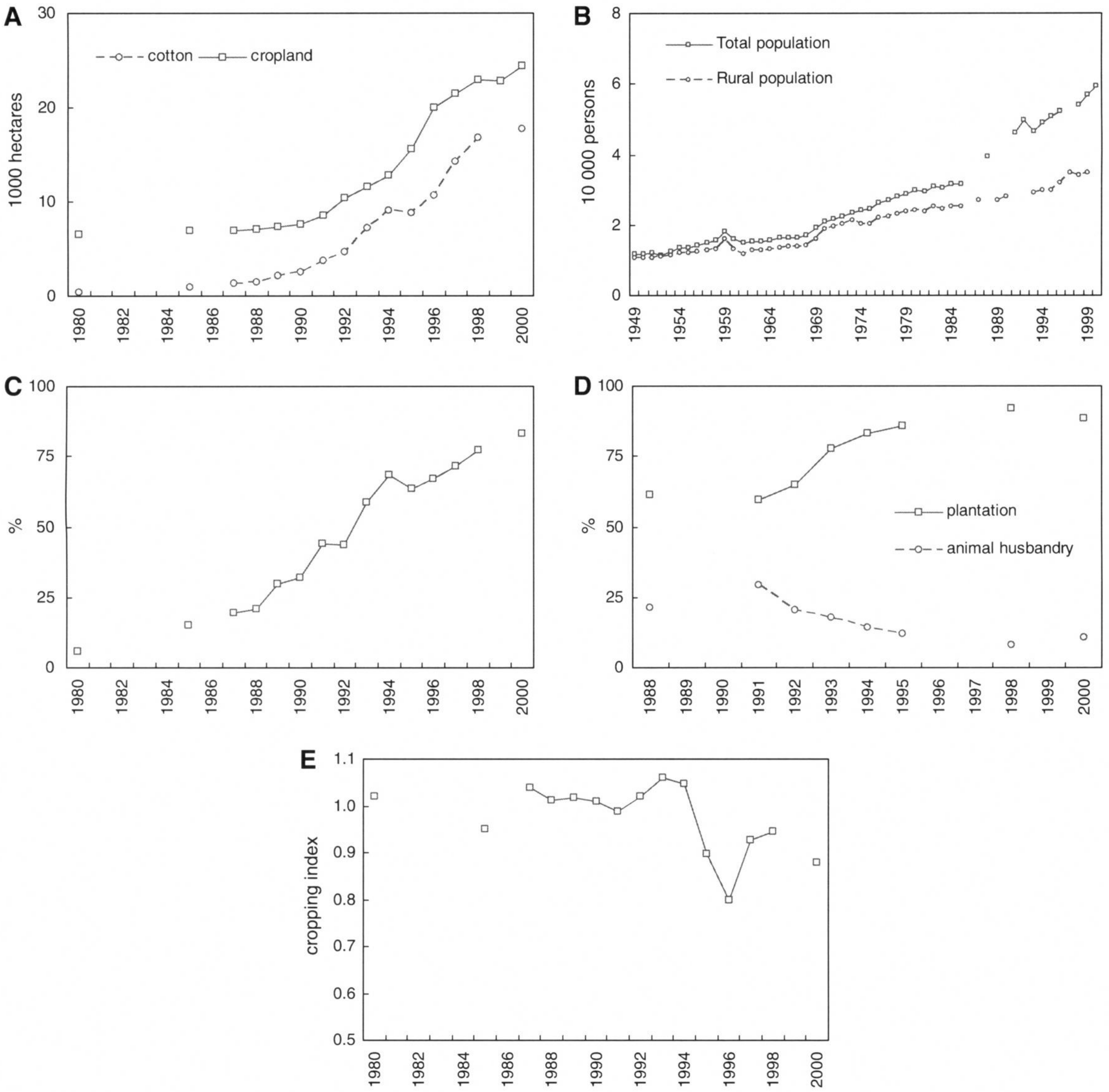

Fig. 6 Socio-economic statistics of Yuli County. **a** Cropland area (1980–2000), **b** Total and rural population (1949–2000), **c** Percent of cotton in total cropland area (1980–2000), **d** Percent of plantation and animal husbandry in total agricultural production (1988–2000), **e** Cropping index (1980–2000). Data sources: Xinjiang Statistics Bureau (1988, 1992–2000), Yuli County Chorography Committee (1993), China Investigation Group of National Statistics Bureau for Rural Economic (1993–2000)

growth, remained steady (Fig. 6b). It was, therefore, implied that population growth was not the intrinsic cause for local land use change such as farmland expansion.

One particular crop, cotton, deserves particular attention. Figure. 6a shows that the area of cotton fields has increased over 40 times in the past 20 years, occupying 6 and 83% of total cultivated land in 1980 and 2000, respectively (Fig. 6c). The statistics reflect the effects of the implementation of local government policy and the rise in the market price of cotton (Han et al. 2001), which together stimulated cotton production in the region. During the same period, pasture production decreased significantly, implying that the local land use change trend was shifting from animal husbandry to agriculture (Fig. 6d). The large area of cultivation trajectories found by this study can, therefore, be explained by this significant move of converting native pasture to cotton fields.

Potential Environmental Problems

Water resource is the key limiting factor for land use in arid zones. Since 1990, the rapid expansion of farmlands along the upper and middle-reaches of the Tarim River has caused a rapid reduction of water flow in the river. In the main source regions for the Tarim River such as the catchments of the Hotan, Yarkant, and Aksu rivers, the area of farmland has doubled since the 1980s (Yimit et al. 2000). Consequently, the river's mid-reach annual runoff was reduced by half in the 1990s. The length of the river's main channel with water was reduced by 320 km, accounting for a 24% decrease (Wang 1999). The shortage of water supply ultimately led to vegetation deterioration and farmland abandonment in the lower reach. This inference is also supported by the local government's statistics, which shows about 10% of total farmland was not planted (Fig. 6e).

CONCLUSION

From the temporal trajectories statistics, 42% of the study area was not changed, and 40% was changed by natural processes. The human-induced changes account for 18%, which were mainly related to the change of irrigation works. The results suggest that in terms of affected area, the human impact on the environment was still relatively minor in this remote area. However, it should also be noted that since the early 1990s, the area of cultivated farmland has increased by over five times (from 124 to 675 ha) with an annual growth rate of over 30% (Xinjiang Statistics Bureau 1988, 1992–2000; Yuli County Chorography Committee 1993; China Investigation Group of National Statistics Bureau for Rural Economic 1993–2000). This indicates that intensified human impacts on the environment would be highly likely in the near future should the trend of this rapid growth continue.

Human activities have had variable local impacts mostly through the construction of irrigation works. The local rural population growth has not put extra pressure on the environment in this area, at least at this stage. The changes in land use policy and commercial markets (immigrants reclaimed land and planted cotton on a large scale), however, have created significant impacts on the environment with expanding farmlands. It has been argued that the rapid expansion of farmland in this area cannot be sustained in the future, largely because of lack of water resources.

Further study is needed to monitor the land use change over the longer term to gain better understanding of the relationships between human activities, natural factors, and land use change. Other vegetation indices methods will be investigated to quantify vegetation condition change instead of using NDVI, which may need the calibration of soil color, particularly in areas with sparse vegetation cover. The long-term environmental impacts will also need to be analyzed in more detail. Based on this, an environmental model can be established to predict the environmental responses to human activities, particularly land management practices.

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AUTHOR BIOGRAPHIES

Qiming Zhou (✉) is a professor of geography and director of Centre for Geo-computation Studies at Hong Kong Baptist University. His research interests include remote sensing landuse and land cover change detection, spatio-temporal modeling, digital terrain analysis, and GIS and remote sensing applications to environment and natural resource management, especially in arid zones.

Address: Department of Geography, Centre for Geo-computation Studies, Hong Kong Baptist University, Kowloon Tong, Hong Kong.
e-mail: qiming@hkbu.edu.hk

Baolin Li is an associate research scientist at the Chinese Academy of Sciences. His research interests include GIS and remote sensing applications to environmental issues and natural resources and human–environment relationships.

Address: State Key Laboratory of Environment and Resources Information System, Institute of Geographical Sciences and Resources Research, Chinese Academy of Sciences, Beijing 100101, People's Republic of China.

Yumin Chen is an associate professor of School of Resource and Environment Science at Wuhan University. Her research interests include Web GIS, digital terrain analysis, image processing applications to environment issues and spatial information management and analysis.

Address: School of Resource and Environment Science, Wuhan University, 129 Luoyu Road, Wuhan, Hubei 430079, People's Republic of China.