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Evaluation of ecological restoration through vegetation patterns in the lower Tarim River, China with MODIS NDVI data

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ABSTRACT

The lower Tarim River had dried up nearly 30 years before an ecological water diversion project (EWDP) for ecological restoration was implemented in 2000. Since then, eight intermittent water deliveries have been carried out for restoring this seriously degraded riparian ecosystem. To evaluate the efficacy and effectiveness of these operations, the Normalized Difference Vegetation Index (NDVI) data set derived from bands 1 and 2 of the MODerate-resolution Imaging Spectroradiometer (MODIS) on board NASA's Terra satellite was applied to identify the spatial and temporal variations of vegetation cover along the river corridor with about 320 km in length. The goal of this study is thus to generate seasonally integrated NDVI (SINDVI) in growing seasons between April and October so as to investigate a general vegetation patterns as well as examine the inter-annual SINDVI for discerning the status of ecosystem restoration. The spatiotemporal variations of vegetation cover were further characterized based on those inter-annual SINDVI data with the aid of Coefficient of Variation (CoV). Research findings indicate that ecosystem integrity was strengthened after a series of water diversion efforts and groundwater table control in the past few years. As the degree of ecosystem restoration is in progress, continuous operation of water diversion is still necessary in response to the needs for restoration of dense vegetation in the riparian buffer within this arid or semi-arid region.

1. Introduction

Vegetation cover is a critical component of terrestrial ecosystems especially in arid and semi-arid regions, which must be sustained by sufficient water (Hadley and Szarek, 1981; Lehouerou, 1984). The vegetation dynamics with respect to space and time is therefore largely dominated by the availability of water (Elmore et al., 2006; Li et al., 2001). The variations of water availability affect the stability of primary productivity, thereby controlling the associated ecological changes and landscape dynamics (Shafroth et al., 2002). When upstream river flows are regulated for multipurpose water resource management, detrimental hydrological and ecological consequences often impact the ecosystem integrity downstream. This has become an increasingly urgent issue in some lower reaches of inland rivers in northwestern provinces of China (Li et al., 2009; Ma et al., 2005; Qi and Luo, 2005).

Due to the intensified anthropogenic activities during the most recent 50 years, the lower Tarim River with about 320 km in length had dried up in 1972, which, consequently, led to a serious decline of vegetation cover and drastic changes in plant community structures along the river corridor (Hao et al., 2009). In order to restore the degraded riparian ecosystem, the Chinese Government invested 10.7 billion RMB to launch the contingent plan via an ecological water diversion project (EWDP) in 2000. In this thrust, fresh water was transported from the Bosten Lake to the lower Tarim River for ecosystem restoration. Ground-water level that also affects plant species diversity along the lower Tarim River was monitored too.

The primary goal of the EWDP is to restore the riparian vegetation in the lower Tarim River. Since 2000, the efficacy and effectiveness of the EWDP have been widely concerned. Several studies were carried out to investigate the ecohydrological processes with respect to ground-water flows, mineralization, and plant diversity through in-situ monitoring and measurements (Chen et al., 2006; Hou et al., 2007; Tao et al., 2008; Xu et al., 2007). Nevertheless, the holistic information of vegetation dynamics with respect to both space and time across the whole lower Tarim River is still missing. Because natural vegetation cover plays a critical role as the major producer of organic matter, the status of ecosystem recovery can largely affect the ultimate environmental conditions in this region. Satellite remote sensing is a useful tool to analyze the vegetation dynamics over space and time (Ringrose and Matheson, 1991).

Vegetation indices have been developed to qualitatively and quantitively assess vegetation covers using spectral measurements (Bannari et al., 1995). The first earth resources satellite, a.k.a. Landsat-

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1, launched in 1972 was a remarkable effort of mankind to use an electromagnetic spectral response for evaluating vegetation covers based on vegetation indices (Weier and Herring, 2006). There are over thirty five vegetation indices that may be applied (Bannari et al., 1995; Ringrose and Matheson, 1991; Weier and Herring, 2006). Most of the vegetation indices use the red and the near-infrared bands, while some other vegetation indices incorporate additional parameters to compensate for atmospheric and/or background corrections. Peddle et al. (2001) did a review of ten most commonly used vegetation indices in the forestry applications. Each vegetation index has strength and weakness, thus, selecting the right vegetation index might greatly affect the accuracy of change detection of riparian forests. For instance, the Ratio Vegetation Index (RVI) does not perform well when the vegetation cover is less than 50%; but it is the best at the dense vegetation cover (Jackson, 1983). In contrast, the Normalized Difference Vegetation Index (NDVI) may reduce the effect of sensor degradation by normalizing the spectral bands (Rouse et al., 1974). Many other vegetation indices were developed to correct for effects of confounding factors, such as background effects (soil brightness and soil color), atmospheric effects (absorption and scattering), and the effects of the sensors' responses and calibration. For example, the Soil Adjusted Vegetation Index (SAVI) is a modified vegetation index reflecting the effects of soil brightness in the background (Huete, 1988). Examples of vegetation indices that are insensitive to atmospheric effects include Global Environment Vegetation Index (GEMI) (Pinty and Verstraete, 1992) and Enhanced Vegetation Index (EVI) (van Leeuwen et al., 1999). It is generally agreed that the NDVI is sensitive in low to moderate dense vegetation such as semi-arid areas (Diallo et al., 1991; Fuller et al., 1998; Kerr et al., 1989; Nicholson et al., 1990; Tucker et al., 1981; Tucker and Miller, 1977). Thus, NDVI was selected in this study.

Besides, vegetation activity has an important seasonality. As vegetation grows, the NDVI increases, vice versa. The cyclic increase and decrease of NDVI over time in a given area is the character of vegetation growth cycle and is taken as an indication of net primary production (Prince and Tucker, 1986; Tucker, 1986; Tucker et al., 1981). Seasonally integrated NDVI (SINDVI) is NDVI integrated over the growing season, which is defined as the sum of the NDVI values for each pixel during the growing period (Hope et al., 2003; Stow et al., 2003). Since the water diversion was intermittent and the vegetation growth was also affected by the climate and other impact factors such as precipitation patterns and geomorphologic features, SINDVI can reflect inter-annual variability and the integrative vegetation cover trends better than NDVI itself.

Many sensors have the geometric and spectral characteristics to monitor vegetation (e.g. AVHRR, TM and MODIS). The MODIS NDVI product is derived from bands 1 and 2 of the MODerate-resolution Imaging Spectroradiometer on board NASA's Terra satellite, which is available since December 1999. In view of drought characteristics of the study area and period, the MODIS NDVI product produced at a spatial resolution of 250 m with a 16-day repeat cycle is an ideal choice to retrieve the SINDVI for studying the impact of water diversion on vegetation cover in the lower Tarim River. This paper thus aims to present a full-scale evaluation on the response of riparian vegetation to the ecological water deliveries in the lower Tarim River. The analysis was carried out by means of examining the spatial patterns and temporal dynamics of the vegetation changes based on the MODIS NDVI data series from 2000 to 2007. The evaluation is expected to help realize a rational restoration objective and irrigation strategies under an intermittent water delivery scheme.

2. Materials and methodology

2.1. Study area and background

The Tarim River Basin is the largest continental river basin in Central Asia. Far from oceans, the lower Tarim River is oftentimes characterized by extremely arid conditions because water vapor was shadowed by the surrounding Tienshan, Pamirs, Kunlun and Altun Mountains. Its annual precipitation varies from 17 to 42 mm, while the annual potential evaporation varies between 2500 and 3000 mm (Hou et al., 2007). It is considered as one of the most controversially environmental degradation regions in the world. Due to stream flow interruption, the lower Tarim River and the Lop Nur Lake (once the largest lake in the arid region, China) dried up in 1972 and 1970, respectively (see Fig. 1).

The lower Tarim River is also named the 'Green Corridor' for vegetation thrived uniquely in the desert areas, which was the main passage of the famous 'Silk Road' in the history. The Green Corridor wandering between the Taklamakan and Kuluk deserts serves as a vital habitat for both aquatic and terrestrial species where its ecological environment is vulnerable due to extremely arid conditions. Since the 1950s, although the natural runoff has not decreased from the head-tributaries of Tarim River Basin, the increasing water consumption in upper and middle reaches of Tarim River has resulted in the reduced discharge gradually from 12×10^8 m^3 (1957–1967) to 7×10^8 m^3 (1986–1995) as recorded at the Kala station (Fig. 1). The construction of the Daxihaizi Reservoir in 1972 obstructed the water flow into the lower Tarim River causing the downstream dried up eventually. The groundwater table had dropped to 8–12 m below ground surface due to lack of recharge by surface water within a 30-year time period (Chen et al., 2008). Natural vegetation of the Green Corridor declined seriously since then. Large patches of herbaceous plants, such as *Phragmites communis Trirn*, *Apocynum venetum L.*, and *Alhagi sparsifolia* had died out (Hao et al., 2009). The former river system had almost merged into desert between Alagan and Taitema Lake, and the terminal lake, Taitema, completely dried up.

Starting from the year 2000, diversion of water from Bosten Lake that is the largest lake in Xinjiang and largest inner lake in China has been implementing and eight intermittent water deliveries had been completed by the end of 2007 (Table 1) (Xu et al., 2007; Tao et al., 2008; Hao et al., 2009). In order to optimize the ecological restoration via the water transfer project, two dedicated water transfer lines between the Daxihaizi Reservoir and Alagan have been used since 2003 to expand the range of vegetation restoration. A total water volume of 22.77×10^8 m^3 was released into the lower part of the river via the Daxihaizi Reservoir.

Although the water diversion has already fostered some fruits, it is far to feel an optimistic future from the perspective of field investigation. Due to decreasing upstream inflow, the Daxihaizi Reservoir was plagued by a long period of drought in 2008 resulting in many withered *Populus euphratica* as well as desertification of riverbed (see Fig. 2a–c, which is taken in Jan. 2008). Not until very recently, the ecosystem started to reveal some level of restoration (see Fig. 2d–f). Thus, our core study area is located from the Daxihaizi Reservoir to the terminal lake (Taitema), with a length about 320 km and an area of 2784 km^2. In order to define a precise study area, we first created a 10 km riparian buffer zone following the landscape of the former Tarim River channel, and then modified the buffer according to TM images, topographic maps, and the characters of NDVI distribution for assessment.

2.2. Materials and methods

Many previous studies have demonstrated that the red (620–670 nm) and near-infrared (NIR, 841–876 nm) spectral channels of the MODIS can be used to detect and monitor vegetation (Huete et al., 2002). The MODIS NDVI is a ratio of the red and near-infrared reflectance. The data set is available on a 16-day basis. Composite is based on data quality and the maximum NDVI for the compositing period. The data is output with 250 m pixels. Within this study, a time series of NDVI observations are deemed useful for examining and assessing the health and density of vegetation. When the NDVI values are close 0, it indicates very sparse

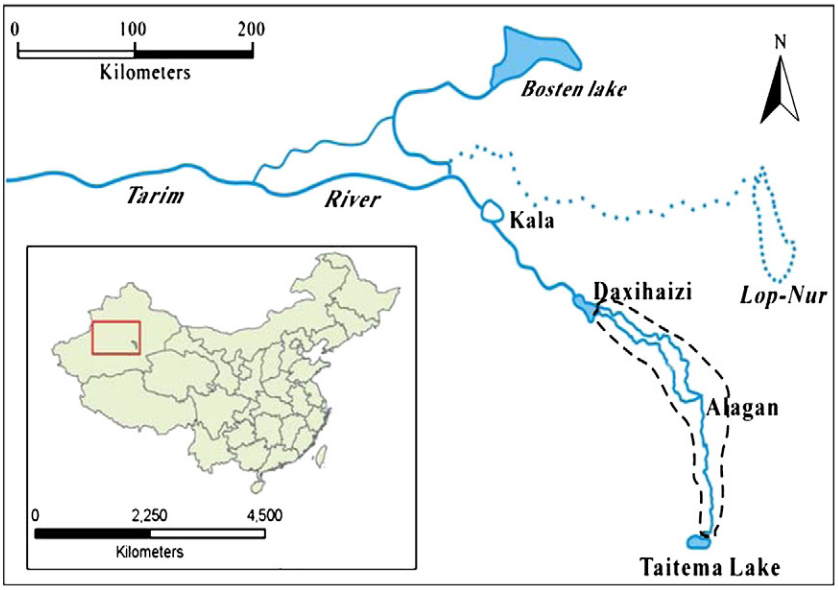

Fig. 1. The location of the study area in Tarim Basin, Xinjiang, China. The core study area is enclosed in the black dotted line.

vegetation. Conversely, dense vegetation can be implied by having higher NDVI values approaching to 1. By using a series of NDVI observations, one can examine the dynamics of the growing season and monitor extreme phenomena such as drought.

Vegetation activity has an important seasonality, and the growing season usually occurs between April and October in this study area. The SINDVI values can be obtained by taking mean of the sum of the 16-day NDVI values between April and October for each pixel with a 250 m resolution. The annual SINDVI value therefore serves as an ecological indicator for synthetically representing the status of vegetation cover of the year.

Coefficient of Variation (CoV) is a simple statistics calculated from the average, or mean (μ) and the standard deviation (σ) of the NDVI time series, X_i, in each pixel (Milich and Weiss, 2000; Vicente-Serrano et al., 2006; Weiss et al., 2001), and the formula is expressed as follows:

$$CoV = \frac{\sigma}{\mu} = \sqrt{\frac{\frac{1}{n}\sum_{i=1}^{n}\left(X_i - \overline{X}_i\right)^2}{\frac{1}{n}\sum_{i=1}^{n}X_i}} \tag{1}$$

This statistic has been widely used to determine the spatial difference of temporal variability in the vegetation activity at different arid and semi-arid regions of the world (Vicente-Serrano et al., 2006; Weiss et al., 2001). Changes in the value of the pixel-level CoV over time can be interpreted as a measure of vegetation dynamics over that time. In this study, the inter-annual CoV based on SINDVI values were calculated. The CoV associated with annual mean SIDVI were used to evaluate the recovery state at a pixel scale.

Table 1
Eight ecological water deliveries to the lower Tarim River.

Delivery	Release period	Water volume (10^8 m^3)	Flow distance (km)
First	14 May 2000 to 13 July 2000	0.98	102
Second	3 Nov. 2000 to 14 Feb. 2001	2.25	215.6
Third	1 Apr. 2001 to 6 July 2001	1.84	310
	12 Sep. 2001 to 17 Nov. 2001	1.98	358
Fourth	20 July 2002 to 10 Nov. 2002	3.31	358
Fifth	1 May 2003 to 6 July 2003	3.41	358
	4 Aug. 2003 to 2 Nov. 2003	2.85	358
Sixth	3 Apr. 2004 to 11 July 2004	1.02	358
Seventh	7 May 2005 to 7 Jun. 2005	0.52	238
	31 Aug. 2005 to 31 Oct. 2005	2.28	350
Eighth	25 Sep. 2006 to 21 Nov.2006	2.33	102
Total		22.77	

3. Results and discussion

3.1. Spatial and temporal patterns of SINDVI

The annual spatial distributions of the SINDVI values from 2000 to 2007 corresponding to the eight ecological water deliveries are shown in Fig. 3. In general, the variations of SINDVI values are obviously caused by the eight ecological water deliveries. Initially, the SINDVI in 2000 and 2001 appeared mildly improved on both sides of the watercourse within the first half river reaches; nevertheless, most areas located far from the watercourse were still dominated with low SINDVI values (<1.0). As the operation of the ecological water deliveries moved on, vegetation cover presented a remarkable improvement spatially after 2002. This can be evidenced by the improved SINDVI values (>4.0) in some areas. The areas with high SINDVI values were also extended to the lower reaches along the riparian buffer. Some areas with high SINDVI values are low-lying areas as a result of groundwater movement in the territory of the water deliveries. Water level was maintained temporarily at the terminal point – the Taitema Lake – during this period. Temporarily, the response of vegetation restoration is salient in concert with the continuous water deliveries. As for the areas that are distant away from the watercourse, the degree of vegetation restoration turns out to be smaller.

The spatially averaged SINDVI values over the lower Tarim River were calculated to assess the quantitative improvements of the vegetation restoration temporally. Fig. 4 represents the mean SINDVI values of all pixels in the time period from 2000 to 2007. It can be divided into three stages: 1) the incipient period in 2000 and 2001, in which the water diversion did not trigger the immediate improvements; 2) the rapid improvement period from 2001 to 2004 attested by the sharp increase of the SINDVI values; and 3) the stable period after 2004 when vegetation growth comes into a relatively stable state. Yet the abrupt drop of the SINDVI value in 2006 may be a concomitant response of the low water delivery in 2005 (i.e., 0.52×10^8 m^3). Over the entire period of the water diversion, it is worthwhile to mention that the mean SINDVI values had increased more than 25% based on the difference between the lowest value in 2001 and the highest value in 2007.

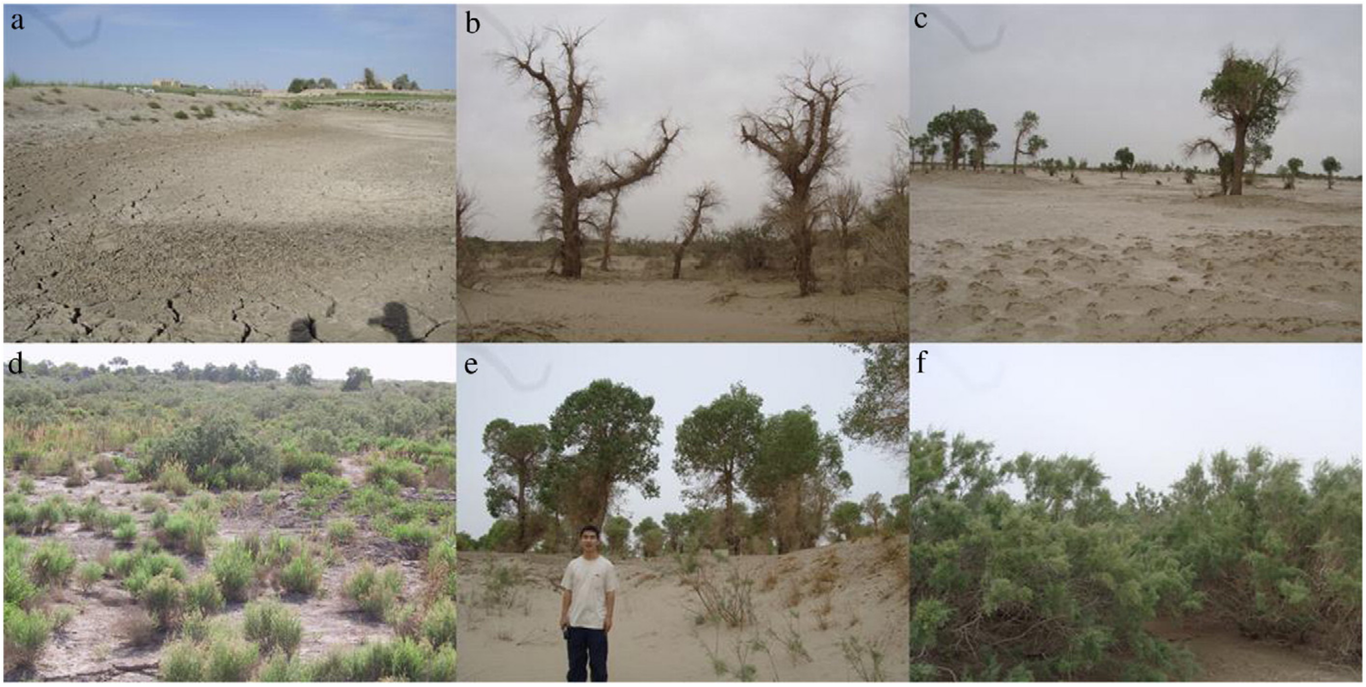

Fig. 2. (a) Dried reservoir (upper left), (b) Withered *Populus euphratica* (upper middle), (c) Desertification of the riverbed (upper right), (d) *Populus euphratica* (lower left), (e) mixed vegetation (lower middle), and (f) *Tamarix spp* (lower right) in the gradually restored riparian vegetation community.

3.2. Evaluation of progressive improvements using CoV

With the discussion in relation to Figs. 3 and 4, it can be observed that the riparian vegetation (i.e., Green Corridor) can be gradually recovered after nearly 30 years of ecological degradation due to the limitation of water availability. During this process, the yearly retrieval of vegetation level may be helpful to elucidate the fluctuations of the ecosystem recovery relative to the ultimate stable state. The yearly means of SINDVI values provide the clues of such progressive improvements. The inter-annual CoV values were calculated for each pixel to further manifest the progressive improvements.

Fig. 5a shows the relationship between the mean SINDVI values and CoV over the whole study area. According to the relationship between the mean SINDVI values and CoV, the study region was

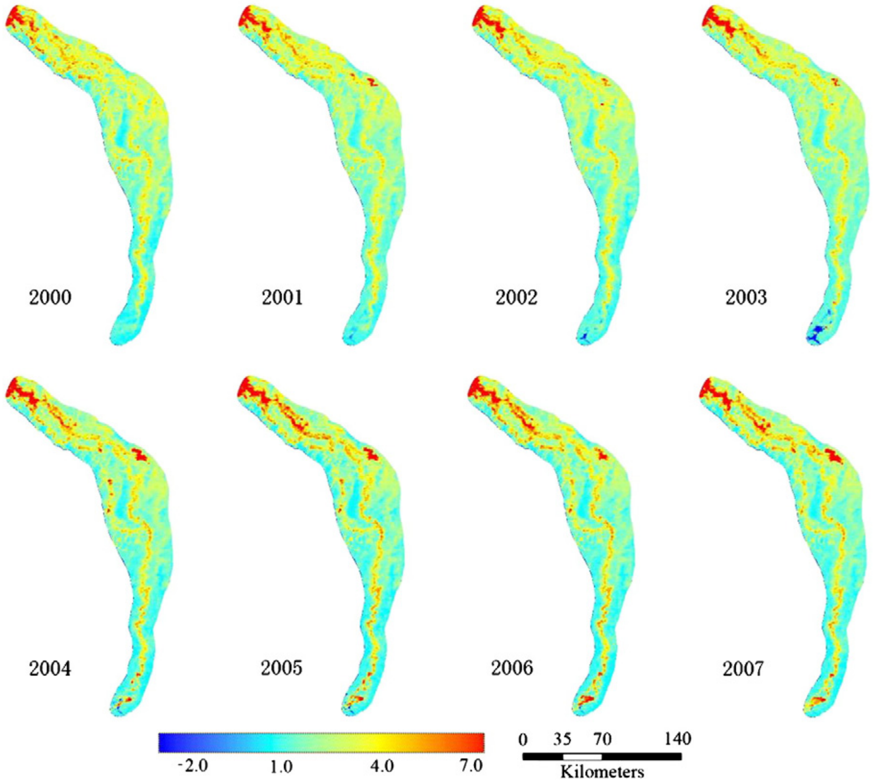

Fig. 3. Spatial patterns of seasonally integrated NDVI (SINDVI) from 2000 to 2007.

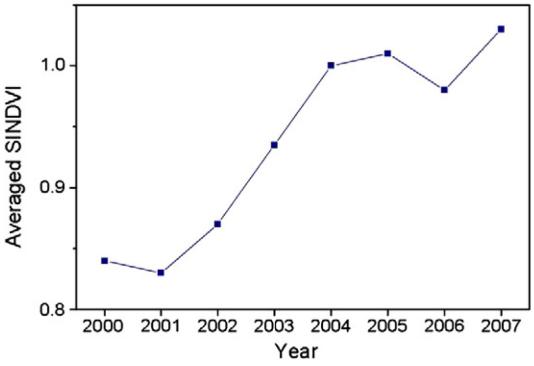

Fig. 4. Time-series of the spatially averaged SINDVI over the lower Tarim River.

subdivided into three types spatially (see Fig. 5b): 1) small or no change areas (in yellow). There are large areas with low mean SINDVI values (<1.5) that coincide with spaces in which a low inter-annual variability of SINDVI (CoV values were lower 0.1). These areas are mainly sandy dotted with little vegetation cover where variation of vegetation shows no significant improvements. When looking back to Fig. 5a, Type I can be discerned as such areas where there have not been affected by the ecological water deliveries so far; 2) rapid improvement areas which can be expressed by green color spatially (see Fig. 5b). When looking back to Fig. 5a, Type II can be discerned as such areas with larger mean SINDVI values ranging between 1.5 and 3.0 and higher CoV than 0.1. These distinctions signify the areas where had experienced vegetation growth in response to the water deliveries; and 3) relatively stable areas which can be expressed by red color spatially (see Fig. 5b). There are also some areas with larger SINDVI values than 1.5 and the higher CoV values ranging from 0 to 0.35, which pinpoint the most developed riparian vegetation areas. Overall, the spatial vegetation patterns as shown in Fig. 5b imply that the vegetation community is still not as stable as expected in the lower Tarim.

3.3. Driving forces and ecological risk analysis

3.3.1. Dense vegetation and water delivery

With the basic understanding of vegetation dynamics previously discussed, there is a need to investigate the riparian vegetation community in this Green Corridor. In general, *Populus euphratica* and *Tamarix spp* are the most important plant species due to their outstanding drought tolerance capability (see Fig. 2d and f). They collectively form the bases of dense vegetation cover in the lower Tarim River. Deng (2007) had established a classification criteria based on a few field samplings with respect to those health shrub and tree (Deng, 2007). Their corresponding MODIS NDVI values are normally larger than 0.106 in August. Following this criteria, the dense vegetation cover was extracted in our study based on the corresponding MODIS NDVI from 2000 to 2007. Fig. 6 presents the relationship between the area of dense vegetation cover and the cumulatively transferred water volume. The correlation between the area of dense vegetation cover and the cumulatively transferred water volume becomes a valuable tool to assess the cost-effectiveness of ecosystem restoration. The regression equation is expressed as Eq. (2) below:

$$y = A_1 exp(-x / t_1) + y_0 \tag{2}$$

in which y_0 is the intercept term (Km^2); A_1 is the pre-exponential factor (Km^2); t_1 is the regression coefficient ($10^8\,m^3$); y is the endogenous variable (dependent variable) standing for the area of dense vegetation cover (Km^2), and x is the exogenous variable (independent variable) standing for the cumulatively transferred water volume ($10^8\,m^3$). To predict the behavior of ecosystem response in association with the water diversion effort in this study, we derived Eq. (3) for use from which the coefficient of determination (i.e. adjusted R^2 value) is up to 0.88.

$$y = 135.31 exp(x / 16.32) - 88.26 \tag{3}$$

Thus, the regression curve in Fig. 6 indicates that the recovery of dense vegetation cover is still in a fast progress mode over years. It is believed that this Green Corridor will be further recovered up to more stable levels if the recovery action can be strengthened by more water deliveries. But what is the limiting factor would be a main concern in this ecological risk analysis.

3.3.2. Interactions between groundwater table and cumulatively transferred water volume

In this study area, precipitation can affect the growth of sparse vegetation due to its small demand for water. The growth of dense vegetation cover was limited to nearby rivers, and it is largely groundwater-dependent. Changing precipitation shows a different level of vulnerability associated with different vegetation communities. Groundwater is an important water resource in support of ecosystem productivity and succession of plant communities in arid and semi-arid regions (Huete, 1988). In the lower Tarim River, riparian vegetation strongly depends on groundwater. Over seasons, depth to groundwater table varies from place to place affected by long-term geomorphologic formation and short-term water deliveries

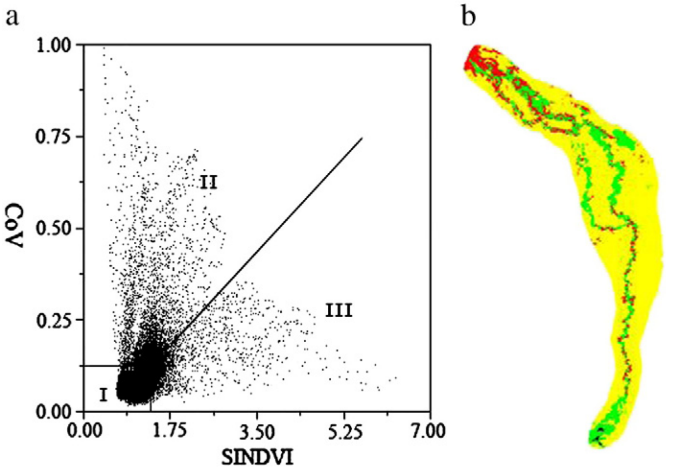

Fig. 5. (a) Relationship between the mean SINDVI values and CoV, and (b) subdivisions of recovery status.

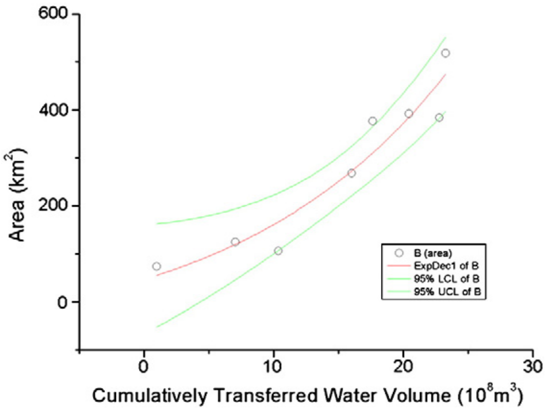

Fig. 6. Relationship between the area of dense vegetation cover and the cumulatively transferred water volume.

and consumption simultaneously. Consequently, the relationship between the changes of groundwater table and the vegetation dynamics becomes a key in regard to ecosystem restoration in this arid or semi-arid region (Caldow and Racey, 2000). Normally, the rapid response to water diversion is the intermittent fluctuations of the depth to groundwater table followed by the corresponding growth of vegetation leading to form the essential structure and function of the local plant community. Some low-lying areas that are not far away from mainstream also show high SINDVI values as a result of higher groundwater levels. Overall, precipitation has limited impact on the restoration of ecosystem and only tree and shrub communities show consistent improvement over the entire study period.

It is therefore important to investigate the interactions between the surface water deliveries and the changing depth to groundwater tables. According to the record, about 7×10^8 m^3 water was released to the downstream of the Tarim River in the first two years. The groundwater table rose up to 5 m or so according to the in-situ monitoring. After the first two efforts of water deliveries, groundwater table eventually reached a proper level that may be able to sustain vegetation growth. However, the riparian vegetation presented a trifling improvement during this operational period because most of the recharged water simply replenished the deep groundwater aquifer. The recovery of vegetation, such as *Populus euphratica*, however, needs a physiological process with the aid of long-term groundwater supply.

It is therefore good to know how much water diversion is necessary to sustain the required depth to groundwater levels directly and support ecosystem restoration indirectly. To explore the relationship between the changes of groundwater tables and the water delivery processes, Fig. 7 portrays a chart comparing the cumulatively transferred water volume against the changing groundwater tables over the study period. With the aid of a companion study recording the changes of groundwater tables (Chen et al., 2008), the trend in Fig. 7 positively confirm that the changes of groundwater tables are directly associated with the amounts of water deliveries in the lower Tarim River. Such an observation indirectly confirms that the vitality of ecosystem restoration via water diversion. With this understanding, variations in Figs. 3 and 4 can be cross-linked with the changes of groundwater tables as a result of the varying amounts of water deliveries (see Table 1).

The previous correlation analysis verifies that the varying depth to groundwater tables is responsive to the amount of water diversion. The relationship between the depth to groundwater tables and the degree of vegetation growth along the river corridor is obvious (Hou et al., 2007; Tao et al., 2008; Xu et al., 2007). Such findings lead to generate a sustainability criterion in which 4–6 m depth to groundwater tables should be maintained in order to ensure the restoration of ecosystem in this region on a long-term basis (Hao et al., 2009). To keep this goal active, Fig. 7 reveals that sufficient and consistent water deliveries within a range of 2–3 $\times 10^8$ m^3 per year are required to keep the stable groundwater level as needed. This is consistent with the value of 2.44 $\times 10^8$ m^3 estimated by a numerical model in the literature (Wang and Lu, 2009).

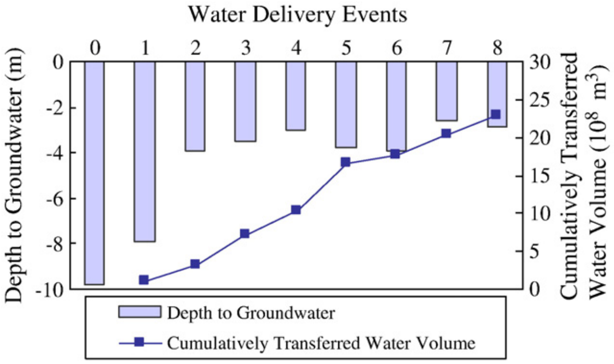

Fig. 7. Change of groundwater table to each water delivery and accumulatively transferred water volume.

Spatially, the water distribution was not homogeneous. According to the hydrological monitoring, 75.6% of water was consumed within the first half section between the Daxihaizi Reservoir and Alagan; 21.6% was consumed in the second half section between Alagan and Taitema Lake; and the rest ran into the Taitema Lake (Deng, 2007). It is due to the fact that the two water transfer pipelines have been adopted since 2003 to optimize the efficacy of ecological restoration by using a cascade design approach. Since then, the groundwater levels have been elevating gradually over time (Xu et al., 2007). This partially explains why the greenness in the first half section of the Tarim River was relatively salient after ecological restoration (see Fig. 5b).

3.3.3. Conflict management, adaptive water resources management and countermeasures

Given that the ultimate goal is to reach a self-sustaining ecosystem by an integrated water resources management plan through the release of more water from upstream to the lower reaches of the Tarim River. From this point of view, there is a conflict of water allocation between upstream and downstream of the Tarim River. This requires the proper control of irrigation upstream, the adequate estimation of essential environmental flow, and the deepened studies of water availability affected by climate change.

Conflict management in the context of integrated water resources management is essential among municipal, agricultural, and environmental sectors. By looking up the structure of vegetation dynamics (Figs. 2–4), it is clear that the EWDP has not yet reached the goal of ecosystem restoration up to its full-scale. Thus, the EWDP should be properly implemented continually. Regardless of the intermittent water deliveries that could revive and protect the degraded natural vegetation to some extent, challenges from more anthropogenic activities and climate change would certainly threaten the possible restoration of ecosystem.

The availability of water for diversion and ecosystem restoration can be determined by two key factors, including the amount of head water available and the agricultural irrigation consumption in the river basin. There are four major headstreams of the Tarim River, which are fed by water from glaciers and snowmelts as well as rainfall in the surrounding mountains. Due to the global warming and regional climate perturbations, an enhanced water cycle was observed, which rendered a paradigm shift from warm-dry to warm-wet phase. As a consequence, precipitation, glacial melt water and streamflows of headstreams increased continuously (Shi, 2003; Shi et al., 2007). The glacial retreat in the 1990s had already caused an increase of surface runoff more than 5.5% in the Tarim River Basin (Yao et al., 2004). The total discharge of the four headstreams was larger than long-term average of river discharge by 18.0%, 12.8%, 21.0% and 17.4% in 2001, 2003, 2005 and 2006, respectively. This implies that recent climate perturbations favored more precipitation or trigger more snowmelts. Anyhow, a relatively ample runoff in the 2000s ended up some beneficial effects on the successful implementation of the EWDP (Sun and Wang, 2006).

On the other hand, large areas of irrigated farmland had been cultivated between mountainous outlets and mainstreams, which consumed a major portion of discharge from headstreams in the past decade (Xie et al., 2007; Zhang et al., 2008). Table 2 summarizes the pattern of agricultural irrigation consumption of Tarim River during the period of the EWDP implementation. Obviously, the irrigation consumption kept on rising after a temporary drop in 2003 indicating the growing demand for food production in this area. As a consequence, discharge into the mainstream was relatively stable during this study period. Yet irrigation water requirement vary from season to season. With these additional water resources available due to global warming, the timing of delivery can also be used in the context of conflict management. Normally, the growth of dense vegetation nearby rivers is not sensitive to the timing of the water delivery because the dense vegetation is groundwater-dependent. From this perspective, timing of environmental flow delivery is flexible. Yet this is not the case in the rest of areas distant away from the watercourse where the timing of water delivery and irrigation water requirements can be harmonized to some extent. In any circumstance, if the total discharge from headstreams drops to a lower level due to continuous population growth and agricultural farming, residual water flow discharging into the mainstream could not be sufficient for use as environmental flow in the lower Tarim River, which may jeopardize the progress on ecosystem restoration eventually.

Overall, agricultural sector which accounts for approximately 90% of the total water consumption and environmental sector that triggers the needs for ecosystem restoration are two major driving forces in conflict management. Sustainable development needs adaptive water resources management to harmonize social and economic demand and foster better ecohydrological processes in this unique river system (Ragab and Prudhomme, 2002). Nevertheless, there is no more potential surface water source left over to exploit in the Tarim Basin, but there is considerable potential for water savings through the applications of modern irrigation techniques such as the adoption of drip and sprinkler irrigation, the applications of plastic row covers, etc. It leads to conclude that future success of ecosystem restoration in the lower Tarim River is intimately tied with a delicate balance among regional population growth, agricultural production, global climate change, and adaptive water resources management.

To promote sustainable development in the future, some possible countermeasures can be proposed as follows in order to: 1) improve the understanding of the ecohydrological cycle in mountainous regions under climate change especially the interactions among permafrost, precipitation, and glacier and snowmelt; 2) increase efficiency and effectiveness of adaptive water resource management strategies especially through conflict management among agricultural, municipal, and environmental sectors in the study area; 3) strengthen the supervision of water allocation for ecological restoration; 4) adjust irrigation techniques for water saving, 5) manage land use planning, and 6) enhance the use of remote sensing tools for environmental flow assessment.

4. Conclusions

The use of MODIS NDVI time series data in this study successfully provides us with an opportunity to monitor vegetation cover conditions over the lower Tarim River at a decadal scale. These multi-year efforts prove that the water diversion for ecological restoration in the lower Tarim River is effective; but the EWDP has not yet reached the goal of ecosystem restoration up to its full-scale. The response of the riparian vegetation growth to a series of water deliveries shows differences in space and time. Currently, ecosystem restoration in the “Green Corridor” is largely restricted to areas adjacent to the watercourse. The development of dense vegetation cover is still sensitive to the cumulatively transferred water volume and the vegetation recovery is still in progress. The beneficial influence of water diversion on the ecosystem integrity can only be confirmed through a long-term process. This indicates that a long-term implementation of the current water diversion strategies may be highly anticipated. Therefore, a proper water diversion policy should be secured and implemented on a long-term basis. Countermeasures such as conflict management among agricultural, municipal and environmental sectors should be proposed for achieving the sustainable development in this arid or semi-arid region. The proper use of remote sensing tools to describe environmental/ecosystem implications and resulting social/economic conditions associated with various environmental flow scenarios will be highly recommended.

Table 2
Source water and agricultural consumption pattern in the study area (unit: 10^8 m^3).

	Source water from four headstreams	Irrigation consumption before discharging into the mainstream	Discharge into the mainstream
2001	266.5	220.0	46.5
2003	258.2	210.6	47.7
2005	272.1	215.2	56.9
2006	268.9	218.6	50.3

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