

Vegetation response to Ecological Water Diversion in the lower Tarim River, Xinjiang, China

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Abstract

To reverse large-scale ecosystem deterioration in the lower reaches of Tarim River (NW China) caused by interruptions in the water flow, an extensive water diversion project was initiated in 2000 to transfer water from the Bosten Lake towards the lower Tarim. Has the water transfer towards the lower Tarim been successful or not, was proved to check the riparian vegetation recovery and dynamic after the water diversion. This paper uses MODIS NDVI and other remote sensing data from 2000 to 2007 to analyze vegetation dynamics connected to changes in water supply. Results indicate that main vegetation types recover as a result of the project. The proportion of NDVI values < 0.1 decreased since 2000 and increased for NDVI values higher than 0.1. The Desert area was reduced from 47.8% to 12.8%, while the area covered by trees and shrubs increased from 2.2% to 15.9%. We interpreted these results as a true recovery of the vegetation. Precipitation rarely contributes directly to the water supply of dense vegetation, such as trees, shrubs and meadows. In contrast, growth of dense vegetation is primarily controlled through water transfer activities. The distribution of trees and shrubs is presently restricted to the surrounding of the river Tarim, with a width ranging from 1-5 km, and this area is correlated with the accumulated water transfer volume ($R=0.96/0.01$). The time period over which the water diversion is implemented can also affect vegetation restoration effects; nevertheless the water table increase is crucial for improvements in self-regulation. As a result, the water transfer volume and implementation time is becoming more flexible to keep a stable oasis ecosystem by the cumulative effects. Peak NDVI values appeared four years after the water transfer was implemented. These peak values mean that water began to support a dense vegetation cover.

Keywords: Ecosystem deterioration, Ecological restoration, NDVI, Water transfer, Central Asia

Zusammenfassung

Um die großräumigen Ökosystemzerstörungen als Folge von Abflussdezymierungen im Tarim-Unterlauf (NW China) zu stoppen und sie möglichst rückgängig zu machen, wurde im Jahr 2000 ein großes Wasserumverteilungsprojekt – vom Bosten Lake zum unteren Tarim – gestartet. War dieser Wassertransfer erfolgreich oder nicht, wurde an Hand der Wiederbesiedlung und Vegetationsdynamik in der Aue des unteren Tarim untersucht. Um die Entwicklung und Verbreitung der Regenerationsfähigkeit der Vegetation zu bestimmen wurde der NDVI (Normalized Density Vegetation Index) aus MODIS- und anderen Fernerkundungsdaten der Jahre von 2000 bis 2007 ermittelt und daraus Beziehungen zwischen der Vegetationsdynamik und der Wasserversorgung abgeleitet. Die Ergebnisse zeigen, dass sich die durchschnittlichen NDVI-Werte erhöht haben und sich die Vegetation als Folge der Wasserzufuhr wieder stärker ausgebreitet hat. NDVI-Werte $< 0,1$ sind rückläufig. Meist kam es zu einer Erhöhung der NDVI-Werte zwischen 0,1 und 0,4. Der Wüstenanteil ging von 47,8% auf 12,8% zurück, der Anteil der Baum- und Strauchvegetation stieg von 2,2% auf 15,9% während des Untersuchungszeitraums. Spärliche Vegetation reagiert äußerst sensibel auf Niederschlagsänderungen. Nach einem Niederschlag kommt es dort häufig zu einem kurzzeitigen Wachstumsschub. Dagegen trägt Niederschlag bei relativ dichter Baum-, Strauch- und Wiesenvegetation nur wenig zum Wachstum bei. Das Wachstum dieser dichten Vegetation wird vor allem durch den Wassertransfer gesteuert. Die Verbreitung der Baum- und Strauchvegetation ist derzeit an einen 1-5 km flussnahen Saum gebunden, dessen Ausdehnung mit der zugeführten Wassermenge korreliert ($R=0.96/0.01$). Der Zeitraum des Wassertransfers kann sich ebenfalls auf die Regeneration der Vegetation auswirken. Allerdings ist der Anstieg des Wassers entscheidend für die Revitalisierung der Vegetation. Insgesamt können die zugeführte Wassermenge und der Zeitraum der Applikation so kumulativ gesteuert werden, dass sich stabile Oasenökosystemzustände einstellen. NDVI-Höchstwerte wurden vier Jahre nach der Wasserapplikation festgestellt. Das heißt, die Wasserzufuhr hat zu einem verstärkten Wachstum der Vegetation und zu einem verbesserten ökologischen Entwicklungspotenzial beigetragen.

Schlüsselbegriffe: Ökosystemstörung, ökologische Regeneration, NDVI, Wassertransfer, Zentralasien

Introduction

Since the 1950s, large-scale ecosystem deterioration has occurred downstream of many inland rivers in Northwest China due to extensive agricultural irrigation in the upper reaches (Qian 2004; Qin 2002; Ma 1997; Hao et al. 2006). Dam construction and ecological water diversion are often invoked in the ongoing debates con-

cerning the impact of land use on watersheds (Geoffrey et al. 2005; Aronson et al. 2006). The phenomenon of waterless rivers and desertification of lakes is wide spread in dryland areas, even in intensively irrigated upstream areas of river catchments. The result of it: the damage of the environment, caused by failed centrally managed large projects, is known as Aral Sea-Syndrome (WBGU 1998, Opp 2007). Life

in these harsh environments depends heavily upon rivers. Location-specific water allocation for environmental purposes is becoming more and more urgent (Richard 2006). The Tarim River, China's longest inland river, runs west to east between the Tianshan Mountains and the Taklamakan Desert, and creates a river oasis that stretches more than 1,300 km through the desert. The main stream does not produce runoff and is fed by precipitation and glacial melt water from mountain regions. The foreland oasis is very vulnerable to the upstream water supply (Mahamut et al. 2002). Between 1949-1993 cropland reclamation in the upper reaches of the Tarim catchment has doubled (Hou et al. 2007). As a result, more than 320 km of river oasis along the river's lower reaches dried up in 1972, and the adjacent lake Lop Nur, once the largest lake in China, was similarly lost (Xia 1987). Because no water fed the ecosystems, significant vegetation vanished, including large and old stands of *Populus euphratica*, a tree well known for its ability to withstand harsh environmental conditions. This vital habitat loss caused severe deterioration of riverine ecosystems.

To restore the dry river and its riparian vegetation, the Chinese government launched its largest environmental restoration project of the year 2000 in this area. By transporting fresh water from its upstream and adjacent valley, it becomes possible to utilize water from Bosten Lake to meet the urgent ecological water demands of the depleted area. Transport activities have been performed since 2000 and a water volume of $23.27 \times 10^8 \text{ m}^3$ was released into the lower part of the valley (Xu et al. 2007). Water inundated the dry riverbed, reaching the river's termi-

nal lake Taitema some 30 years after its disappearance.

During the course of the water diversion project, particular attention was paid to record and analyse ecological responses. Research was needed to determine whether this water management project has been successful or not. We are interested in knowing which plant cover has been restored, as well as in gaining an understanding of the employed method's viability as a sustainable practice. In addition, we must study the various effects of differential water transfer on vegetation and the period of time necessary to complete restoration under different conditions. Because vegetation is the most basic and direct indicator of eco-environmental change (Breckle 2000, Runge & Zhang 2004, Zhanbin et al. 2006, Novikova, N & Kuzmina, Zh. 2008) field observation and analyses aiming at understanding hydro-ecological processes between groundwater, mineralization and riparian systems were carried out (Xu et al. 2004; Chen et al. 2006). However, few assessments were based on large-scale vegetation dynamics, and the impacts caused by different water transfer volume and different implemented time periods.

A number of remote sensing data and methods have proven valuable for evaluating vegetation cover in arid regions (Aosier et al. 2007; Schmidt et al. 2000). Compared to on-site monitoring, remote sensing data has the advantage of chrono-sequence and spatial distribution. This study focuses on changes in vegetation cover and the relationship between water supply and vegetation growth. We modelled remote sensing data series, covering more than 320 km of the river oasis to reveal the vegetation evolu-

tion response to the urgent ecological water diversion activities. The results were expected to serve as a reference for a more rational water diversion plan.

Material and methods

Study area

The study area is located in the east of the Taklamagan Desert in the Tarim River basin (Lat. 39°24'08"-40°45'10"N; Long. 87°20'00"-88°35'00"E) within the Xinjiang-Uighur Autonomous Region of China (Fig. 1). This region is characterized by extremely arid conditions due to its continental location and its additional water vapour shadowing by the alpine Tianshan and Kunlun Mountains, with an annual solar radiation of 3118.7 h, annual precipitation of 17.4-33.6 mm (with a peak between June and August), and annual potential evaporation of approximately 2671.4 to 2902.3 mm (Hou et al., 2007; Thomas et al., 2005). However, supplied

with precipitation and glacial meltwater in mountain regions, the rivers enable a growing human population to practice extensive agriculture in the oases. The irrational expansion of water consuming agricultural activities in the upper reaches has resulted in an ecological disaster for the lower reaches. Dam construction in the Daxihaizi reservoir (see Fig. 1) has certainly played a role in the down-river degradation. Completion of the dam has severed the bio-ecological river connection between southern and northern areas of the largest desert in China. The core study area extends from the Daxihaizi reservoir to the Taitema Lake. In order to define a precise study area, a 10 km buffer zone based on the former Tarim river channel (two lines between Daxihai and Alagan) was marked, and then modified the buffer according to TM images and topographic maps. In this manner, we defined a region in which it was possible to analyze the effects of water diversion on the re-

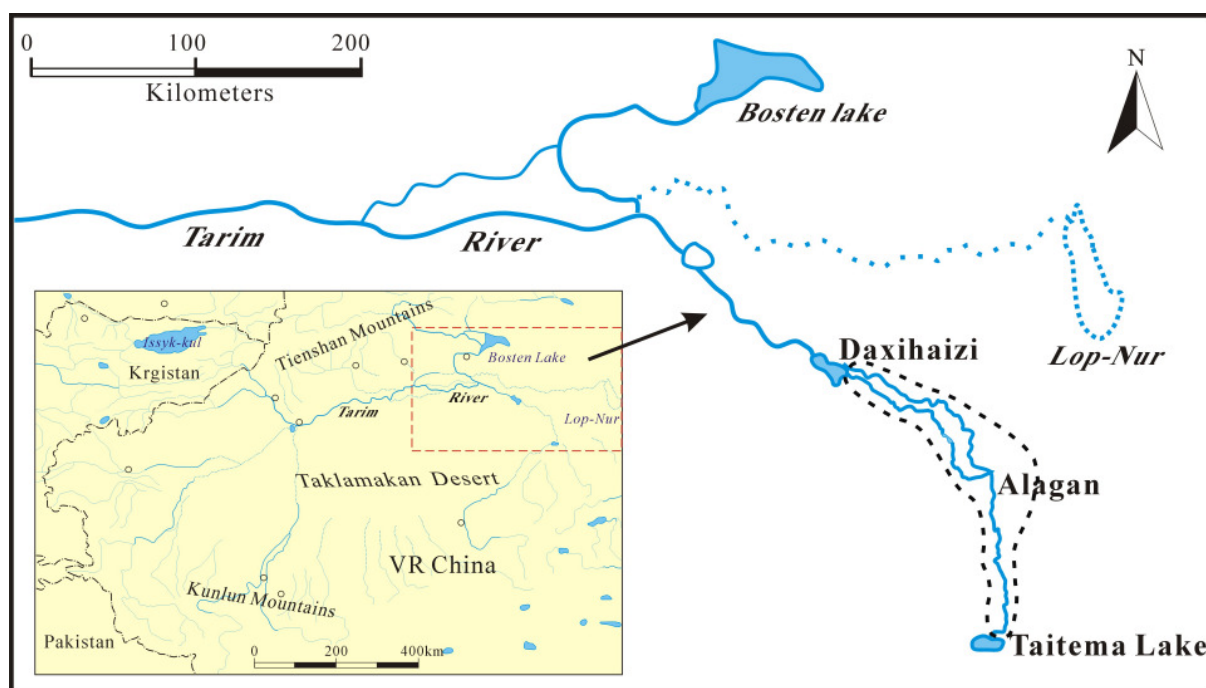


Fig. 1: Study location in the Tarim River Basin, and core study area enclosed with black dotted line

gional vegetation cover. There are two water diversion sources, the upstream region of the Tarim River and the Bosten Lake.

Data and analysis

The Normalized Difference Vegetation Index (NDVI) is an algorithm ratio of red and near infrared reflectance. It is useful for assessing the vitality and the density of the vegetation cover. NDVI values near 0 indicate very sparse vegetation. Dense vegetation is indicated by NDVI values approaching 1. A distributed time-series of NDVI observations can be used to monitor the vegetation dynamic or to study phenomena caused by drought or water supply change during the growing season. The MODIS NDVI dataset is derived from bands 1 and 2 of the Moderate-Resolution Imaging Spectroradiometer on-board NASA's Terra satellite and has been available for 16-day periods since 2000 (NASA, 2008). Composite images are based on data quality and the maximum NDVI for the compositing period, with a maximum spatial resolution of 250 m pixels. Taking into account the vegetation's growing season and the time during which the water was transferred, we analyzed the period from mid-April to early November. Spatially, the analyses primarily focused on vegetation and the composition and distribution characteristics of different vegetation types in areas benefiting from water diversion. Altogether, 112 MODIS NDVI images were included in this study, spanning a period from April 2000 to November 2007. The core study area covers 68034 MODIS NDVI 250 m grids.

To obtain spatial and temporal characteristics as well as to concern with their relationship with

the water diversion events, analyses were carried out both on NDVI values and vegetation types during the growing seasons. The vegetation types were classified in accordance with criteria established by Deng (2007) which are based on field samplings and corresponding MODIS NDVI values. Following this method of classification, the vegetation coverage was divided into four types: 1) Desert (0~0.056), 2) Sparse vegetation (0.056~0.078), 3) Meadow and steppe (0.078~0.106), and 4) Tree and shrub communities (>0.106).

To a certain extent, vegetation coverage is also affected by local precipitation. In order to distinguish the impact of water diversion from that of precipitation, TRMM PR monthly-accumulated rainfall data series (3B43_V6) were introduced to the study for the purpose of analyzing the fluctuation of water supply from rainfall. The TRMM PR dataset is a good choice for regions without in situ precipitation monitoring (Yatagai et al. 2006).

Results and discussion

Water diversion

The water diversion project presented in this study ran for eight years, from 2000 to 2007. During this period, there were nine intermittent releases, with a transfer time of approximately 1000 days (Tab. 1). The prophase water diversion benefited from abundant water in the Bosten Lake valley. The total water transfer from Bosten Lake reached $23.91 \times 10^8 \text{m}^3$ according to monitoring data compiled from the first seven releases. After the water reached the Daxihaizi reservoir, $20.44 \times 10^8 \text{m}^3$ flowed downstream from the control dam, of which $12.81 \times 10^8 \text{m}^3$ rushed in

Table 1: Activities of water transfer to the lower reaches of the Tarim River 2000 - 2007

Water diversion	Release duration	Water volume ($\times 10^8 \text{m}^3$)	Flow advance distance (km)	Terminal lake surface area (km^2)
First	14 May 2000 - 13 July 2000	0.98	106	0
Second	3 Nov.2000 - 14 Feb.2001	2.25	215.6	0
Third	1 Apr.2001 - 6 July 2001	1.84	310	0
	12 Sep.2001 - 17 Nov.2001	1.98	358	4.5
Fourth	20 Jul.2002 - 10 Nov.2002	3.31	358	16.7
Fifth	1 May 2003 - 6 July 2003	3.41	358 two lines	30
	4 Aug.2003 - 2 Nov.2003	2.85	358 two lines	200
Sixth	3 April 2004 - 11 July 2004	1.02	358 two lines	-
Seventh	20 May 2005 - 30 Sep.2005	2.80	358 two lines	-
Eighth	25 Sep 2006 - 21 Nov.2006	2.33	-	-
Ninth	10 Oct 2007 - Nov 2007	0.50	-	-
Total		23.27		

“-” data not available

from Bosten Lake, accounting for 63% of the total amount of water transferred. Only $7.62 \times 10^8 \text{m}^3$ of water came from the upper stream of the Tarim River, contributing a smaller value of 37% to the total water transferred. The runoff reached the terminal lake Taitema six times. Most of the diverted water was absorbed by ground along the river. Only a small part evaporated from the lake's surface (Deng 2007). Spatially, $15.5 \times 10^8 \text{m}^3$ of water were consumed within the first half section between the Daxihaizi reservoir and Alagan. This accounts for 75.6% of the water consumed, while $4.43 \times 10^8 \text{m}^3$ were consumed in the second half, between Alagan and Taitema Lake. These values accounted for only 21.6% of the total water consumed. $0.49 \times 10^8 \text{m}^3$ of water ran into the Taitema Lake (Deng 2007).

Due to an extremely large amount of runoff that was provided by Bosten Lake, up to $9.57 \times 10^8 \text{m}^3$ of water were released from 2002 to 2003, form-

ing a 200km^2 water surface on the terminal lake Taitema.

In order to optimize the ecological effects of the water transfer project, two water transfer lines, between the Daxihaizi reservoir and Alagan, have been used since 2003 to expand the range of vegetation restoration.

NDVI process and its main driving forces

Local vegetation growth is often determined by variables such as soil type, climate, water supply, etc. Both climate and soils conditions are usually relatively stable. That is why water supply becomes the most important factor affecting vegetation growth, especially in arid regions. Relationship between NDVI, water diversion and precipitation is presented in Fig. 2.

The growth season in this study has been observed to be between May and October. The NDVI value is the average of the entire the study area, exhibiting a relatively low level (<0.1). The

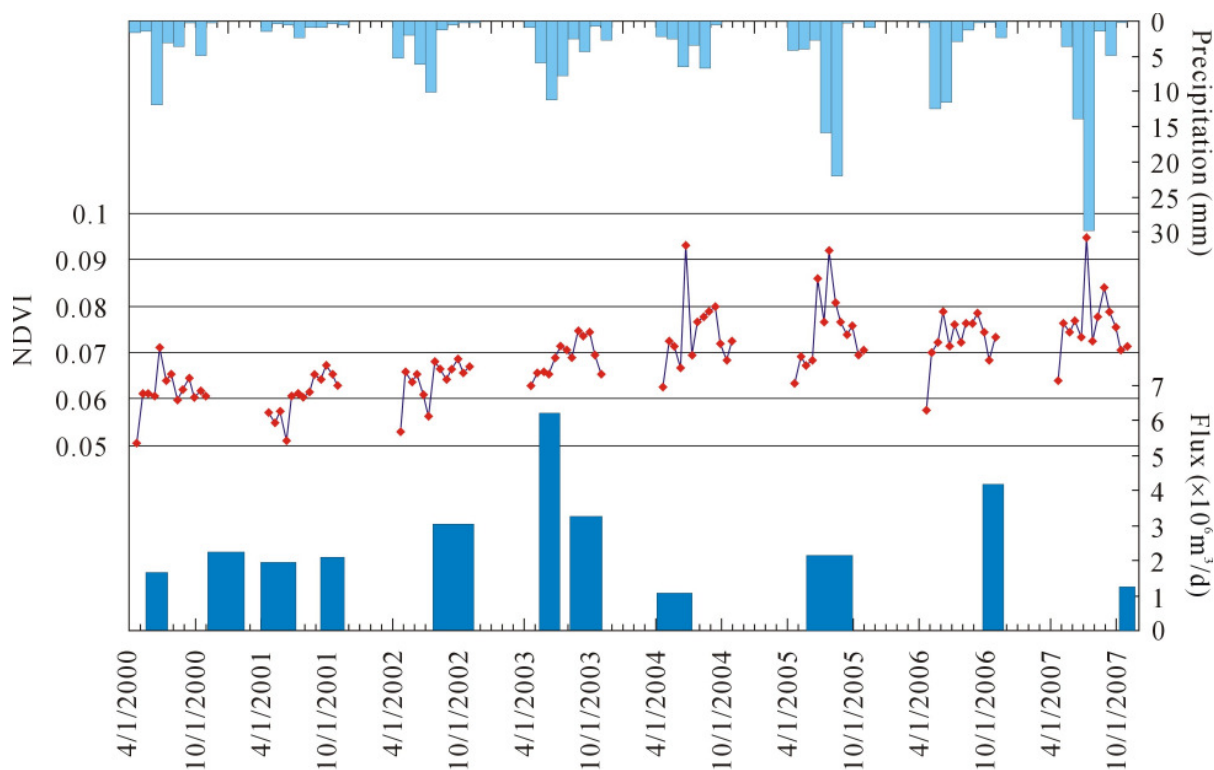


Fig. 2: Relationship between NDVI, water diversion and precipitation; the width of the blue bar represents the period of water transfer, its height represents the flux of the transfer per day, and its area represents the volume of water transfer.

NDVI process indicates an expansion of vegetation cover from 2001 to 2007, with an especially significant increase from 2002 to 2005. Almost all values are lower than 0.07 between 2000 and 2002, there is an improvement in 2003, and most of the values have been above 0.07 since 2004. As important phenomena, some peak NDVI values emerge in 2004, 2005, and 2007 during growing seasons. These peak values indicate a more sufficient water supply during the summer growing season. To some extent, water has begun to satisfy a higher demand of vegetation growth. Where did this water come from?

In comparison with nearby regions, seasonal NDVI values and vegetation development have changed dramatically and they show annual differences. This indicates that the vegetation was affected by different factors, or dominated by a variable factor.

Precipitation generally correlates well with NDVI values in regions of arid climate (Liping et al. 1994). Most of the monthly rainfall is less than 15 mm in this area. Therefore, it is not easy to form infiltration storage due to the high evaporation rates under such arid conditions.

Water was diverted more frequently in the years 2000 to 2003, with subsequent releases of a reduced volume only once per year. The water transfer occurred after the onset of the growing season in 2006 and had only moderate effects on the vegetation growth—no peak NDVI values were observed during this year, indicating that the season in which the water diversion takes place can affect its impact on primary production, but this impact may not happen immediately. This is also apparent in the 2007 data. No water transfer occurred during the months of January and October. The water transfer was performed

much later than those carried out in 2006, causing a peak in vegetation value during the month of July.

Distribution and trend of different NDVI value intervals

To observe the transformation of NDVI values and to reveal the distribution of different NDVI value intervals, statistical analyses were performed for different NDVI value intervals based on the better growing season data from 2000 to

2007. The results show that the lower value range (<0.1) accounts for the greatest portion of change (Fig. 3). Its amount is continuously decreasing. Which has accounted for 96.5% of the total grids in 2000, and dropped to 80% in 2005. Almost all ranges showed an improvement from 2000 to 2004. While the value ranges (0.1-0.3) dropped in 2005, and this drop extended into all ranges whose NDVI value is higher than 0.1 in 2006. And the drop in NDVI is coincident with drop in volume and frequency of water transfer.

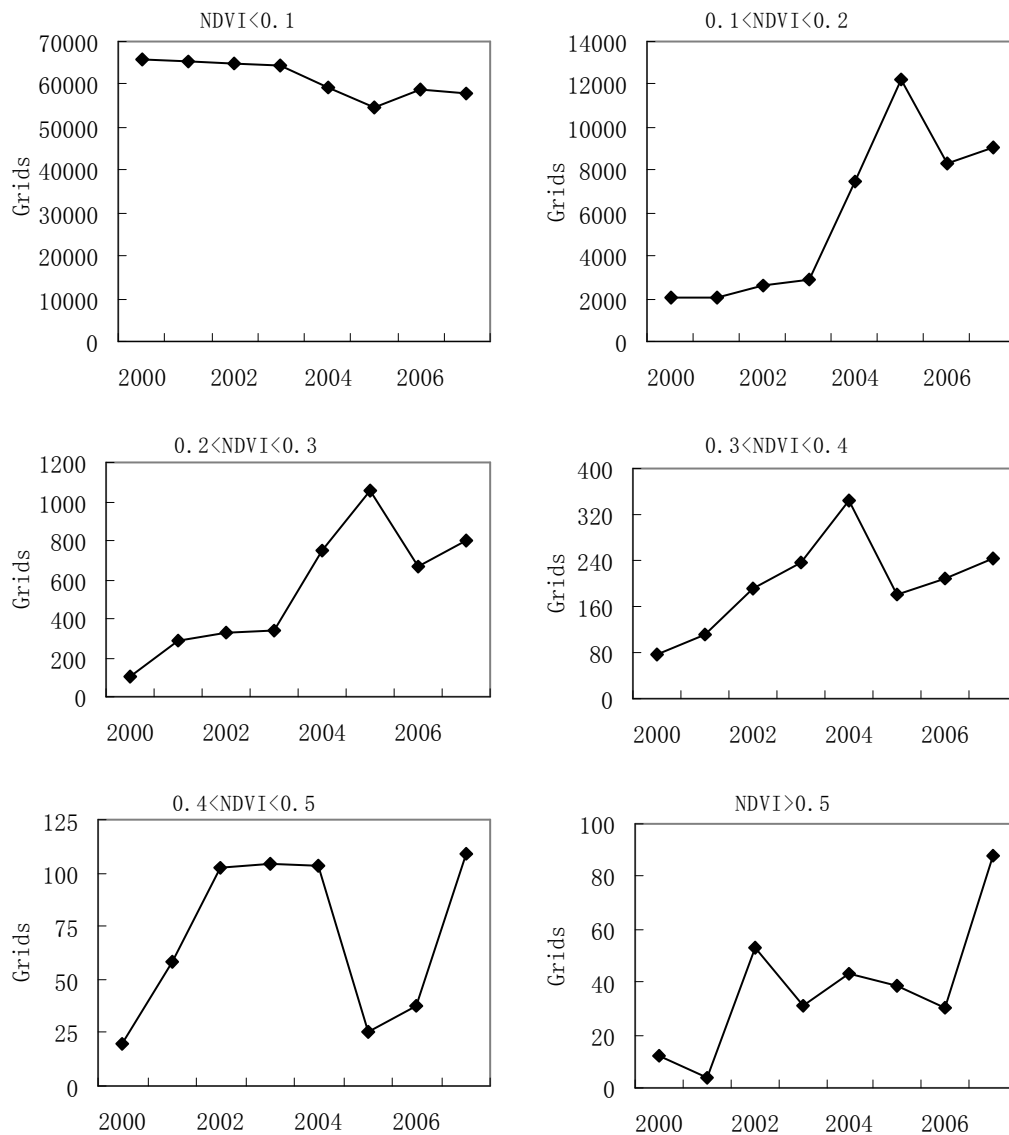


Fig. 3: Grid amount and its changes of different NDVI value intervals

Only the ranges which NDVI value is higher than 0.4 show swift improvement in 2007.

Changes of vegetation cover values

The perspective of changes in vegetation types can provide a better understanding of the vegetation coverage changes than that of NDVI itself. August is the best growing season. Therefore, the classification was carried out based on the NDVI images in August. In order to visualize a spatial process, we calculated the vegetation coverage classification process from 2000 to 2007 and presented it in a sequence (Fig. 4). Although water diversion started in 2000, most of the water that was released entered the soil to replenish deep ground water sources that had long ago been depleted.

This was proved by higher groundwater levels after the water transfer (Chen et al. 2006, Hou et al. 2007). The runoff advanced only 106 km from the Daxihaizi reservoir outlet (one-third of the whole length). Vegetation recovery was limited to the upper third of the river; main parts of the other area were still dominated by desert. Even the former Tarim river channel, for which it is difficult to observe a clear river profile by analyzing only the vegetation patterns, is dotted with small oases that have benefited from advantageously lower topography.

The vegetation improved gradually and has reached a relatively fair level only three years after the project was initiated. The area of the

desert, detected with the help of Moderate-Resolution Imaging Spectroradiometer, decreased significantly (cf. Fig. 4 and 5), and a strong, green, ecological corridor was slowly reestablished.

Considering the spatial distribution of water consumption, more than 75% of the water being transferred was consumed before arriving in Alagan. In the first half section of the channel (two water transfer lines were adopted since 2003 to optimize the water's ecological impact), water supply is more sufficient than in the second half. As a result, the vegetation cover between the Daxihaizi reservoir and Alagan is much wider than that in the lower Alagan, where the vegetation coverage is still characterized by an obviously linear profile.

Different vegetation cover types have a different vulnerability to water scarcity and also perform different ecological functions (Thevs et al. 2005). At this site, the type of vegetation cover was determined by the degree to which ecological demands for water were satisfied. Therefore, statistics concerning vegetation coverage may reflect the spatio-temporal changes that occur in the water supply and transform between different vegetation cover types (Fig. 5).

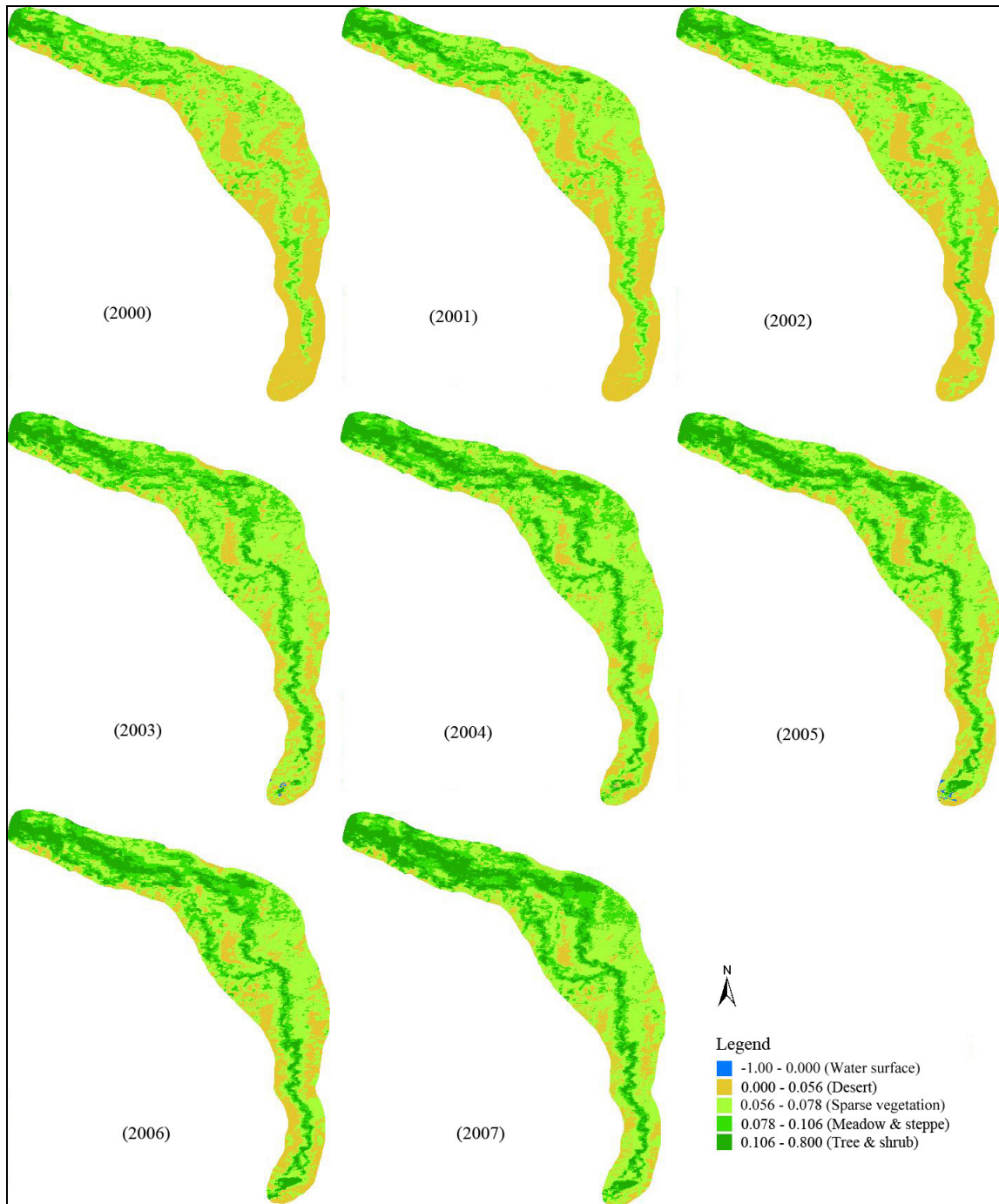


Fig. 4: Different types of vegetation growth situations in August from 2000 to 2007

According to Fig. 5, the desert area did not diminish immediately after water diversion was initiated. In fact, the significant reversal has been occurring since 2002. After this time, the desert area was reduced from 2033 km² to 547 km², its ratio reduced from 47.8% to 12.8%. On the other hand, almost all types of vegetation cover have

increased since 2001. In particular, the ratio of trees and shrubs shows a trend toward growth, from 95 km² in 2000 to 675 km² in 2007. The ratio increases from 2.2% to 15.9% (Tab. 2); restricted to nearby rivers its width ranges from 1 to 5 km (Fig. 4). As a result, the desert area had become the smallest component by 2007. It is

noteworthy that there was a break in 2006, in which the desert area expanded. This may be explained by the water diversion that occurred at the end of September, after the growing season.

improvement for the entire study period. This shows a different vulnerability of different vegetation communities.

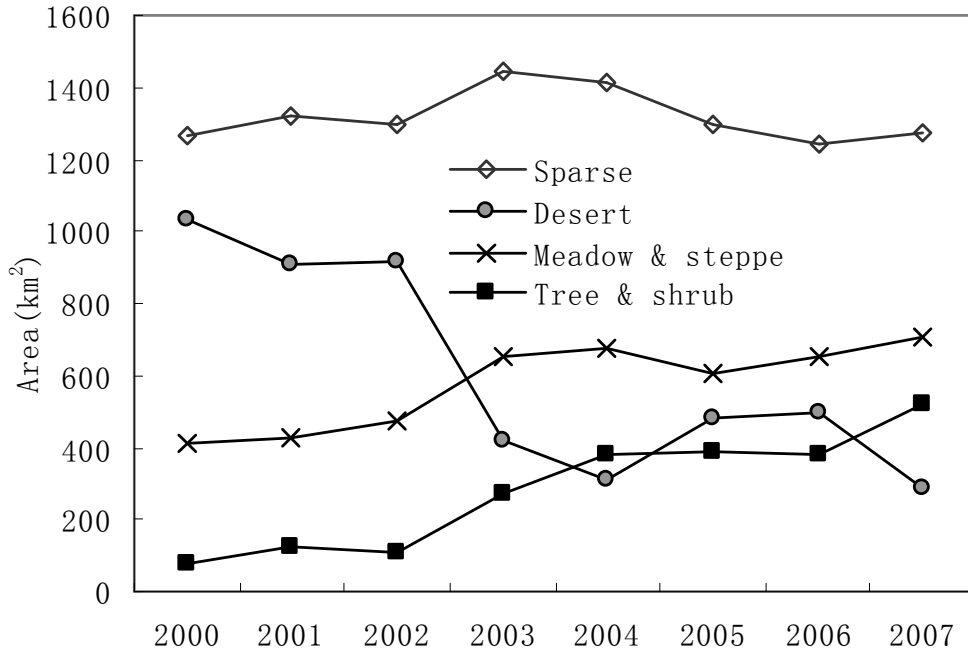


Fig. 5: Change of different vegetation cover types from 2000 to 2007

At the same time, the precipitation is also less than that of 2005 and 2007. Sparse vegetation cover allows the desert to reclaim land. On the other hand, although the time when water was transferred is even much later than in 2007, taking advantage of the water transfer storage in 2006, trees and shrub also show a good improvement and generated in some desert area even a sparse vegetation cover. On the whole, only tree and shrub communities show consistent

Precipitation and vegetation

Precipitation too, has some contribution to local water supply. But there is no significant relation between average NDVI value and precipitation in this study area during the study period. This is slightly different from other nearby regions, where the NDVI value is often sensitive to precipitation. Due to its limited quantity, precipitation relevance is not an important factor affecting every vegetation types in this study

Table 2: Percent change in the area of four vegetation types from 2000 to 2007

	2000	2001	2002	2003	2004	2005	2006	2007
Desert	42.8	47.8	37.3	24.9	21.7	19.5	27.0	12.8
Sparse vegetation	39.6	35.4	47.2	44.2	44.6	51.1	37.6	51.5
Meadow and steppe	15.4	12.3	12.0	21.5	20.7	16.7	24.0	19.8
Trees and shrubs	2.2	4.5	3.5	9.4	13.0	12.7	11.4	15.9

area. However, precipitation can affect the growth of sparse vegetation due to its small demand for water supply (as evidenced by the relatively strong connection observed between sparse vegetation and precipitation). Since many processes in nature have exponential dependencies, exponential model was presented to attempt to explain the observed trend in sparse vegetation growth under precipitation change (Fig. 6). An improvement towards a lower NDVI value often occurs after a season of higher

Relationship between the area of trees and shrubs and accumulated water transfer

The water transfer activities contributed to different spatial units and vegetation coverage in different levels according to the vegetation coverage classification and their evolution process. Meadows, trees and shrubs neighbouring the river steadily benefited from water transfer. Relationship between the area of tree & shrub communities and accumulated water volume is modeled by exponential model (Fig.7).

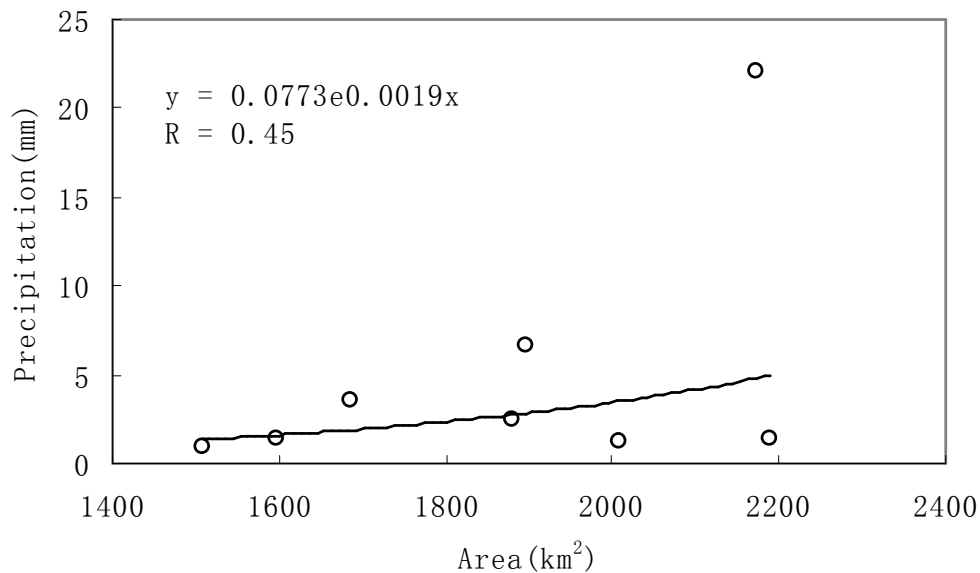


Fig. 6: Relationship between local precipitation and sparse vegetation areas

precipitation, but this is only limited to sparse vegetation distribution, which can be observed by the transformation from desert to sparse vegetation coverage in 2006 and 2007. The dense vegetation coverage was limited to nearby rivers, thus, riverine vegetation is groundwater-dependent, outside oases is vegetation rain-water-fed.

As an important vegetation cover type, the development of trees and shrubs shows a strong correlation with accumulated water transport, with a coefficient of $R=0.96/0.01$. To some extent, this encourages an optimistic prognostic for the future. The vegetation cover along the former ‘green corridor’ would lead to optimistic predictions of the restoration process in buffer areas near the river with trees and shrubs, the most stable communities. That is why, if water transfer proceeds, ecological water demand may reduce

gradually, taking advantage of both a rising ground water table and an improving vegetation community with better survival capabilities. The effects of water diversion may not appear immediately, so it is important to study the cumulative effects of large-scale projects like these ones examined. During the first several years, the volume and implemented time of wa-

significant vegetation development, and considering that no water diversion happened in the corresponding period, the water supporting the peak NDVI values could only come from the rising ground water table due to accumulated water transfer.

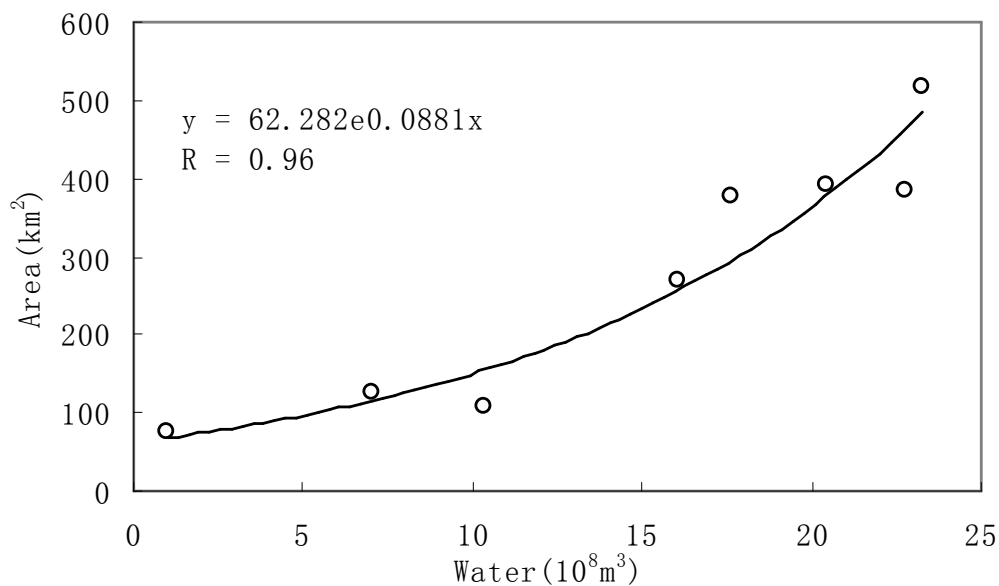


Fig. 7: Relationship between trees and shrub area and accumulated water transport

ter transfer is important, though later in the process it is possible to proceed with more flexibility, which also provides an understanding of an optimized water diversion plan in order to produce a better ecological response with limited water resources in the future.

The mean NDVI values reach a relative high level in 2004, 2005, and 2007 during the growing seasons. In particular, in 2007, although no water was transferred from January to October, the mean NDVI values were at peak in August, with some of the unit values even approaching 0.80. Since the precipitation can not bring such

Potential and differentiation of vegetation revitalisation

According to the NDVI images, the vegetation restoration area range may extend as far as 30 km from the ecological water diversion project itself. With water supply limited, vegetation recovery in the lower Alagan is not as strong as in its upper reaches. At present, an ecological connection was re-established basically across the desert. Appearance of some peak NDVI values indicates that the ecosystem has become stable and relatively independent with respect to the transportation of accumulated water, which will result in the rising of the water table. These ex-

treme values reveal that further improving potential of the ecological stabilization. The vulnerability of the ecosystem improved gradually and became less sensitive to changes in water supply when it became self-regulatory.

Water tables are a direct factor affecting the vegetation growth. Different amounts of water diversion do result in different water tables. However, this paper did not discuss changes in the water tables specifically. An evaluation of vegetation restoration by different levels of the water table, a proper water transfer volume, and the time required to keep a proper water table at a sustainable level is essential for the ecological water diversion project.

Another variable is the impact of climatic change. The prophase of water diversion benefits from ample runoff into the Bosten Lake. Studies in the Bosten Lake valley indicate that climate change has a great impact on the runoff in mountain areas because the small-sized glaciers are more sensitive to climate warming. When those small-sized glaciers situated in a lower altitude melt away, a sharp drop in the runoff period is

likely (Sun et al. 2006). This change in the original water supply would affect not only irrigation but also the sustainability of ecological water diversion, which should be taken into account in the water diversion plan. Because of the effect of climate change, runoff had dropped sharply in the Bosten Lake valley, and water diversion from Bosten Lake decreased significantly since 2002. If this drop becomes common in other runoff areas of the upper Tarim River, it is unclear what the outcome will be. After all, most of these rivers have similar water supply characteristics to those of the Bosten lake valley.

Acknowledgements

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