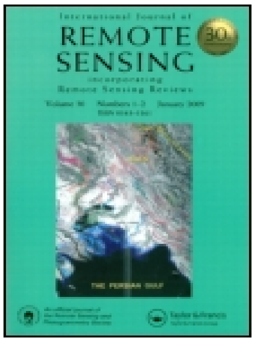

International Journal of Remote Sensing

ISSN: 0143-1161 (Print) 1366-5901 (Online) Journal homepage: http://www.tandfonline.com/loi/tres20

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**To cite this article:** Xiaomei Jin, Jintao Liu, Songtao Wang & Wei Xia (2016) Vegetation dynamics and their response to groundwater and climate variables in Qaidam Basin, China, International Journal of Remote Sensing, 37:3, 710-728, DOI: 10.1080/01431161.2015.1137648

**To link to this article:** http://dx.doi.org/10.1080/01431161.2015.1137648

INTERNATIONAL JOURNAL OF REMOTE SENSING, 2016
VOL. 37, NO. 3, 710–728
http://dx.doi.org/10.1080/01431161.2015.1137648

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# Vegetation dynamics and their response to groundwater and climate variables in Qaidam Basin, China

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**ABSTRACT**

This article discusses an evaluation of Moderate Resolution Imaging Spectroradiometer (MODIS) time-series data for monitoring vegetation variation in Qaidam Basin, Northwest China. In this study, 16 day composite 250 m normalized difference vegetation index (NDVI) products (MOD13Q1) acquired from 2000 to 2011 were processed to determine vegetation cover fraction (VCF) for detecting the annual dynamics of different types of vegetation cover in the basin and the products were validated by comparing field measurement in spatial distribution. The results show that the annual NDVI value increased from 0.126 to 0.172 on average between 2000 and 2011. The basin interior is dominated by desert and 74% of the area is covered by low-density shrubs and bare soil. Both areas of bare soil and low-density vegetation present a decreased rate, whereas medium-, medium-high-, and high-density vegetation show increase trends in the vegetation cover. Generally, the vegetation fluctuation depends on various attributes such as climate change, elevation, water table depth, and total dissolved solids (TDS) in arid areas. We found strong statistical correlation between NDVI time series and climatic factors such as air temperature and precipitation. There is also an agreement between the spatial distribution of NDVI value and elevation, because elevation has important impacts on the distribution of vegetation pattern, which are different in coverage. The vegetation dependent on water table depth is more complicated: shrubs of *Phragmites australis, Artemisia desertorum,* and *Tamarix ramossissima* Ledeb. are sensitive to water table depth and the maximum NDVI occurred at a water table depth shallower than 2 m. However, high-height shrub such as *Nitraria Schoberi* L. reflects less dependence on water table depth. Normally, vegetation can develop well at TDS between 0 and 3 g $l^{-1}$ whereas *Tamarix ramossissima* Ledeb. can still survive when the TDS is larger than 8 g $l^{-1}$.

**ARTICLE HISTORY**
Received 30 April 2015
Accepted 20 December 2015

## 1. Introduction

As a main component of the ecosystem, vegetation plays an important role in water cycle and energy exchange on the ground surface (Zhang et al. 2013; Xiao and Moody

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2005; Hoffmann and Jackson 2000; Nemani et al. 1996). It is a sensitive indicator in global change study and can be a natural link among atmosphere, soil, and water (Kutiel et al. 2004; Li et al. 2003). Regarding shrubs, grasslands, forests, and agricultural crops, vegetation can prevent land desertification and conserve water and soil. In arid and semi-arid areas, vegetation is usually sparsely distributed, and patterns of vegetation distribution are frequently studied using remote-sensing information at a large scale (Rigge et al. 2013; Elmore et al. 2000; Hurcom and Harrison 1998). Long-term change in vegetation can potentially detect early signals of slow land degradation or an improvement in a broad scale.

The normalized difference vegetation index (NDVI), derived from the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS), has been widely used as an index for monitoring and quantifying vegetation change over time. It is extremely sensitive to plant growth and can well reflect the degree of vegetation cover to a certain extent. A series of scientific studies on regional vegetation change has been carried out based on NDVI data (Nash et al. 2014; Li and Fox 2012; Spruce et al. 2011; Lunetta et al. 2006; Reed 2006; Anyamba and Tucker 2005). Some of such research areas are in northwestern China, and they mainly focus on vegetation change such as shrubs, alpine meadow, and grassland (Zhang et al. 2014; Song et al. 2011). Herein, a time series analysis for 250 m MODIS NDVI was used to present vegetation variation for Qaidam Basin, northwestern China.

Evaluation of the influence of environmental factors on NDVI is also very important for vegetation variation analysis. Climate change, topography, and water availability are vital factors impacting vegetation dynamics in both arid and semi-arid areas (Eamus et al. 2006; Naumburg et al. 2005; White, Kumar, and Tcheng 2005; Nemani et al. 2003). Climate variables such as temperature and precipitation usually control vegetation development, and NDVI has been revealed to be strongly related to these two climate factors (Sonfack et al. 2013; Clerici, Weissteiner, and Gerard 2012; Feilhauer, He, and Rocchini 2012; Wessels et al. 2007; Azzali and Menenti 2000). Precipitation and temperature generally shows a pattern of change over a long time, and thus may indicate an NDVI trend in some arid areas. Climate change may also improve the detection of NDVI variation with time on a large scale. Additionally, topographic variabilities including elevation, slope, and aspect can cause significant heterogeneities and result in different vegetation distribution and composition (Pfeffer, Pebesma, and Burrough 2003; Walsh et al. 2001; Franklin, Woodcock, and Warbington 2000). A correlation analysis between elevation and vegetation pattern was performed in some studies and it was found that topography exerts a dominant effect on vegetation distribution, along with climate variabilities such as solar radiation, precipitation, and temperature (Jin et al. 2009; Velázquez-Rosas, Meave, and Vázquez-Santans 2002). In arid and semi-arid environments, water table depth is reported to be an important factor impacting the vegetation cover and this ecosystem can be defined as groundwater-dependent vegetation (Lv et al. 2013; Jin et al. 2011; Benyon, Theiveyanathan, and Doody 2006). However, different vegetation types respond diversely to variations in water table depth. Some species are phreatophytic vegetation and cannot survive without groundwater, whereas some plants are non-groundwater-dependent vegetation, where they absorb groundwater occasionally when available and can also remain alive without it. Thus, water table depth can be an indicator to identify land-surface vegetation pattern in some arid areas (Goedhart and Pataki 2011; Wierda et al. 1997; Stromberg, Tiller, and Richter 1996). Although research on the impact of climate change, topography, and water table depth on vegetation can be helpful to explain ecosystem response to land-use change, our comprehension is far from adequate since vegetation pattern is mostly heterogeneous in space and can be affected by numerous factors.

This study takes a representative area of plateau sparse vegetation ecosystem – Qaidam Basin – as the study area, 250 m MODIS NDVI data with temporal resolution of 16 days from 2000 to 2011 as the data source, to investigate the spatial distribution pattern and the inter-annual variation trend of sparse vegetation over the past 12 years. The correlation between climate variabilities and NDVI was illustrated in the monitoring response of vegetation growth to climate change. Additionally, two-fold significance was addressed in this research: (1) the impact of elevation on the vegetation distribution characteristics and dominant plants in different elevations; and (2) the responses of vegetation distribution on water table depth and total dissolved solids (TDS).



## 2. Study area

Qaidam Basin is located in the northern part of Tibet Plateau, China, and stands between 34°40′–39°20′ N and 90°00′–99°20′ E (Figure 1). The total basin area is around 276,233 km$^2$ and the interior basin is 152,393 km$^2$. Surrounded by the Qilian, Qimantagh, and Altun mountains, the Qaidam Basin is a plateau basin and the elevation ranges from 2652 to 6600 m. The study area here includes both the interior basin and the surrounding mountains.

Basically, the growing seasons of Qaidam Basin are from May to September. The annual air temperature of the central basin is 4.77°C and it is only 1.53°C at the boundary of the basin. Owing to the strong sunshine and arid temperate climate, the annual precipitation spatially varies between 16 and 190 mm from west to east, and mostly it is insufficient for vegetation growth. In contrast, the annual pan evaporation ranges from 1974 to 3183 mm (obtained from the observed pan evaporation of eight meteorological stations), especially in the western parts of the interior basin where the annual evaporation can be several times greater than the annual rainfall. However, this mostly happens

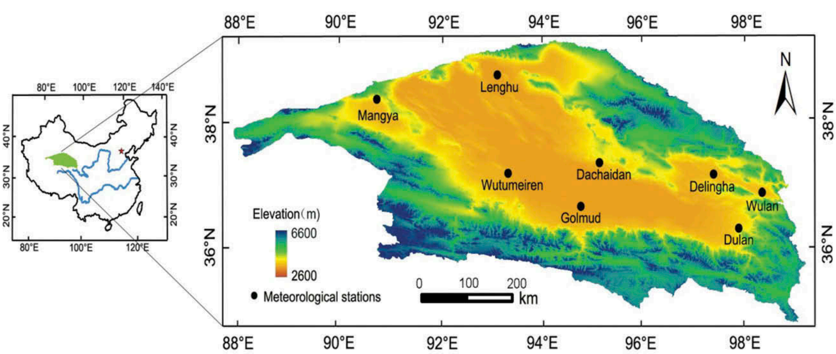


Figure 1. Location and DEM map of Qaidam Basin. The eight black points represent the weather stations.

in the arid interior basin and the climate in the mountainous areas with high elevation is usually cold and wet.

Spatially, the interior basin is dominated by a desert covered with low vegetation coverage *xeric* and *halophytic* plant species such as *Artemisia desertorum, Phragmites australis, Calligonum mongolicunl, Tamarix ramossissima* Ledeb., *Nitraria Schoberi* L., *and Achnatherum splendens*. With high elevation, the mountainous area around the Qaidam Basin is mainly covered by alpine meadow. Sixty-four lakes are distributed in the basin and they receive recharge from streams and groundwater. The evapotranspiration (ET) process results in a major loss of the lake water in the interior basin. With 48 salt lakes distributed in the area, the basin is rich in salt, oil, and coal minerals.

The interior basin is mainly distributed along the alluvial plain and its main soil type is fine sandy gravel. Almost all of the vegetation grows in this fine sandy gravel except for *Phragmites australis*. There is clay distributed in the western part of the interior basin and the abundantly-growing plant is *Phragmites australis* because of the high soil moisture in the clay. The clay is also distributed in the mountainous area, which is covered by the alpine meadow.



## 3. Material and methods

### 3.1. *NDVI map*

The NDVI data from MODIS can illustrate the spatial and temporal variations of vegetation. The MODIS NDVI data has been corrected for ozone absorption, molecular scattering, and aerosols (Friedl et al. 2002; Zhan et al. 2000). With 250 m spatial resolution, the MODIS NDVI data has been used in a wide range of research, such as drought monitoring, global vegetation variation, agricultural, and hydrologic modelling (Caccamo et al. 2011; Hwang et al. 2011; le Maire et al. 2011; Wardlow, Egbert, and Kastens 2007; Lunetta et al. 2006). In this study area, 96 MODIS NDVI images of the 16-day composites of June, July, August, and September in the four years from 2000 to 2011 were used since these four months are the most active season for vegetation growth during a year in Northwest China. The pattern of vegetation cover in these regions can be best reflected by the NDVI values of June, July, August, and September. The NDVI increases with vegetation growth and its values range from −1 to 1, where positive NDVI values indicate vegetation and negative values correspond to an absence of vegetation such as bare soil, waterbody, snow, or ice (Myneni et al. 1995).

### 3.2. *Vegetation cover fraction map*

Vegetation cover fraction (VCF) is one of the important variables for reflecting vegetation growth and understanding the ecosystem changes. It is sensitive to land desertification and land degradation in both arid and semi-arid areas. VCF is defined as the percentage of vegetation covering the land-surface area, and it can quantitatively assess the vegetation community cover condition and forest management. It is also an important index for global vegetation change monitoring and regional climate modelling (Jiménez-Muñoz et al. 2009; Trimble 1990). It can be determined from remote-sensing data using NDVI (Gutman and Ignatov 1998).

In Qaidam Basin, the VCF is obtained using Equation (1) as follows:

$$\mathrm{VCF} = \frac{(\mathrm{NDVI}) - (\mathrm{NDVI})_s}{(\mathrm{NDVI})_v - (\mathrm{NDVI})_s}, \tag{1}$$

where $(\mathrm{NDVI})_v$ and $(\mathrm{NDVI})_s$ represent the values of NDVI for 100% vegetation and bare soil, respectively. In the Qaidam Basin, the $(\mathrm{NDVI})_v$ and $(\mathrm{NDVI})_s$ correspond to NDVI values for 98% and 3% of accumulative percentage, respectively.

### 3.3. *ET map*

In this study, the ET map was applied to determine the NDVI threshold between bare soil and vegetation. First, MODIS Surface-Reflectance Product (MOD 09) and land-surface temperature data (MOD 11) were selected to estimate the ET rate on a large scale using the Surface Energy Balance System (SEBS) algorithm (Su 2002; Su et al. 2001). For consistency purposes, the product of MOD 11 was resampled into the same spatial resolution of 500 m as MOD 9, and these two products of June, July, August, and September during 2008–2010 were used in SEBS in this study to estimate the daily ET. Second, for correlation analysis with ET, the MODIS NDVI maps of the same periods were upgraded to the same 500 m-resolution grid using the arithmetic mean. The new NDVI maps match the ET distribution maps. There are in total 1,104,932 pairs of ET and NDVI values. The NDVI values were grouped by 0.005 value ranges and the corresponding daily ET values were averaged. Third, the non-linear relationship between NDVI and daily ET can determine the NDVI threshold of vegetation and bare soil since this non-linear relationship can be explained as follows. A pixel becomes totally covered by water when the NDVI is smaller than 0.02 and ET (mainly evaporation from the water surface) reaches its maximum value. As the NDVI increases from 0.02, the pixel is covered more and more by bare soil and reaches minimum evaporation at an NDVI threshold. As the NDVI increases beyond this point, the pixel is covered less and less by bare soil and more and more by vegetation and ET thus increases to a high value. Therefore, the bare soil and vegetation areas can be differentiated by this NDVI threshold in Qaidam Basin.

### 3.4. *Depth to water table map*

Field measurements of groundwater level in the Qaidam Basin were performed at Wutumeiren (WTM), Nomuhong (NMH) areas, and Wulan basin (WL) during June 2011. Groundwater levels in most of the sites were measured in wells, as shown in Figure 2. There were 131 groundwater-level measurements in the WTM area, 134 in the NMH area, and 148 in the WL basin. The contour maps of water table depth in these two areas were constructed by interpolating field measurements to the same 250 m-resolution grid as NDVI data using ordinary Kriging (Isaacs and Srivastave 1989). In most part of the Wulan area, the water table depth is less than 8 m, and the depth in the WTM area is less than 3 m.

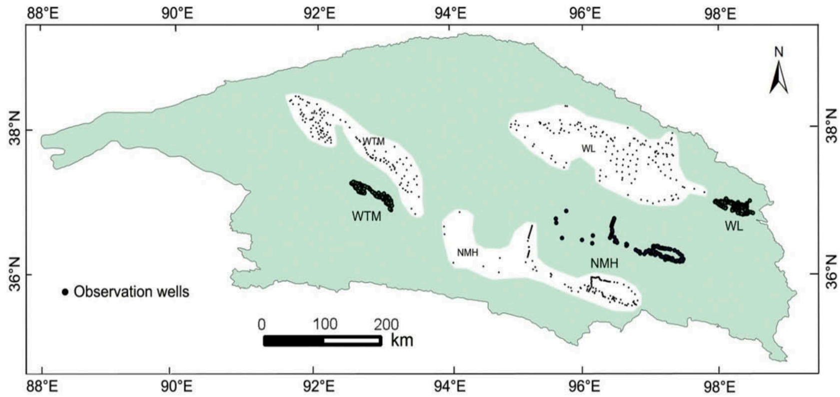


Figure 2. Distribution of groundwater observation wells in WTM, NMH, and WL areas.



### 3.5. *TDS data*

A total of 207 samples of groundwater were collected in WTM, NMH, and WL areas of Qaidam Basin during the summer of 2010–2011. The TDS of these samples were measured and 191 values with TDS smaller than 10 g $l^{-1}$ were used to discuss the effect of TDS on vegetation.

## 4. Results

### 4.1. *Spatial and temporal distribution of NDVI*

The average NDVI image of 2011 is illustrated in Figure 3 and the results showed that the NDVI varied from −0.05 to 0.47 and it gradually increased from west to east. The mountainous area is distributed around the basin and mostly covered by alpine meadows, whereas the basin interior is dominated by desert. The statistics of NDVI values with different land-cover classes is presented in Table 1. It shows that the interior basin is mainly covered by desert (42.7%) and low-NDVI shrublands (32.51%). The high-NDVI shrublands, alpine meadow, and farmland account only for 4.08%. The waterbody with very low NDVI (<0.02) is 2.54% of the total basin and mostly are salt lakes. By statistics of the percentage of Qaidam Basin shown in Figure 3, the distribution of NDVI was found to be consistent with the moisture condition. The majority area with $0.02 \le$ NDVI < 0.055 can be seen in the western arid region and that with NDVI > 0.1 in the eastern area of the basin. This can be mostly explained by the status that the spatial distribution of NDVI is decided by the climate condition.

The time series of mean NDVI of Qaidam Basin can reflect the overall dynamics of vegetation with time, which can be linked with the change of the eco-environment. Thus, the temporal variation of NDVI can serve as an indicator of eco-environmental variation in an arid area. Figure 4 plots the variation of intra-annual mean NDVI associated with all pixels of Qaidam Basin during the period of 2000–2011. From 2001 to 2005, the mean NDVI value increased from 0.126 to 0.156, then dropped to 0.145 in 2008; between 2008 and 2010, the NDVI increased rapidly up to a maximum value of

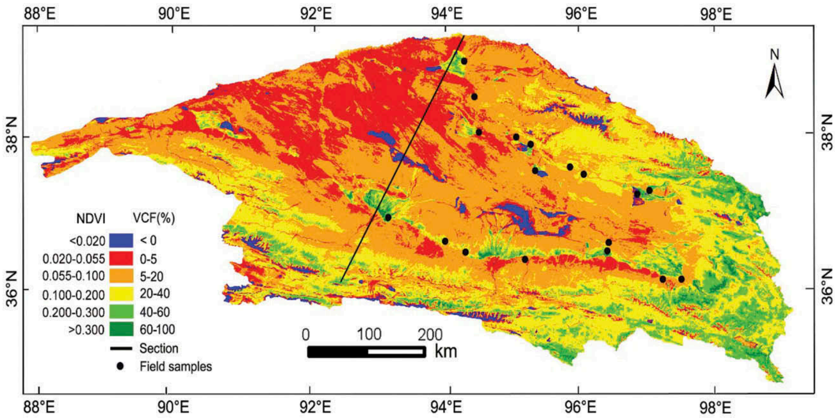


**Figure 3.** NDVI and VCF distribution of 2011 in Qaidam Basin. The black solid line is a cross section of different land-cover classes and the black points are VCF field samples.

**Table 1.** Statistics of NDVI distribution in Qaidam Basin.

| NDVI | <0.020 | 0.020–0.055 | 0.055–0.100 | 0.100–0.200 | 0.200–0.300 | >0.300 |
|---|---|---|---|---|---|---|
| Landscape | Waterbody | Desert | Low-NDVI shrub | Moderate-NDVI shrub | High-NDVI shrub, alpine meadow | Farmland, alpine meadow |
| Percentage (%) | 2.54 | 42.70 | 32.51 | 18.17 | 3.85 | 0.23 |

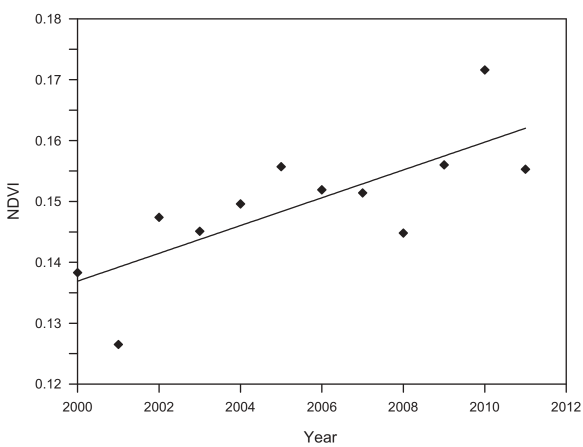


**Figure 4.** Long-time variation of NDVI in Qaidam Basin during 2000–2011.

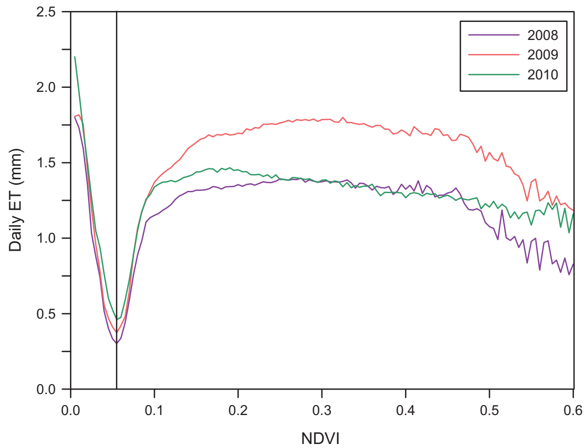


Figure 5. Relationship between NDVI and daily ET during the period 2008–2010 in Qaidam Basin.



0.172, and since then, it decreased back to 0.155 in 2011. Overall, the NDVI values fluctuated between 0.126 and 0.172.

## 4.2. *NDVI threshold between bare soil and vegetation area*

Figure 5 presents the non-linear relationship between NDVI and daily ET during 2008–2010. The variation of NDVI with ET during the three years was similar and the maximum daily ET was obtained at an NDVI value of 0.005. As the NDVI increases, ET decreases to its minimum of 0.3 mm at an NDVI value of 0.055, and the ET increased when the NDVI increased beyond 0.055. This relationship can be understood as that a pixel is totally covered by water when the NDVI is very low (<0.02) and the evaporation of water surface is in a maximum value. As the NDVI increases, the pixel is covered more and more by bare soil and its evaporation reaches the minimum value at NDVI = 0.055. The pixel is covered less by bare soil and more by vegetation and ET increases when the NDVI increases beyond 0.055. Therefore, it can be deduced that there is vegetation on the ground when the NDVI is larger than 0.055. Further validation analysis of NDVI in different land-cover classes is shown in Figure 6. A typical section (Figure 3) was selected from north to south in the basin and it is crossed different land-cover classes. The NDVI

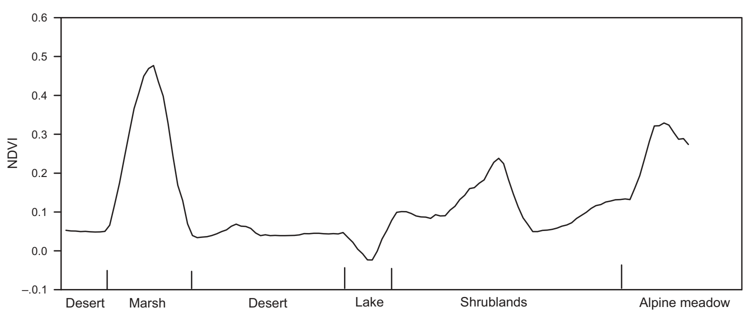


Figure 6. NDVI of different land-cover classes in the section.

of marsh in the north part of the basin varied between 0.055 and 0.476. The NDVI ranged from −0.02 to 0.02 over the waterbody and from 0.055 to 0.250 over shrublands. The alpine meadow with NDVI = 0.162–0.360 is mainly developed in the southern part of the basin.

## 4.3. *Changes in VCF*

The VCF can be used to quantitatively evaluate the status of land surface: higher VCF indicates higher vegetation cover, bare soil has small VCF values, and negative VCF is generally caused by waterbodies. Using the average NDVI of June, July, August, and September of each pixel in Qaidam Basin over 2011, the spatial distribution of VCF was calculated (Figure 3). The result shows that in 2011 48.4% of the study area was covered by low- and medium-density vegetation, 7.2% of the basin was occupied by medium-high- and high-density vegetation, and 41.6% was bare soil (Table 2). In the present study, the VCF of June, July, August, and September from 2000 to 2011 in the Qaidam Basin was estimated and the inter-annual VCF change of different classes is illustrated in Figure 7. The 41.6% of the basin with bare soil (VCF = 0–5%) and 32.1% of the area with low-density vegetation (VCF = 5–20%) showed a decreased rate, whereas the variation rate in the other classes corresponded to an increase in vegetation cover. In general, the variation of VCF during these 12 years was significant. The area of bare soil dropped from 134,526 $km^2$ in 2000 to 119,333 $km^2$ in 2011 and the negative annual variation rate is very significant (Figure 7(*a*)). The low-density vegetation area showed a relatively insignificant trend to decrease with year (Figure 7(*b*)). Compared with the above decrease trend, the areas of medium-density vegetation, medium-high-density vegetation, and high-density vegetation showed an increase of vegetation cover during these 12 years (Figure 7(*c*)–(*e*)).

To examine the true value of VCF, field samples were collected in July 2012. Eighteen samples were designed and located by the possible area with the water table depth shallower than 5 m (Figure 3). The area of each sample was 0.5 km × 0.5 km. Four to seven plots of 1 m × 1 m, 5 m × 5 m, and 10 m × 10 m were measured in each sample based on different vegetation statuses. To reflect the total feature of vegetation in samples, the plots were distributed randomly in each sample. Vegetation characteristics of species composition, numbers, diameter, and height of canopy were recorded in each plot. To improve the accuracy of VCF by field samples, the visual estimated results of four to seven plots were averaged and the arithmetical mean value was considered as the measured VCF of this sample. The comparison between the estimated VCF and the measured VCF of 18 samples is listed in Table 3. The maximum difference in coverage of the same sample was

**Table 2.** Statistics of VCF of July 2011 in Qaidam Basin.

| VCF (%) | Classification | Area percentage (%) |
|---|---|---|
| <0 | Waterbody | 2.8 |
| 0–5 | Bare soil | 41.6 |
| 5–20 | Low density | 32.1 |
| 20–40 | Medium density | 16.3 |
| 40–60 | Medium-high density | 5.0 |
| 60–100 | High density | 2.2 |

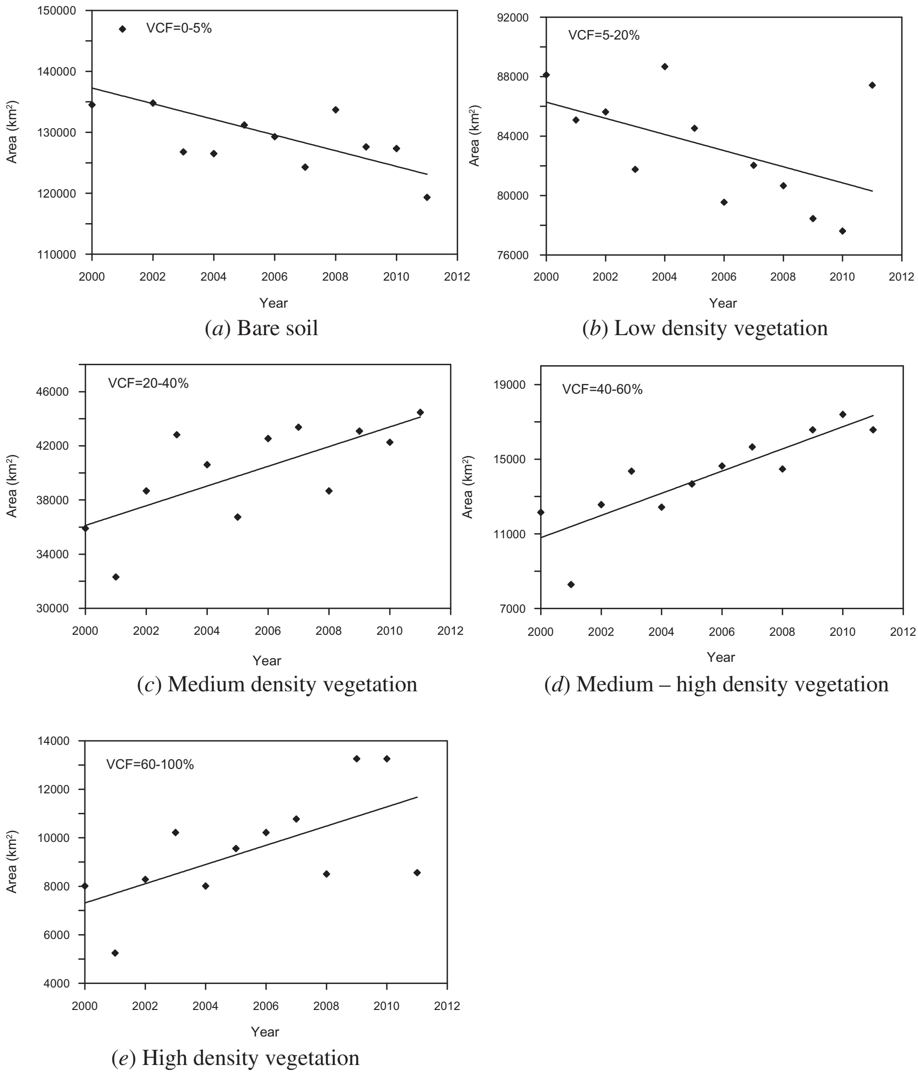


**Figure 7.** VCF variation of different classes during the period 2000–2011 in Qaidam Basin.



8.04%, whereas the minimum value was 0.06%. Mostly, the error in samples with dense vegetation coverage was smaller than those samples with low VCF. The average absolute error of 18 samples was 2.79%. It was also noted that the estimated VCF and the measured VCF of the field survey were very relevant to coefficient of determination $R^2 = 0.965$.

VCF can be also an index for land desertification. Combining previous research work and the specific conditions of Qaidam Basin, land desertification can be divided into four classes: severe degree (VCF ≤ 10%), moderate degree (VCF = 10–30%), light degree (VCF = 30–50%), and no desertification (VCF > 50%). Figure 8 summarizes the change in land desertification in Qaidam Basin from 2000 to 2011. It shows that the area of severe land desertification decreased remarkably in the basin. It reduced by about 25.8% in severe degree areas from 2000 to 2011 while the other three degrees increased by

Table 3. Comparison between estimated VCF and measured VCF by field survey.

| No | Plants | Estimated VCF (%) | Measured VCF (%) | Deviation (%) |
|---|---|---|---|---|
| 1 | *Artemisia desertorum* | 16.36 | 13.53 | 2.83 |
| 2 | *Artemisia desertorum* | 4.54 | 9.74 | −5.2 |
| 3 | *Phragmites australis* | 17.34 | 22.95 | −5.61 |
| 4 | *Tamarix ramossissima* L. | 54.24 | 52.97 | 1.27 |
| 5 | *Artemisia desertorum* | 5.32 | 6.37 | −1.05 |
| 6 | *Phragmites australis* | 42.39 | 40.16 | 2.23 |
| 7 | *Mixed xeric plants* | 32.10 | 32.82 | −0.72 |
| 8 | *Phragmites australis* | 67.82 | 67.32 | 0.5 |
| 9 | *Agropyron cristatum* | 24.51 | 21.21 | 3.3 |
| 10 | *Achnatherum splendens* | 35.33 | 33.68 | 1.65 |
| 11 | *Artemisia desertorum* | 18.93 | 15.47 | 3.46 |
| 12 | *Achnatherum splendens* | 30.44 | 34.87 | −4.43 |
| 13 | *Mixed xeric plants* | 3.47 | 8.63 | −5.16 |
| 14 | *Agropyron cristatum* | 15.83 | 16.08 | −0.25 |
| 15 | *Nitraria Schoberi* L. | 9.85 | 13.63 | −3.78 |
| 16 | *Nitraria Schoberi* L. | 15.93 | 15.24 | 0.69 |
| 17 | *Nitraria Schoberi* L. | 11.90 | 11.84 | 0.06 |
| 18 | *Nitraria Schoberi* L. | 5.80 | 13.84 | −8.04 |
| Average deviation | | | | 2.79 |

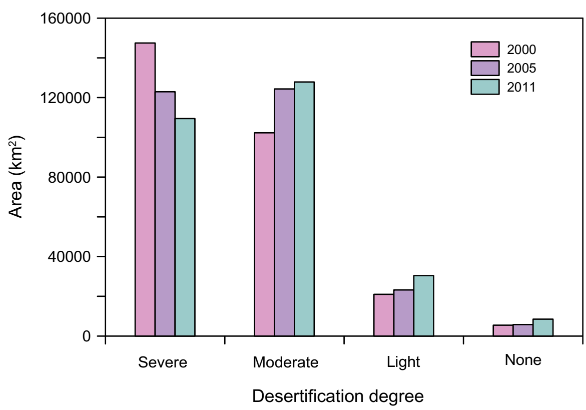


Figure 8. Change of land desertification in Qaidam Basin from 2000 to 2011.

Table 4. Degree of land desertification in Qaidam Basin (km$^2$, %).

| | Severe | | Moderate | | Light | | None | |
|---|---|---|---|---|---|---|---|---|
| Year | Area | Portion | Area | Portion | Area | Portion | Area | Portion |
| 2000 | 147497 | 53.4 | 102307 | 37.0 | 21002 | 7.6 | 5428 | 2.0 |
| 2005 | 122961 | 44.5 | 124307 | 45.0 | 23190 | 8.4 | 5775 | 2.1 |
| 2011 | 109453 | 39.6 | 127822 | 46.3 | 30441 | 11.0 | 8517 | 3.1 |

24.9%, 44.9%, and 56.9%, respectively, at the same time. Table 4 lists the situation of land desertification of Qaidam Basin from 2000 to 2011. This is evidence that a severe degree of land desertification appears to be decreasing with time and the eco-hydrological situation has actually improved in the Qaidam Basin as a result of climate change.

# 5. Discussion

## 5.1. *NDVI distribution and climate*

The mean NDVI, as a coarse index of biomass, proves sensitive to climate change (Zeng and Yang 2009). Solar radiation, precipitation, and temperature are key factors of vegetation growth through both direct and indirect mechanisms (Yu et al. 2012). Both temperature and precipitation affect the steppe vegetation in Qaidam Basin since it is in arid and semi-arid alpine environments. Considering the relationships between the monthly mean NDVI of June, July, August, and September and the corresponding monthly average temperature and monthly cumulative precipitation, it was found that NDVI increased with an increase in precipitation and air temperature (Figure 9). Considering the monthly average temperature and cumulative precipitation obtained from the eight weather stations during 2000–2011 as independent variables, a linear regression of the mean NDVI *versus* the two climate factors was established. The coefficients of determination between NDVI and temperature, precipitation were 0.617 and 0.658, respectively. Therefore, it can be concluded that the NDVI change basically depends on the water condition.

## 5.2. *NDVI variation and elevation*

Another relevant factor that influences plant growth in plateau environments is elevation since elevation can determine precipitation and temperature patterns, which affect the soil moisture availability and thermal conditions on a regional scale. In general, soil moisture increases for higher precipitation and results in less ET with rising elevation, but temperature decreases. In order to understand the impacts of elevation on steppe vegetation, we selected the typical section in Figure 3 and developed a simple method to define the relationship between NDVI and elevation. In this method, the elevation image was resampled with the same spatial resolution as NDVI and then patches in the section were defined as 250 m elevation intervals from 2700 m to 5200 m. The corresponding NDVI larger than 0 was averaged in this elevation interval. Figure 10

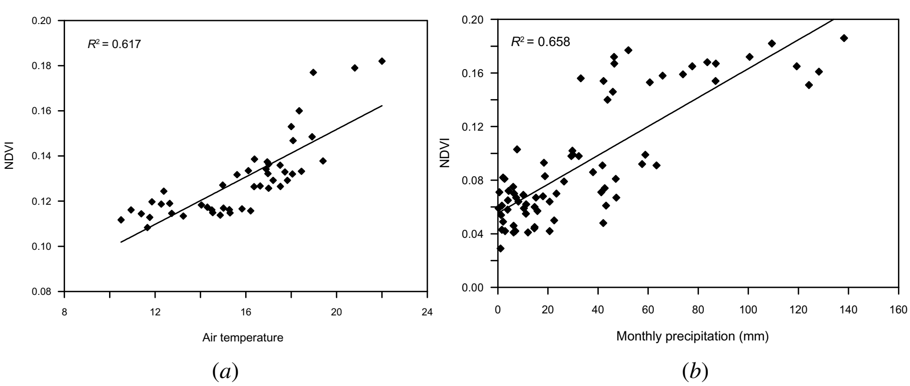


**Figure 9.** The relationships between NDVI and climate factors in the Qaidam Basin. (*a*) The relationship between NDVI and monthly average temperature; (*b*) the relationship between NDVI and cumulative monthly precipitation.

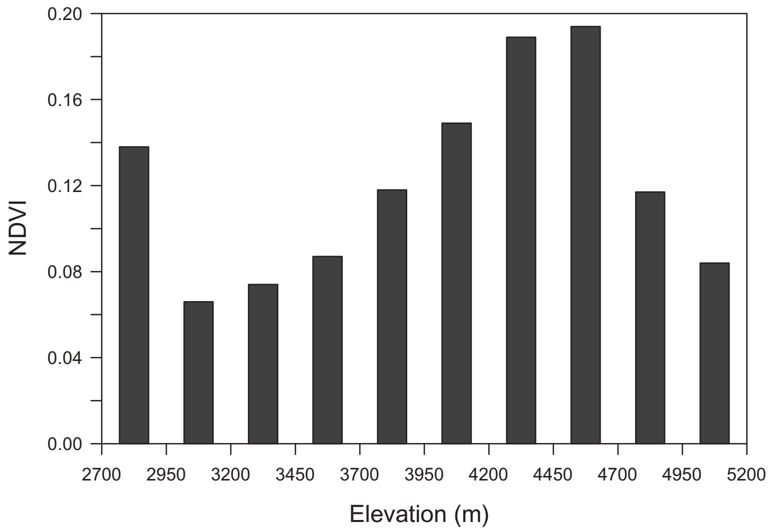


**Figure 10.** The relationship between NDVI and elevation in Qaidam Basin.



shows the distribution of NDVI across these elevation intervals in the typical section. Higher NDVI in the 2700 and 2950 m elevation intervals reflect basin interior and significant shrubs in these elevations. We also note that these elevation intervals occupied a small portion of the basin and it mainly distributed along the vegetation zone from the east to the west in middle-south of the basin. The maximum NDVI was distributed in elevation between 3950 m and 4700 m and it is mostly the alpine meadow in the south border of the basin. Lower NDVI values distributed in the 2950 m and 3700 m elevation intervals show desert and bare soil in these elevations. These elevation intervals are mainly in the northern area and comprise a relatively big portion of the basin. Thus, the spatial distribution of NDVI has complex correlations to elevations, which is due to variations in background moisture and temperature conditions.

### 5.3. *NDVI and depth to water table*

In arid and semi-arid areas, the vegetation distribution is certainly related with groundwater. From the eco-hydrological point of view, groundwater is a fundamental resource providing the transpiration water for vegetation. In dry lands particularly, groundwater plays an important role in the diversity, function, and structure of plants (Robinson et al. 2008). In the vast basin interior of Qaidam Basin, groundwater is the key factor restricting vegetation distribution. The dynamics of depth to water table are vital to better understand the diversity and distribution of vegetation growth.

NDVI is a composite index impacted by all species in a location since it is represented by the average vegetation cover of the entire canopy at each site. Therefore, the relationship between NDVI and depth to water table reflects the average vegetation growth of all plants to water table depth. In Qaidam Basin, some of the species were extremely sensitive to water table depth whereas others were not. To examine the different dependencies of vegetation on depth to water table, the arithmetic mean

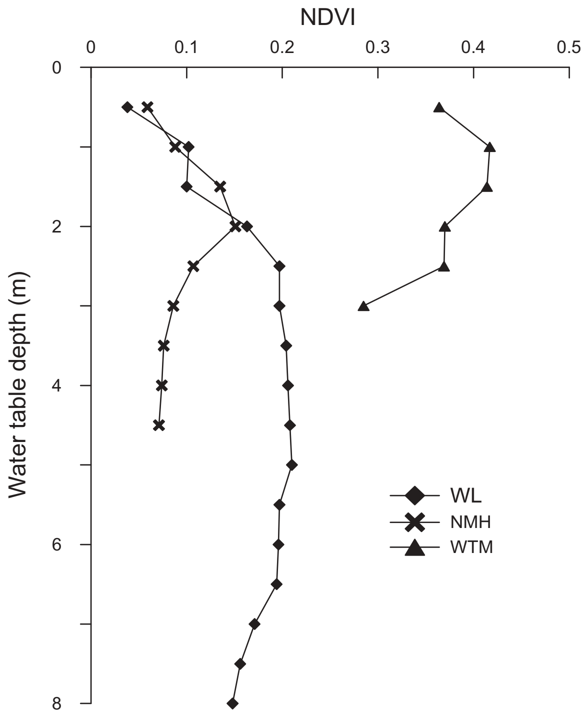


**Figure 11.** The relationship between NDVI and water table depth.



NDVI values of WTM, NMH, and WL areas were calculated with increase of water table depth (Figure 11). Analysis was restricted to these three areas where the water table depth is mostly less than 8 m, and 0.5 m intervals of water table depth were used to capture a group of NDVI values. As illustrated in Figure 11, for zone WTM, the mean NDVI declines with increasing water table depth. This phenomenon agrees well with field investigation: in WTM where the water table depth is shallow (less than 3 m) and the area is covered by shrubland dominated by *Phragmites australis*, the density of shrubs is larger than other areas. The root zone of *Phragmites australis* is shallow so that it is highly dependent on groundwater availability. In the NMH area, there is a similar trend of decrease in NDVI with increase of water table depth when the depth is larger than 2 m. The density and vegetation cover of shrubs are significantly smaller than those in the WTM zone. These shrubs in the NMH area are mainly dominated by *Artemisia desertorum* and *Tamarix ramossissima* Ledeb. Higher soil salt content hindered plants' growth when the water table depth is less than 1 m and large NDVI occurred at the water table depth of 2 m. Below 2 m depth, deep water table depth incurs an increased resistance to water flow to the roots and further to the canopy and results in lower NDVI. The NDVI change indicates that shrubs in the NMH zone are also dependent on groundwater depth. In contrast, the relationship between vegetation and water table depth in the WL zone was more complex because the plant in this zone is a mixture of crops and shrubs. The relatively larger NDVI values occurred at the water table depth between 2.5 m and 6.5 m. A small part of croplands is located in the WL area. The higher NDVI values in the shallow water table depth may correspond to the farmland since crops are

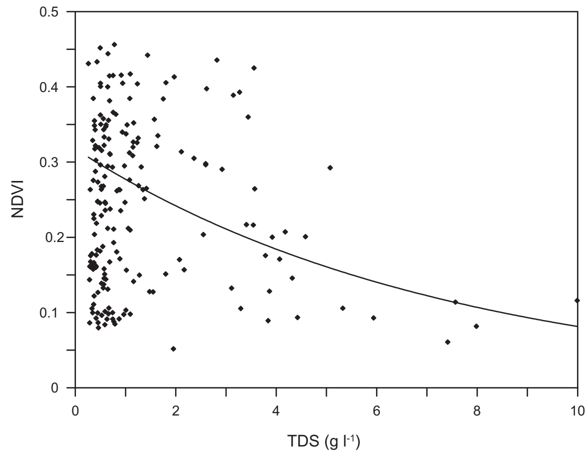


**Figure 12.** Scatter plot of NDVI and TDS in Qaidam Basin.

irrigated and thus have larger NDVI. The other high NDVI values with deep water table depth may reflect the shrubs. Shrubs, such as *Nitraria Schoberi* L., are commonly distributed in the WL area. A large part of the height of *Nitraria Schoberi* L. is larger than 0.8 m and the density is extremely high in some places. This type of shrub can extend roots to a depth of 12 m or more in the arid region. Therefore, the vegetation dependent on groundwater is significantly different in Qaidam Basin.

### 5.4. *NDVI and TDS*

TDS is a measurement of the dissolved salts in the water. It can cause nutrient imbalance and affects the availability of nutrients to plant roots. In general, water with a TDS value of over 5 g $l^{-1}$ is unsuitable for irrigation of many plants. However, the sensitivity and tolerance of vegetation to TDS are significantly different in arid areas, such as *Tamarix ramossissima* Ledeb. can tolerate very high levels of TDS. In Qaidam Basin, TDS is also one of the important factors limiting vegetation growth. The scatter plot of TDS and the corresponding NDVI are shown in Figure 12. Although the TDS values vary from 0 to 10 g $l^{-1}$, a dark cloud of points concentrates in the area of TDS < 2 g $l^{-1}$. The frequency distribution of NDVI is less when the TDS is larger than 2 g $l^{-1}$ and almost no vegetation can survive in TDS over 8 g $l^{-1}$. To validate the result, some typical vegetation was investigated and the measurement shows that the suitable TDS level for *Artemisia desertorum, Phragmites australis, Calligonum mongolicunl*, and *Nitraria Schoberi* L. is between 0 and 3 g $l^{-1}$, whereas for *Tamarix ramossissima* Ledeb. and *Achnatherum splendens* it is in the range of 3–10 g $l^{-1}$.

## 6. Conclusions

MODIS NDVI was used in this study to illustrate the spatial and temporal distribution of vegetation in Qaidam Basin, northwestern China. Basically, NDVI values increased with time and fluctuated between 0.126 and 0.172 from 2000 to 2011. The basin interior is mostly covered by desert while the mountainous area is mostly covered by alpine meadows. The NDVI threshold between bare soil and vegetation area is 0.055. VCF was evaluated and 74% of the basin area is covered by low-density vegetation and bare soil. In general, bare soil and low-density vegetation showed a decreased rate whereas other classes corresponded to increased trends in vegetation cover.

In terms of impact factors, the NDVI was observed to increase with year; this was argued to be due to the rise of air temperature and precipitation. The effect of water table depth on vegetation is more complex since some plants are dependent on groundwater while others are not. In Qaidam Basin, *Phragmites australis* was seen to be highly dependent on groundwater and the corresponding water table depth is shallower than 3 m. Shrubs of *Artemisia desertorum* and *Tamarix ramossissima* Ledeb. are also sensitive to water table depth and the maximum NDVI occurred at the water table depth of 2 m. High-height shrub such as *Nitraria Schoberi* L. can extend roots to a depth of 12 m or more in Qaidam Basin. TDS is another important factor for limiting vegetation growth. Generally, no vegetation can survive in TDS over 8 g $l^{-1}$. It was found that the suitable TDS level for *Artemisia desertorum, Phragmites australis, Calligonum mongolicunl*, and *Nitraria Schoberi* L. is between 0 and 3 g $l^{-1}$, whereas for *Tamarix ramossissima* Ledeb. and *Achnatherum splendens* it is in the range of 3–10 g $l^{-1}$.

## Acknowledgements

We would also like to thank the EU project of Integrated Geo-spatial Information Technology and Its Application to Resources and Environment Management towards the GEOSS (IGIT) (FP7) for the help in this research. Finally, the authors would like to acknowledge the anonymous reviewers for their constructive comments in this article.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This work was supported by the National Natural Science Foundation of China [41372250] and Fundamental Research Funds for the Central Universities [2652014046] granted by Ministry of Education of China.

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