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P.A. Propastin, M. Kappas, N.R. Muratova

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# A remote sensing based monitoring system for discrimination between climate and human-induced vegetation change in Central Asia

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P.A. Propastin
*Department of Geography, Georg-August University Göttingen, Göttingen, Germany and Laboratory of Remote Sensing and Image Analysis, Kazakh Academy of Science, Almaty, Kazakhstan*

M. Kappas
*Department of Geography, Georg-August University Göttingen, Göttingen, Germany, and*

N.R. Muratova
*Laboratory of Remote Sensing and Image Analysis, Kazakh Academy of Science, Almaty, Kazakhstan*

## Abstract

**Purpose** – This paper aims to demonstrate the importance of taking into account precipitation and the vegetation response to it when trying to analyse changes of vegetation cover in drylands with high inter-annual rainfall variability.

**Design/methodology/approach** – Linear regression models were used to determine trends in NDVI and precipitation and their interrelations for each pixel. Trends in NDVI that were entirely supported by precipitation trends were considered to impose climate-induced vegetation change. Trends in NDVI that were not explained by trends in precipitation were considered to mark human-induced vegetation change. Modelling results were validated by test of statistical significance and by comparison with the data from higher resolution satellites and fieldtrips to key test sites.

**Findings** – More than 26 percent of all vegetated area in Central Asia experienced significant changes during 1981-2000. Rainfall has been proved to enforce most of these changes (21 percent of the entire vegetated area). The trends in vegetation activity driven by anthropogenic factor are much scarcer and occupy about 5.75 percent of the studied area.

**Practical implications** – Planners, decision makers and other interest groups can use the findings of the study for assessment and monitoring land performance/land degradation over dry regions.

**Originality/value** – The study demonstrates the importance of taking into account precipitation and the vegetation response to it when trying to analyse changes of vegetation cover in drylands with high inter-annual rainfall variability.

**Keywords** Deserts, Environmental management, Climatology, Central Asia, Landforms

**Paper type** Research paper

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## Introduction

Desertification refers to land degradation at arid, semi-arid and dry sub-humid areas and has been seen as one of the major environmental problems in large parts of the land surface. Desertification is considered as result of a series of complex natural, mainly climatic, and anthropogenic processes that leads to gradual environmental degradation or loss of the lands biological and economical productivity. The processes leading to desertification manifest in all compartments of ecosystems and are divided into the following groups: vegetative, biological, chemical, hydrological, and morpho-dynamical (UNCOD, 1977). Drylands occupy about 40 percent of the land surface, contain about 30 percent of the world's carbon and provide habitat to more than 1 billion humans. Their rangeland supports approximately 50 percent of the world's livestock. Taking into account the importance of these territories for the survival of the mankind it is not surprising that the international community is making intensive efforts to combat desertification in drylands and to preserve them from further degradation.

The first step on the way to stop and combat desertification is to detect areas already degraded or undergoing degradation and to assess the desertification degree. International institutions like FAO or UNEP have developed multidimensional methodologies for desertification assessment and promoted the monitoring of desertification with these methodologies. Common approaches to assess desertification demand for measurements of different indicators, which usually describe one or more aspects of desertification and provide data on threshold levels, status and evolution of relevant processes (FAO/UNEP, 1984; Veron *et al.*, 2006). Usually, these indicator measurements require both extensive fieldworks and analysis of remotely sensed data.

Degradation of vegetation cover is one of the most important and the most effective desertification indicator and can be rather easily monitored over broad areas using satellite imagery. Satellite derived Normalized Difference Vegetation Index (NDVI) has been commonly used as a general proxy of vegetation conditions and is a convenient tool for monitoring of vegetation cover at all scales from global to local. The vegetation absorbs a great part of incoming radiation in the visible portion of the electro-magnetic spectrum (VIS = 380-730 nm) and reaches maximum reflectance in the near-infrared channel (NIR = 730-1100 nm). The NDVI, defined as ratio (NIR-VIS)/(NIR + VIS), represents the absorption of photosynthetic active radiation and hence is a measurement of the photosynthetic capacity of the canopy. The NDVI is established to be highly correlated to green-leaf density, absorbed fraction of photosynthetically active radiation and above-ground biomass and can be viewed as a surrogate for photosynthetic capacity.

The NDVI has successfully served as a vegetation indicator in many studies on drought in watching desertification and land degradation (Kogan, 1997; Weiss *et al.*, 2001; Wessels *et al.*, 2004; Symeonakis and Drake, 2004). However, in many cases, the only use of NDVI for desertification monitoring can be problematic, for the reason that vegetation cover performance is strongly predicated on macro- and micro-climatic factors, such as temperature and rainfall distribution change, local topography characteristics etc. (Nicholson and Farrar, 1994; Yang *et al.*, 1998; Li *et al.*, 2002; Wang *et al.*, 2003). Therefore, discrimination between different causes of change in vegetation cover, climate and human activity is rather difficult. The neglecting of this aspect can lead to mistakes by evaluation of land conditions. For example, the contemporary greening patterns in the Sahel are proofed to be driven by an increasing trend in rainfall (Olsson *et al.*, 2005; Anyamba and Tucker, 2005). A methodology of discrimination between human and climate influence on vegetation cover can be based on identification of the climate signal in the inter-annual dynamics of vegetation activity. Once the climate signal is identified, it can be removed from the trends in vegetation activity. The remaining vegetation changes can be attributed to human influence. A number of recent studies have already developed monitoring systems for land degradation assessment that separate the dynamics of vegetation cover driven by climate and by human activity (Evans and Geerken, 2004; Li *et al.*, 2004). However, these and other similar monitoring systems have been designed for the use in a certain geographical region and are rather difficult transferable in other regions. Besides, all existing monitoring systems for desertification assessment based on the use of remotely sensed data are not perfect and the remote sensing community is making a good deal of effort to improve these systems using the most modern understanding of desertification and its causes.

In this study the authors have developed a simple and effective monitoring system for separation of driving forces for degradation and rehabilitation of vegetation cover in the former Soviet Republics of Central Asia (Figure 1). This separation is based on synchronous monitoring of two desertification indicators: vegetative and climatic. The monitoring system utilized a remotely sensed derived NDVI a dataset and dataset of precipitation amounts over the whole area of Central Asia during the period of 1981-2000. We examined inter-annual trends in vegetation activity and precipitation over the study period and separated climate-induced trends from human-induced. Furthermore, the monitoring system developed in this study enabled us to detect degradation/rehabilitation of vegetation cover in areas where no significant trends could be defined. Areas of degradation and rehabilitation of vegetation cover were mapped and measured.

## Data used in the study

### *GIMMS NDVI dataset*

Global inventory monitoring and modelling studies (GIMMS) NDVI dataset is a derivate from the Advanced Very High Resolution Radiometer (AVHRR) data and is freely available on the internet. The National Oceanic and Atmospheric Administration

**Figure 1.**
Map displays the region of the former Soviet Central Asia. The total area is about 6.5 million km$^2$

(NOAA) launched the AVHRR in 1978. AVHRR NDVI product has been broadly used for monitoring vegetation activity and environmental changes at regional and global scales (Xiao and Moody, 2004).

The authors used a dataset of GIMMS NDVI over the region of Central Asia associated with the period of 1981-2000. The GIMMS NDVI data, at 8 km spatial resolution, are originally processed as 15-day composites using the maximum value procedure to minimize effects of cloud contamination (Holben, 1986). Initially, the GIMMS dataset was designed to remove non-vegetated signals, which are effects of sensor degradation and stratosphere aerosols derived from the eruption of Mt. El-Chichon in 1982 and Mt. Pinatubo in 1991. The GIMMS dataset is already calibrated for sensor differences and orbital drift. However, before the GIMMS NDVI dataset was used in our monitoring system, we had thoroughly investigated it for occurrence of any non-vegetated noise. Various little noises remaining in the dataset were eliminated by calibrating the data against three time-invariant desert targets using a method described by Los (1993). After that, the data were averaged to generate a mean growing-season NDVI, mean summer NDVI and mean spring-summer NDVI for each year.

### *Precipitation dataset*

A monthly precipitation dataset used in this work originated from the global climatologic dataset produced by the School of Environmental Science, University of East Anglia (www.cru.uea.ac.uk/). New *et al.* (2000) gives a full description of the dataset and explains methods used for its derivation. This grid raster data are interpolated from climate station records and have a basic spatial resolution of 0.5.

For this work, the monthly precipitation data were resized to 8 km resolution to get a regional vision and to match the 8 km NDVI dataset. In order to minimize information distortion and loss during the conversion process, we used an interpolation method known as kriging with external drift. The use of an additional variable, altitude significantly decreased all negative consequences on the resizing of the source 0.5° dataset.

## Methods

### *General purpose of the methodology*

Satellite derived NDVI has proven to be an effective tool for monitoring vegetation cover and its conditions both at inter-annual and intra-annual time-scale. Previous studies have also shown a strong relationship between inter-annual changes in vegetation activity and precipitation, particularly in dry regions (Nicholson and Farrar, 1994; Richard and Poccard, 1998; Yang *et al.*, 1998; Li *et al.*, 2002; Wang *et al.*, 2003). Precipitation has a substantial control on NDVI through annual precipitation also in Central Asia. Examples demonstrating strong relationships between inter-annual dynamics of NDVI and precipitation in Central Asia are presented in Figure 2. The graphs display the time-series of annual precipitation and growing season NDVI over Kazakhstan and Uzbekistan during the period 1982-2000. To produce these graphs, data were averaged over the country's territory. This control, however, should be predictable in every point of the study area where the relationship between NDVI and precipitation are statistically significant. Since in drylands NDVI is usually stronger affected by rainfall than any other factors including human activities, assessment of desertification may not be based on the use of NDVI time-series alone, it should also take into account the rainfall.

Generally, speaking in terms of climatic effects on vegetation cover, a permanent or contemporary decrease of annual precipitation causes a decrease of photosynthetic activity of vegetation and diminishes the biological productivity potential of ecosystem. In this case one can speak only about desertification caused by climatic forces. However, if the human actions in the ecosystem does not adapt to the new conditions of the rainfall scarcity, the climate-induced degradation processes may be reinforced by human influence. Both driving forces of desertification, climate change and human impact, are closely interrelated in a compound of desertification processes. A separation of these driving forces is very difficult.

Nevertheless, a few recent studies tried to find solution of this problem by identification and removing the climatic signal from inter-annual NDVI dynamics (Li *et al.*, 2004; Evans and Geerken, 2004). The authors developed a simple monitoring system based on a concept of synchronism/non-synchronism between trends in rainfall and NDVI. This concept and the developed model will be thoroughly addressed in the next sections.

### *Concept of synchrony/asynchrony between long-time trends in precipitation and NDVI*

Since both climate conditions and climate variations have a substantial control on vegetation cover, we based our concept on the assumption that the response of vegetation to precipitation is relatively constant over time if there is no change in external factors, particularly human activity. A changed response to rainfall in an otherwise responsive area could be the result of change in human activity and influence.

This concept is explained on an example framework (Figure 3). In panel (a), the upward trends in NDVI and precipitation are synchronous. Obviously, here we observe improving vegetation cover due to increasing precipitation amount alone. In panel (b), the downward trends in NDVI and precipitation are also synchronous. In this case, decreasing NDVI is only driven by a decrease of precipitation without any human-induced worsening of vegetation cover, because human impact is not evident in the vegetation trend. In (c), the trends are asynchronous. NDVI increases even as

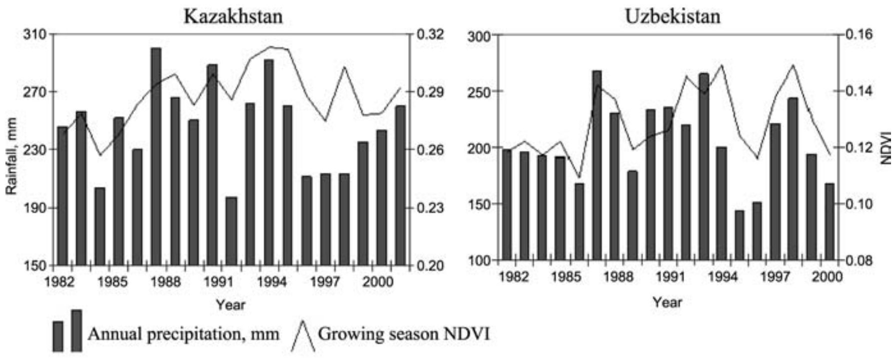

**Figure 2.**
Time-series of annual precipitation and the mean growing season NDVI for Kazakhstan and Uzbekistan

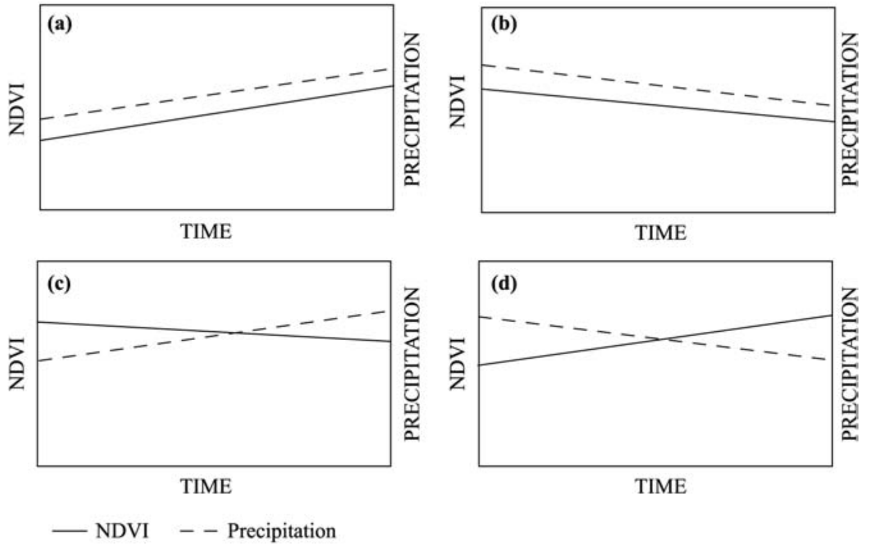

**Figure 3.**
Scenarios illustrating how the combined use of NDVI and precipitation time-series may help to detect vegetation cover being improved or degraded

precipitation decreases. This would indicate a case when vegetation cover is recovering due to diminishing human impact. In (d), the trends are once more asynchronous, but an increase of precipitation did not cause an improving of vegetation cover. On the contrary, the NDVI trend is negative. Here, we can suppose human-induced degradation of the vegetation cover.

However, degradation or improvement of vegetation cover is not always clearly manifested in NDVI trends. Despite the fact that, at some places, vegetation might not exhibit any significant changes, processes of degradation or rehabilitation of vegetation cover may go on. These processes may be revealed through observation of corresponding precipitation dynamics. If at these places precipitation amount shows any significant upward or downward trend, the response of vegetation to precipitation is changing over time. As the authors suggested that the response of vegetation to precipitation is an indicator for performance of vegetation cover, the authors can consider in such cases undergoing degradation or improvement caused by anthropogenic factor. These cases are presented in Figure 4. Both panels demonstrate vegetation cover being constant over the time of observation. However, in case (a) a significant increase of precipitation occurs during the time. This rainfall

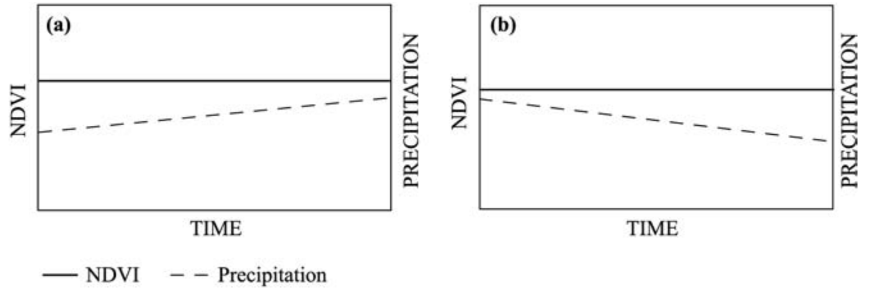

**Figure 4.**
The same as in Figure 3 but for the areas without significant trends in NDVI

increase does not force any improvement of vegetation activity. It means a drop of vegetation response to precipitation what could be a consequence of a degradation process driven by non-climatic factors, particularly human influence. In Panel (b) is shown an opposite case.

Figure 5 illustrates a theoretical and conceptual framework for discrimination between climate-induced and human-induced trends in vegetation cover. The framework aims to help by understanding the model that will be described in the following sections.

### *Model: Identification of climate signal in vegetation change*

The monitoring system based on synchrony/asynchrony concept would work only in areas where relationship between trends in vegetation and trends in climate factors are statistically significant. The first step of monitoring was to detect areas with statistically significant relationship between precipitation and NDVI. These areas were detected by regressing time-series of NDVI against precipitation amount at the per-pixel scale. On this way we derived a map of areas where the control of vegetation dynamics by precipitation is statistically significant and strong enough.

The second step was to find out pixels located within these areas, which exhibit any statistically significant trend in NDVI over the period of 1981-2000. These pixels represent territories of climate-driven change in vegetation cover. If the trend is negative, the territory is considered to undergo degradation of vegetation cover driven by a precipitation decrease. If the trend is positive, the territory undergoes improvement of vegetation cover. For example, if an area reveals statistically significant correlation with precipitation and NDVI increases throughout the study period, it considers to indicate a precipitation-driven improvement in vegetation cover (Figure 3(a)). If a trend in NDVI is negative and an area reveals strong relationship with precipitation, it considers indicating degradation of vegetation cover due to decrease in precipitation (Figure 3(b)).

### *Model: Identification of anthropogenic signal in vegetation change*

In general, vegetation cover reacts very sensitively on changes of precipitation particularly in dry regions (Yang *et al.*, 1998; Richard and Poccard, 1998; Li *et al.*, 2002;

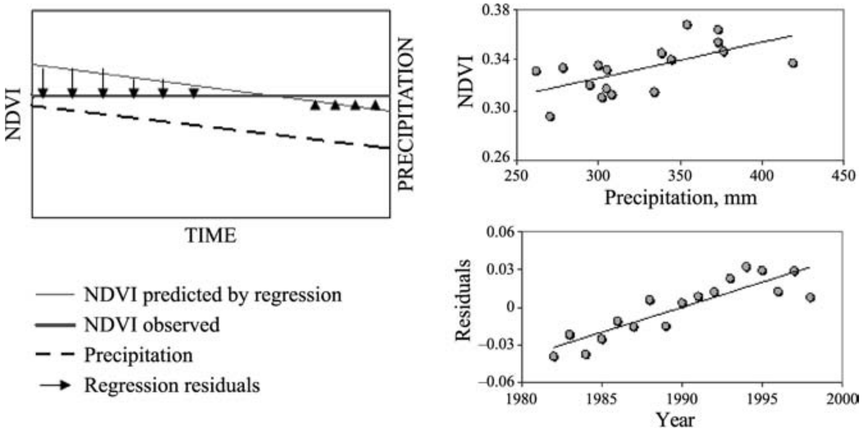

**Figure 5.**
The same as in Figure 6 but for the case of a human-driven improvement of vegetation cover

Wang *et al.*, 2003). If the response of vegetation to precipitation remains constant, increase/decrease of vegetation activity should exactly reflect changes in precipitation. That is the rule for undisturbed vegetation cover. Disturbance of vegetation cover is manifested through changing its response to climate (Wessels *et al.*, 2004; Li *et al.*, 2004). Generally, a worse response of vegetation to climate means a degradation of vegetation cover caused by non-climatic factors, particularly human impact, while a better response means an improvement of vegetation conditions. Figure 3 ((c) (d)) presents examples of human-induced changes in vegetation cover. In both cases the trends in NDVI are opposite to trends in precipitation.

However, degradation or rehabilitation of vegetation cover may also occur without any significant change in corresponding NDVI values (Figure 4). Figure 4 (a) demonstrates a case where there is no trend in NDVI over time but vegetation response to precipitation is getting worse. This would indicate a case of human-induced degradation of vegetation cover. An opposite case is shown in Figure 4 (b). Here, vegetation cover demonstrates increasing response to precipitation.

To detect human-induced trends in vegetation cover, the authors analysed linear regressions between NDVI and rainfall time-series over the period 1981-2000. For a given value of rainfall, a value of NDVI predicted by the regression, abbreviated as$NDVI_{pred}$, was obtained for every pixel and for each year, this value was considered to reveal the climatic component. The observed NDVI, abbreviated as$NDVI_{obs}$, may show deviations from the regression line (Figure 6 (a)). Positive deviations indicate a better response of vegetation to precipitation while negative deviations indicate a worse response. Deviations in $NDVI_{obs}$ from $NDVI_{pred}$ expressed in the regression residuals were computed at pixel-by-pixel basis for every year. On this way, the authors derived the response strength for every year and every pixel. In order to detect change in response strength, the authors looked into time-series of regression residuals. The authors suggested that any trend through time presented in the residuals would indicate changes in NDVI response not due to the climatic variable. A negative trend would mean diminishing response of vegetation cover to climate. This reduce can be caused either by a decrease of vegetation cover or by a change in plant species composition. According to this suggestion, this negative trend, if it was statistically

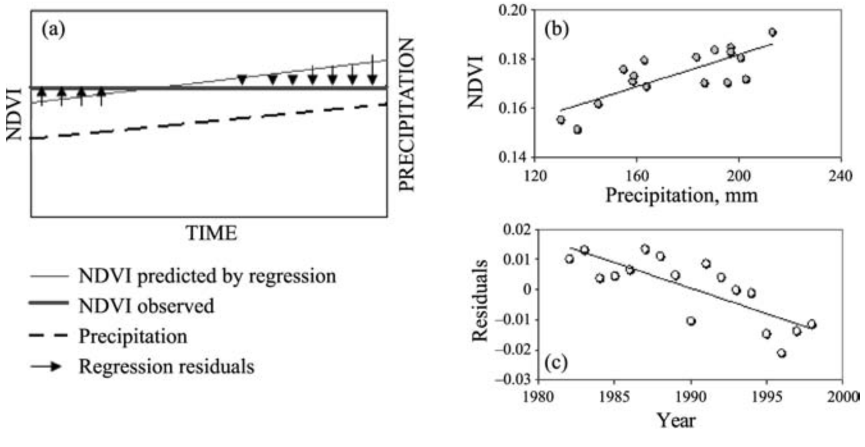

**Figure 6.**
Potential effects of degradation on the observed rainfall-NDVI relationships

significant, would indicate an area experiencing human induced degradation. Examples illustrating how the trends of regression residuals reflect changes in vegetation response to precipitation are shown in Figure 6 and Figure 5. Panel (a) in Figure 6 shows steady decrease of deviation of $NDVI_{obs}$ from $NDVI_{pred}$over the time. The deviation value turned from positive into negative during the observation period. That means a decreasing response of vegetation cover to precipitation. Even though precipitation amount rose, NDVI value remained at the same level. Panel (b) shows a regression between NDVI and precipitation for an area with similar situation and panel (c) shows residuals from the regression arranged in a time-sequence. An opposite case would indicate a positive trend in residuals and is presented in Figure 5.

## Results

### *Precipitation signal in the inter-annual dynamics of NDVI*

From the previous studies it seems to be important to test several different analysis periods in order to find an optimum correlation between time-series of NDVI and precipitation. It is also apparent that over an area of about 6.5 million km$^2$ dryland it is unlikely that a single analysis period will provide the best correlation. Instead, the authors would expect the optimum correlation period to vary with different vegetation communities, with soil properties, with morphological characteristics (Nicholson and Farrar, 1994; Yang *et al.*, 1998; Wang *et al.*, 2003; Li *et al.*, 2002). Hence, correlations are calculated for many different combinations of precipitation and NDVI, allowing identification of its distinct optimum correlation (growing season, summer, spring-summer etc.). The authors also tried to generate time series of precipitation accumulated over two and more years and calculate correlation between them and time series of NDVI.

Figure 7 shows the results of correlation calculations at the per-pixel level. The map demonstrates the best correlation coefficient obtained for every pixel using different analysis periods and precipitation accumulations. Our calculations revealed the borders of the precipitation-dependent areas in Central Asia and Kazakhstan. According to the results, about 75 percent of all vegetated pixels exhibited a

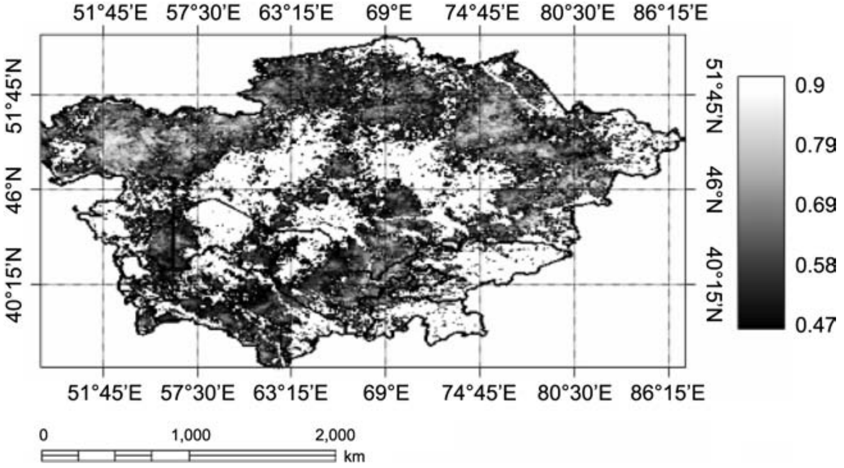

**Figure 7.** Spatial distribution of the best correlation coefficient ($p < 0.05$) between inter-annual NDVI and precipitation derived by using different combinations of NDVI and precipitation

statistically significant correlation with precipitation over the 1981-2000. The value of the correlation coefficient ranges from 0.47 to 0.92 indicating existence of a strong relationship between NDVI and rainfall in these territories.

### *Long-time trends in NDVI*

Spatial distribution of trends in growing season NDVI (April to October) from 1981 to 2000 over Central Asia is shown in Figure 8. In the north and south of the region upwards trends spread broadly from the west border to the east. Especially high increases in NDVI are associated with areas covered by forest vegetation in the mountainous regions in the south as well as with areas covered by steppe vegetation. Steppe occupies wide areas that stretch a broad band from the west to the east over the whole study region. On the other hand, NDVI decreased in some areas located in the central part, especially between the Caspian Sea and the Aral Sea, as well between the Aral Sea and the Balkhash Lake. Taken over the entire study region, about 21 percent of all vegetated pixels exhibited statistically significant upward trends of the growing season NDVI throughout the study period, while 6.72 percent of all pixels exhibited significant downward trends.

### *Explanation of NDVI trends by precipitation*

In order to identify trends in NDVI driven by precipitation factor, the authors compared the areas that exhibited significant correlation between NDVI and precipitation with the areas of significant trends in NDVI. Intersection of these both maps results in detecting pixels with NDVI trends caused by climate change. The resulted map is shown in Figure 9. The map presents pixels that show both significant trend in NDVI and significant correlation with inter-annual precipitation. The map displays two categories of the climate-induced NDVI trends: positive trends which are considered to represent an improvement of the vegetation cover, and negative trends which are believed to indicate degradation of the vegetation cover. The entire area of

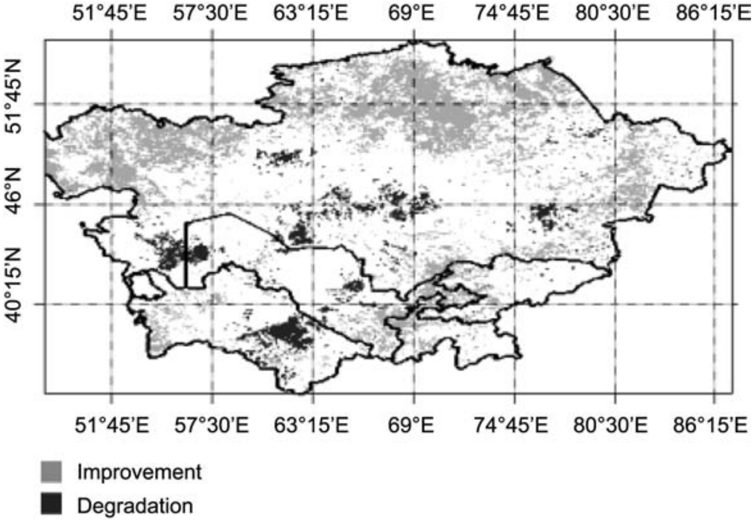

**Figure 8.**
Spatial distribution of statistically significant ($p < 0.05$) inter-annual changes in mean growing season NDVI over the period 1981-2000

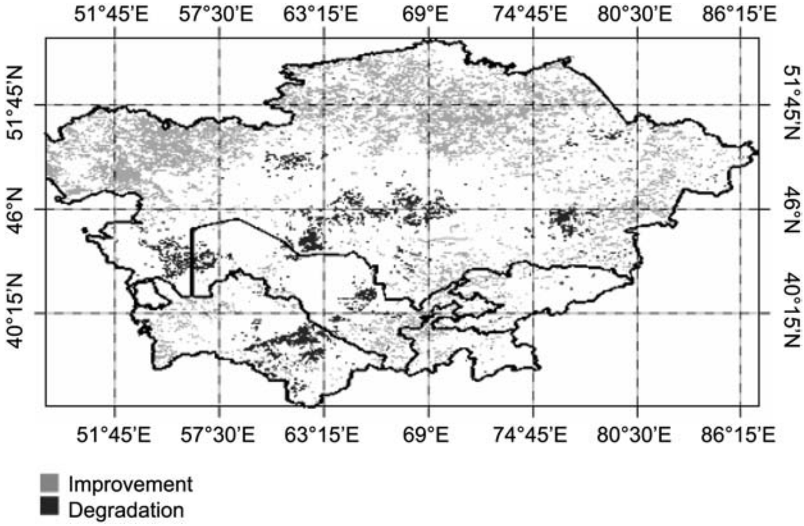

**Figure 9.**
Inter-annual changes in NDVI explained by precipitation

precipitation driven trends is considerably less than that of all significant trends. About 15 percent of all vegetated area is proved to exhibit upward trends in NDVI driven by precipitation change. More than a half of significant downwards trends in NDVI (4.7 percent of the entire vegetated area) showed a strong correlation with precipitation.

Even a great deal of significant inter-annual changes in vegetation cover are proofed to be dependent on trends in precipitation, a great part of the NDVI trends remained unexplained by precipitation. One would expect that the unexplained part of the NDVI trends could be driven by other internal and external factors. One of the most important of them is human impact. The role of the human impact by explaining NDVI trends will be investigated in the next section.

### *Detection of areas of human-induced NDVI change*

The response of vegetation to climate is among other things determined by non-climatic factors such as specific characteristics of plant physiology or structure of vegetation canopy. In arid regions, annual and perennial species as well as grass and shrub species differ in their response to precipitation. Changes in vegetation type may also affect changes in the response of vegetation cover to rainfall. The man has a very strong influence on vegetation cover, changing its biomass, structure, and mixture of vegetation types. Therefore, in the precipitation dependent regions such as Central Asia, human impact should be reflected in the response of vegetation cover to precipitation factor, and the authors can measure this impact when detecting the change of this response in time. On this way, it should be possible to identify not only signals of vegetation degradation but also signals of vegetation improvement driven by human impact.

The detection of change of the vegetation response was made through observation of the deviations from the regression between the time-series of NDVI and precipitation. The regression line was understood as the climatic signal. Deviation of the observed NDVI value from the value predicted by the regression was understood as an indicator for the vegetation response to climate. Thus, any positive deviation indicates better response while any negative deviation indicates worse response. Having calculated these deviations for every year the authors derived time-series of annual vegetation response for every pixel. These time-series contained important information about evolution of the vegetation response to precipitation. Extraction and interpretation of this information enabled identifying areas of vegetation change that was caused by human impact. The authors supposed that any time-trend in vegetation response would indicate a change of characteristics of the vegetation cover. A positive trend would represent an enlargement of the vegetation response to precipitation. It means that the vegetation improves its effectiveness of rain use. A consequence of that is an increase of vegetation primary production per rainfall unit. It leads to a general increase of aboveground biomass. A negative trend would represent an opposite development.

For a given value of rainfall, a value of NDVI was obtained for each pixel and for each year from individual regression of NDVI on rainfall. This obtained value of $NDVI_{pred}$is associated with the precipitation signal in the inter-annual changes of NDVI. Deviations in $NDVI_{obs}$ from $NDVI_{pred}$ expressed in the regression residuals were computed at pixel-by-pixel basis for every year. After that, the authors computed trends in regression residuals over the study period. Pixels with statistically significant trends within the precipitation-dependent zones were mapped as areas of human-induced vegetation change. The map of human-induced change in vegetation cover and results of area calculations is presented in Figure 10 (a). The map shows areas of improvement and degradation of vegetation cover derived by the analysis of regression residuals. Figure 10 (b) demonstrates the results of area measurements for climate-induced and human-induced vegetation change in Central Asia and Kazakhstan (in percent from the entire vegetated area). Generally, human impact has a weak influence on the inter-annual trends of NDVI. The results show that, as a whole, only about 5.75 percent of all vegetated territory is considered to undergo a human-induced change of vegetation cover.

### *Validation of the model at the local scale*

The results of the modelling have been tested at a number of sites exhibiting both positive and negative trends of regression residuals. Example of an abandoned

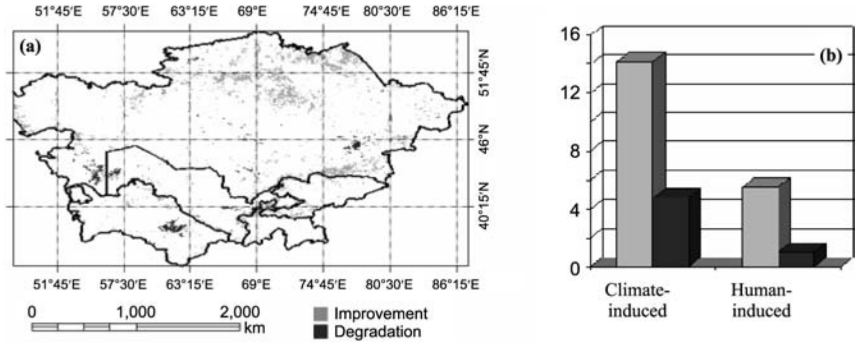

**Figure 10.**
(a) Distribution of vegetation change induced by human impact and the area of this impact measured in percent from the entire vegetated area (b)

agricultural area is presented in Figure 11. The corresponding regression between NDVI and precipitation and time-series of residuals are displayed in Figure 12. After arranging the regression residuals in accordance with the time, clear trend could be observed. This area could be characterized by a positive trend of vegetation response to precipitation and can be evaluated as area with improving vegetation cover caused by diminishing human activity.

A number of the test sites revealed traces of human activities leading to degradation of vegetation cover. It will be demonstrated on one example. This test site is located in the southern part of the Moyunkum Sands in the southeast of Kazakhstan. Originally, the area was covered by woody and grass vegetation, the *Haloxylon*-forest extends from south-west to north-east as a broad stripe with a width from 10 to 25 km (Figure 13, a). Because of a lower reflectance in blue spectrum, the areas occupied by *Haloxylon* thickets occurs deep dark in the 1 channel of Landsat and can be easy

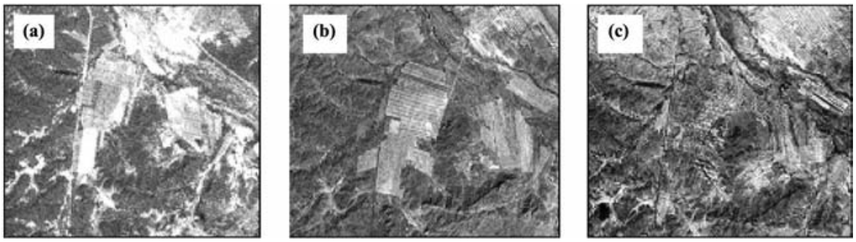

**Figure 11.**
Traces of land-use change in satellite data at a test site in the northern Kazakhstan: (a) Landsat MSS image from 1975, (b) Landsat TM image from 1992, (c) Landsat ETM + image from 2001

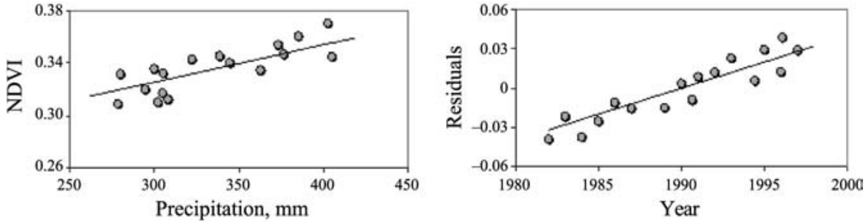

**Figure 12.**
(a) Regression between mean growing season NDVI and precipitation for the test site shown in Figure 11. (b) Time-series of regression residuals

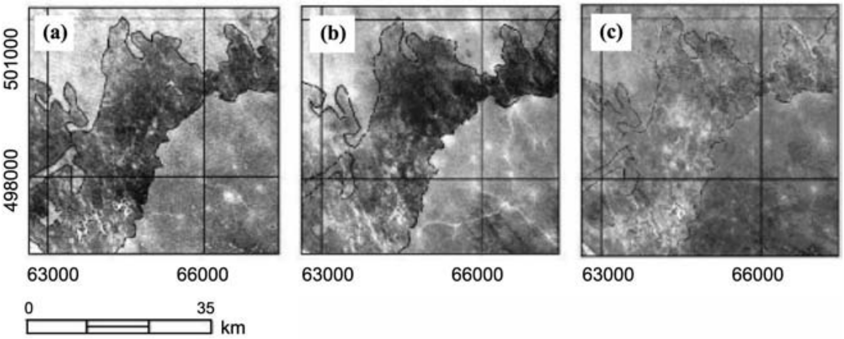

**Figure 13.**
Time series of Landsat subsets (band 1) from a test site in the Moyunkum sands with clear signs of land degradation

identified and mapped. On the Landsat image from 1990, many light areas, especially in the western part, occurred within the contour of *Haloxylon's* stripe (Figure 13, b). On the third Landsat image shouted in year 2000, the light areas widespread over the significant part of the image associated with *Haloxylon* occurrence (Figure 13, c). Field surveys in this region in 2004 and 2005 as well as reports from local officials verified a clear sign of massive destruction of vegetation cover caused by intensive wood felling. Wide areas of the *Haloxylon*-forest are already completely cut out; at many places the wood cutting continues intensive at the present time. As a result of wood cutting, surfaces with only thin, rare vegetation cover composed by dwarf shrubs and ephemerals were formed among overgrown sands on many places. When these areas are grazed, they easy get trampled by livestock. After that, bare sand surfaces and even mobile forms of sand such as barkhan chains and barkhan ridges appeared. The destruction of vegetation cover, a decrease of biomass and higher rates of soil loss in this region resulted in a drastic decrease of vegetation response to precipitation over the period 1981-2000. That caused a negative trend of regression residuals (data not shown).

## Discussion

This study demonstrated a model for monitoring changes in vegetation activity and detecting their driving forces. The theoretical background for the model separating the driving forces of vegetation change was the concept of trends synchronism/non-synchronism. This concept understands vegetation response to precipitation as a constant if no change of external conditions occurs. The authors considered that any processes of improvement or degradation in the areas of stable response of vegetation cover are driven by climate factor alone. A change in the response of vegetation to climate has been understood as an effective indicator for human-induced change. Mathematically, this response is expressed in deviations of observed values from the NDVI values predicted by the corresponding regression model between NDVI and precipitation. These deviations were computed for every year and each pixel. Any statistically significant trend of deviations found in a certain pixel over the study period reflects a change in vegetation response and is considered to be a representative sign for human-induced change of vegetation cover. Computed trends of regression deviations help to detect areas with diminishing or increasing vegetation response to rainfall. These areas were mapped as areas of human-induced improvement or degradation of vegetation cover. Results of the modelling were validated by test of statistical significance and by comparison with the data from the remote sensing systems of fine resolution and fieldtrips to key field sites.

The model being applied to the study region found that most part of the trends in NDVI observed in Central Asia during the period of 1982-2000 is explained by the precipitation change. The inter-annual precipitation dynamics have driven about 75 percent and 82 percent of all positive and negative trends in NDVI respectively. That amounts to 15.5 percent and 4.7 percent of the entire vegetated area of Central Asia. The trends in vegetation activity driven by anthropogenic factor are much scarcer and occupy only about 5.75 percent of the entire vegetated area. Thus, about 4.15 percent of the entire vegetated area demonstrated the upward human-induced trend, while the downward trend occurred in only 1.60 percent of the entire area. The results clearly demonstrated that the area of the upward trend in vegetation activity significantly overwhelm the area of the corresponding downward trend. The reason for this seems to be a rapid decrease of anthropogenic activity over the most area in Central Asia due to the collapse of the Soviet Union in 1991 and a fundamental change in land-use practice as well as favourable climate development over most part of the region. Some relevant previous studies reported about significant increase in vegetation activity over particular regions in Central Asia. These studies suspected diminishing anthropogenic activity to be the major cause for it. De Beurs and Henebry (2004) reported that the institutional changes in Central Asia positively affected land surface phenology at spatial resolution relevant to meso-scale meteorological models. Robinson *et al.* (2002) investigated land degradation and desertification in pasture lands in the central Kazakhstan and found significant improvement of them associated with the period from 1991 to 2000. Nonetheless, there also are contradict studies reported about worsening of climate conditions over several parts of the formerly soviet Central Asia that are unfavourable for vegetation growth.

No doubt, the ecosystems of Central Asia represent a gigantic reservoir of carbon, and, on the one hand, they play a very considerable role in the global change, on the other hand, they are very sensitive to the contemporary climate change. Both the climatic conditions and physio-geographic patterns vary significantly within this region. Climatic type, soil properties, vegetation type, and landforms show a high variance within the region's eco-geographic zones. Therefore, the authors have to expect a high variance both in impact of the contemporary climate change and in the change of human influence. The model presented in this paper revealed this variance signifying spatial distribution of vegetation changes driven separately by climate and by human influence. That is an advantage of this study over the previous related studies from this region (De Beurs and Henebry, 2004).

However, each model is only a gross misspecification of reality and one or more relevant variables are either omitted from the model or are represented by an incorrect functional form. One of the improvements of the monitoring system presented in this paper may be the incorporation of temperature into the model. Recent remote sensing based studies on vegetation dynamics reported about significant role of the spring temperature for increase in vegetation activity over high latitudes in North America and Eurasia (Zhou *et al.*, 2001). The region of Central Asia has experienced a warming trend in order of 1-2°C since the beginning of the twentieth century. This might have a strong impact on the regional temperature and precipitation regimes and also on vegetation cover. The authors based the monitoring system on the assumption that Central Asia is a region where rainfall is the main climatic controlling factor (what has been proved in the results of this study: about 75 percent of the entire territory exhibited strong relationships between NDVI and rainfall). But the authors might expect that in many areas temperature could also play an important role. It means that some trends in NDVI could be driven either exclusively by temperature or by both rainfall and temperature. An incorporation of temperature into the model and a re-examination of climate and human-induced vegetation trends taking into account this new variable can be objective of a further research. Another source of model's uncertainty is the use of 0.5° precipitation data. This spatial resolution of the origin rainfall dataset is much larger than that of the used satellite data (8 km). The process of conversion of the rainfall data leads to distortion of information and certainly influences the end results of the model. The use of more progressive geostatistic's techniques for data conversion or acquisition of a dataset with a spatial resolution closer to 8 km would significantly reduce the uncertainty of the model.

## Conclusions

The study developed a monitoring system for assessment degradation/improvement of vegetation cover and discrimination of their two driving forces, climate change and anthropogenic activity. The monitoring system bases on the concept of synchrony/asynchrony in the trends of vegetation and climate, which has been presented and thoroughly described in this paper. This monitoring system used the temporal response of vegetation to precipitation as major indicator for degradation or improvement of the vegetation cover. Trends in vegetation response over the study period (1982-2003) have been considered to indicate positive or negative changes of vegetation cover driven by human impact. Inter-annual time-series of the satellite derived normalized difference vegetation index (NDVI) and precipitation served as input data into the monitoring system, which has been successfully tested over the region of formerly Russian Central Asia. The results obtained at the regional scale were afterwards validated at the local scale using data from fieldwork and satellite imagery of higher spatial resolution.

The authors suggest that the monitoring system developed in this study is a useful tool for controlling the effects of rainfall in order to separate between human-induced and climate-induced land degradation. The technique allows the monitoring trends in vegetation cover driven by influences of other than climate. By doing so, it gives valuable hints to potential areas submitted to human-induced changes of vegetation cover. Once identified, they can be examined in more details with focus on their vegetation cover status, the forces driving biomass production and the most suitable rehabilitation measurements.

Examples from test sites showed that both negative and positive trends in vegetation response can result from changes in human impact. Thus, a rapid deforestation at the second test site results in a significant negative trend, while abandonment of agricultural land at the first test site results in a strong increase of the vegetation response. However, concerning human-induced change in vegetation cover, the monitoring system can evidently identify areas where there has been a reduction or increase of vegetation response to rainfall amount, but the exact reason of this change can not be determined by this method alone. For identification of scrupulous reasons (exact forms of human activities driving the change) for human-induced land degradation or improvement of a certain area a closer investigation using high-resolution remote sensing data and field work is needed. It is therefore envisaged that the developed monitoring system would be a part of a multi-scale, complex, monitoring program, where it can serve as a general tool to identify areas of climate- and human-induced vegetation changes (hot spots). Field survey and analysis of high-resolution satellite images can track aspects of anthropogenic land cover change and are required, in order to provide validation data for the monitoring system products.

The study demonstrates the importance of taking into account precipitation when trying to analyse changes of vegetation cover in drylands with high inter-annual rainfall variability. In precipitation-dependent regions such as Central Asia the inter-annual change of vegetation cover is significantly predicted by the inter-annual rainfall dynamics. This signal could be used for discrimination between the climate-induced vegetation change and the vegetation change triggered by other factors, mainly by human impact.

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## About the authors

P.A. Propastin is currently a Postdoctoral Research Associate in the Department of Cartography, GIS and Remote Sensing at the Georg-August University, Göttingen, Germany. His main research activities focus on the integration of remote sensing and GIS in studies on climate dynamics and their impacts on the vegetation cover in Asia. P.A. Propastin is the corresponding author and can be contacted at:ppropas@uni-goettingen.de

M. Kappas is Head of the Department of Cartography, GIS and Remote Sensing, Georg-August University of Göttingen, Germany. His current research interest is in physical geography and the quantitative exploitation of satellite remote sensing data for the characterization of terrestrial surface properties.

N.R. Muratova is Head of the Department of Remote Sensing and Digital Image Analysis at the Space Research Institute of the Kazakh Science Academy, Almaty, Kazakhstan. Her scientific interests focus on the remote sensing of vegetation, the diagnostics and evaluation of satellite-derived surface data, and climate-vegetation interactions.