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Land-use change and land degradation in Turkmenistan in the post-Soviet era

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ABSTRACT

The Central Asian Newly Independent States have experienced dramatic political and economic changes over the last three decades. Despite these changes, significant areas of the drylands in this region have not been studied since the 1980s. Landsat images acquired before and after the collapse of the Soviet Union, were analyzed to evaluate land-use/land-cover changes and desertification processes in northern Turkmenistan. Vegetation and crust indices, albedo, and spectral mixture analysis, supplemented by field work, were applied to estimate the long-term degradation/re-growing of vegetation cover.

The major land-use change identified was an 86% increase in irrigated agricultural areas, equivalent to a loss of about 4500 km^2 previously available for natural pastures. Pastures adjacent to the irrigated (and populated) areas were not affected, and in many places, increased vegetation cover was observed. The main degradation processes in these pastures are flooding and technogenic desertification; both occur around man-made structures. Remote pastures have experienced a higher degree of vegetation degradation, mainly due to the development of soil biogenic crust. These observations emphasize the controversy and variability of land degradation processes in this region: distant pastures show a degradation trend, while closer to populated areas, there are signs of rehabilitation.

1. Introduction

From ancient times to the present day, pastoral livestock production has been one of the main agricultural activities in the Central Asian newly independent states (the former Central Asian Republics of the USSR). In Turkmenistan, where more than 80% of its territory is occupied by the Karakum Desert, the main land use is nomadic livestock breeding (Rustamov, 1994). Studies involving rangeland assessment have focused mainly on grazing impact (e.g. Pickup and Chewings, 1994; Trodd and Dougill, 1998). These studies identified vegetation cover and production variability as the parameters to be assessed as indicators of desertification processes (Hostert et al., 2003). According to Manzano and Na'var (2000), livestock grazing is the most significant anthropogenic activity causing rangeland degradation in terms of vegetation cover and species community. Taking into account the limited carrying capacity of the Karakum Desert pastures and the fact that 90% of the livestock's forage is obtained from natural sources (Rustamov, 1994), any factor that changes the fragile balance can lead to the destruction of the pastures as a valuable livelihood resource.

Water availability is the key limiting factor for sustainable livestock breeding in the region (Lunch, 2003). During the Soviet times, the government provided water to the distant pastures and small stockbreeding settlements were supported. In the post-Soviet era, this approach became no longer feasible as local government retreated from providing services, such as maintaining the existing pipelines and remote watering points (especially those that are, so-called, "engineering" wells). As a result, more than 25% of pastures are not currently used because of a lack of water (Babaev and Kharin, 1999). At the same time, official sources have reported an up to nearly 300% increase in the number of livestock in Turkmenistan since the 1980s (FAO, 2009). In addition, the transition to a market economy forced people to migrate closer to the central villages in the oases and to shift from nomadic livestock breeding to land cultivation. Based on this information, and following Lunch (2003), who noted the change in water resources

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and livestock management due to decollectivisation, our assumption was that the traditional seasonal migrations of herds ceased, leading to livestock concentration near the settlements and water wells close to the irrigated zone year round. Consequently, significant changes in vegetative cover would have taken place in these areas, as well as in the abandoned remote pasture areas. The other assumption was that the transition zone between irrigated oasis and the Trans-Unguz Karakum Desert remains the most affected region since the 1980s, taking into consideration that it was the traditional source of firewood for the local population and of forage for the livestock.

The last assessment of Turkmenistan's pastures was carried out in the late 1980s – before the collapse of the USSR. These assessments indicated that 60–80% of pastures are degraded at different levels (Middleton and Thomas, 1992; Kharin, 1994; Babaev and Kharin, 1999). The vastness of the Central Asian natural pastures, the underdevelopment of infrastructure and the lack of modern technical means have restricted proper monitoring of these pasturelands. These factors also reflect the difficulty of performing field work in these areas. The current study presents an attempt to assess the status of natural rangelands by using methods of remote sensing, following the dramatic political and economical changes, which took place all over the former Soviet Central Asia. The primary goal of this study was to assess land-use and land-cover changes in the region of northern Turkmenistan and to reveal the spatial trends of these changes using remote sensing methods. The specific objectives of the study were to: (1) monitor land-use changes and determine the available pasture area; (2) monitor land-cover changes within the pasture areas in order to reveal their trends (degradation of natural pastures versus rehabilitation) and rate as well as the causes for these changes; and (3) create a quantitative vegetation assessment. Spatio-temporal vegetation condition and cover changes are key indicators/variables of desertification. Knowing the current state of the pastures and the trend of their changes is an important factor for developing strategies for livestock breeding – the second most important economic sector in Turkmenistan's economy.

2. Study area

The research was conducted in northern Turkmenistan within the limits of the Dashoguz province (*oblast'* according to the Soviet administrative division and *velayat* at present) located between 39.5°–42.7°N and 56.4°–61°E (Fig. 1). The total area of the province is 73,430 km^2 (Rajapov and Yazkuliev, 2002). The climate is arid and extremely continental. Mean annual rainfall ranges from 97 mm in the north (Dashoguz meteorological station) to 118 mm in the south (Darvaza meteorological station) with a notable contrast between seasons and significant inter-annual variability. Most of the annual precipitation occurs during winter and early spring (October–April). The dry period lasts for 4–5 months (Fig. 2). Mean temperature in January is 2.6 °C in the south and −2.2 °C in the north; as of July that changes from 31.8 °C in the south to 29.2 °C in the north (Orlovsky, 1994).

As can be seen from Fig. 1, the province includes three physical-geographic regions: a) the north-western flat lowland consisting of the Sarykamish depression and the adjacent ancient alluvial deltaic plain of the Amudarya River; b) the irrigated oasis, which is part of the modern Amudarya delta – the largest irrigated agricultural area in Turkmenistan, and c) the Trans-Unguz Karakum Desert. The research was mostly concentrated in the Trans-Unguz (or "Zaunguz" in Russian literature) Karakum Desert, which is an ancient elevated alluvial–proluvial plain. The relief of the region alternates between so-called "kyrs" (long flat-topped rubbly sub-meridian ridges) and wide inter-ridge depressions. The inter-ridge depressions are occupied by 5–8 sandy ridges at a height of 7–12 m and sometimes with takyrs (flat clay pans or playas). Kyrs are composed of almost horizontal layers of sandstone underlain by dense sandy–clay layers formed in Miocene (*Sarmatian* deposits). The heights of the kyrs vary from 80 m in the southeast to 15 m in the northwest; width is between 200 and 2000 m with steep slopes. Takyrs are ellipsoidal shallow depressions of varying size, characterized by fine-texture, low permeability and high runoff coefficients (Maman et al., 2011). Soils are sandy and grey–brown with takyr and solonchak patterns in the western Trans-Unguz Karakum, and soddy, grey–brown sandy desert primitive soils exist in the eastern part of the region (Kharin, 1994; Assessment Report, 2006). Saline ground water lies at depths of 15–40 m.

Vegetation consists of *Haloxylon persicum*, *Astragalus,* several species of *Calligonum*, *Salsola*, *Artemisia* and ephemera (mainly *Carex physodes*), all distributed on the sandy ridges and kyrs encroached by sand deposits. Of these dominant species, *C. physodes* (the local name "*ilak*") is considered the most valuable forage for livestock due to its high nutritional value. The vegetation of the kyrs without sand is represented by *Artemisia*, *Salsola arbuscula*, *Stipa* and other perennials; ephemera are distributed at a lesser extent. The black sandy moss *Tortula desertorum* occurs in the inter-ridge depressions. The growing season lasts 200–270 days (from March to November). Spring (March–May) is the season of ephemera vegetation, while the second growing peak occurs in September–October due to development of the bushes. Although the Trans-Unguz Karakum Desert is extremely hostile to human habitation, the nomadic population has used it for consumptive and productive purposes (Babaev and Arnageldyev, 1999).

Dashoguz province is one of the main producers of cotton, rice and wheat in Turkmenistan. It is also the most populated area, with a population of 1.2 million and a population density of 100 persons per km^2 in the Amudarya River deltaic area (10 times more than the country's average) (FAO, 2009). The intensive development of large-scale irrigation projects aimed at expanding the agricultural area under cotton was launched in the mid 1950s by the central Soviet government (O'Hara, 1997). Traditionally, the desert pastures adjacent to the irrigated lands have been strongly influenced by human impacts. According to previous assessments carried out in the 1980s (Kalenov and Orlovsky, 1986; Kharin, 1994), the pastures of northern Turkmenistan suffered from a decrease in vegetation cover and soil water logging, as a result of anthropogenic activities. The main human activities responsible for vegetation cover degradation are overgrazing, logging of *Haloxylon* shrubs for firewood and construction projects. Moreover, the construction of the "Central Asia–Centre" gas-pipe, water-pipes to the Trans-Unguz Karakum Desert and natural gas survey and exploration facilities have created irregular movements of vehicles throughout this region. In the absence of infrastructure, vehicle movement leads to disturbance of natural vegetation. Water logging occurred due to several reasons, among them the construction of irrigation and drainage canals without waterproof covers with consequent flow of drainage and excessive irrigation water to the adjacent desert pastures, and diversion of drainage water to the desert depressions.

3. Materials and methods

3.1. Remote sensing data

Remote sensing has been an effective and cost-efficient method for observing dryland ecosystems and monitoring land-cover changes (Hassan and Luscombe, 1990; Collado et al., 2002). Remote sensing data for this study comprised multi-sensor and multi-temporal data covering the research area. Analysis was carried out using ERDAS IMAGINE, ENVI, and ArcGIS software.

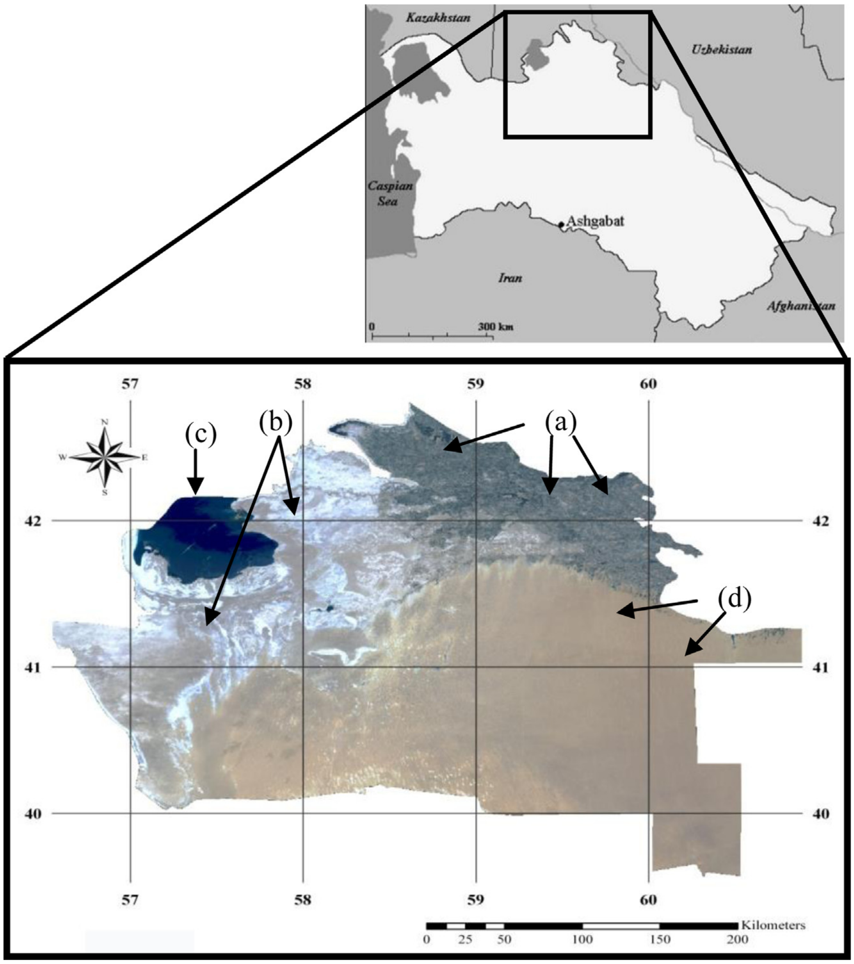

Fig. 1. The study area as seen by Landsat ETM+ imagery (2004). (a) Oasis (cultivated and populated areas); (b) Ancient Sarykamish delta; (c) Sarykamish Lake – collector of drainage water; (d) Trans-Unguz Karakum Desert (Zaunguz Karakum in the Russian literature).

To monitor land-use and land-cover changes, Landsat images from 1987 and 2004 were retrieved from the United States Geological Survey (USGS), at the correction level 1G. The level 1G correction includes geometric and radiometric correction of all images and Scan Line Corrector (SLC) gap-fill for images acquired in 2004. The 1987, 2004 images were Landsat TM and Landsat ETM+, respectively, at 30 m resolution. A total of 8 images was used – four Landsat 5 TM images, representing the 1986/1987 growing season, and four adjacent Landsat 7 ETM+ images, representing the 2003/2004 growing season. The choice of years for comparison was determined according to the similarity of rainfall amount and distribution for the 1987–1988 and 2003–2004 rainy seasons, as measured at the Darvaza meteorological station (40°05.10′ N; 58°20.92′ E). In both seasons, the amount of precipitation was above the multi-year average – 160 mm and 140 mm in the rainy seasons of 1986/1987 and 2003/2004, respectively. Selection of years with similar precipitation levels minimizes the short-term climatic fluctuation effect (droughts) and isolates the changes caused by human activities. The image dates coincided with the end of the rainy season and in/or close to the presumed peak of the vegetation season: April – beginning of May. During this time, both annual and perennial vegetation are present; thus, biomass and cover are at their highest levels.

Prior to image analysis, atmospheric correction was done using the procedure elaborated by Chavez (1996).

3.2. Field data

A two-week field campaign was conducted in April–May 2006 to support the remote sensing analysis. Four nested line plots

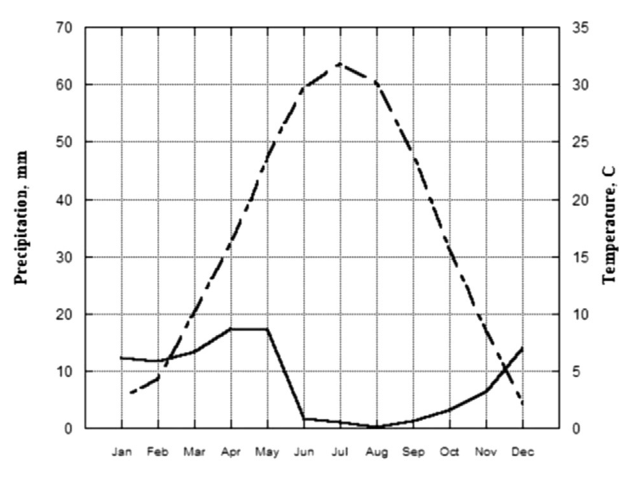

Fig. 2. Climate diagram of Akmolla meteorological station. Data represents the typical precipitation and temperature of the research area (1936–2004). – · – Temperature —— Precipitation.

(McCoy, 2005) and two transects were established during the field campaign. In each, three parameters were studied: 1) herbaceous biomass – air-dried weight collected from 50 × 50 cm testing plots, taken every 50 m along the transects and plot lines; 2) dominant species composition – physiognomic categories of herbaceous annuals and perennials and shrubs in three size categories within 2 m of each side of the transect line; and 3) visual estimation of vegetation cover. The locations of plots and transects were determined based on the type of pasture, preliminary results of the image analysis, and, last but not least, accessibility of the area.

In areas, where soil biogenic crust was identified, samples of the biogenic soil crusts were taken from 10 × 10 cm plots. The samples were weighted and oven-dried for 48 h at 65 °C. Later 0.1 M of hydrochloric acid was added to eliminate soil carbonates, and the free-carbonate samples were furnace at 105 °C for 5 h to determine the crust biomass.

Spectral signatures of dominant vegetation and soil types were collected during the field campaign. The field spectra were measured using CROPSCAN MSR5 spectrometer, in five wavelengths corresponding to the Landsat bands. A total of four soil spectra and seven dominant vegetation species was collected (Fig. 3). The spectral signature of the sand was taken from the bare top of the sand ridge in the Trans-Unguz Karakum. For vegetation, the canopy spectral signatures of several types of bush vegetation, as well as herbaceous/grass cover, were measured. The spectrometer was held above the top of the canopy in order to capture the whole plant structure while minimizing soil effects.

3.3. Image analysis

Field data and preliminary analysis indicated that land-use types in the study area consist of settlements and cultivated agricultural areas (here after referred to as oasis) and pasture. Visual interpretations of reflectance values, geometric shape, and the Normalized Difference Vegetation Index (NDVI, Rouse et al., 1973) images were used to manually digitize the two different land-use classes. The resulting maps were used to calculate the area of the oasis. Accuracy was evaluated by a set of 200 randomly distributed points in our 2004 land-use map. Pasture areas were given a value of 0 and agriculture and settlements were given a value of 1. The points were exported to Google Earth to evaluate accuracy. An overall accuracy of 94% ($\kappa = 0.92$) was achieved.

To reveal the location and trend of changes of the vegetation cover and productivity, the following image algebra procedures were applied: (a) calculation of Weighted Difference Vegetation Index – WDVI (Cleavers, 1989) – a vegetation index that takes into account the soil background of different soils, thus allows for comparison between areas with different underlying soil types; (b) albedo calculation (Liang, 2003); and (c) Biogenic Soil Crust Index – BSCI (Chen et al., 2005). The WDVI was based on soil maps supplied by our Turkmen partners, and was used to identify vegetated areas, such as the inter-ridge depressions, and separate them from the bare sand dune tops. The albedo and BSCI were used to identify and monitor the extent of soil biogenic crust. In addition, because WDVI do not differentiate between vegetation condition and vegetation cover (Asner, 2004), spectral mixture analysis (SMA) was applied to quantify vegetation cover – a bio-physical measure of ecosystem condition and a critical parameter in arid pasture and land degradation assessment.

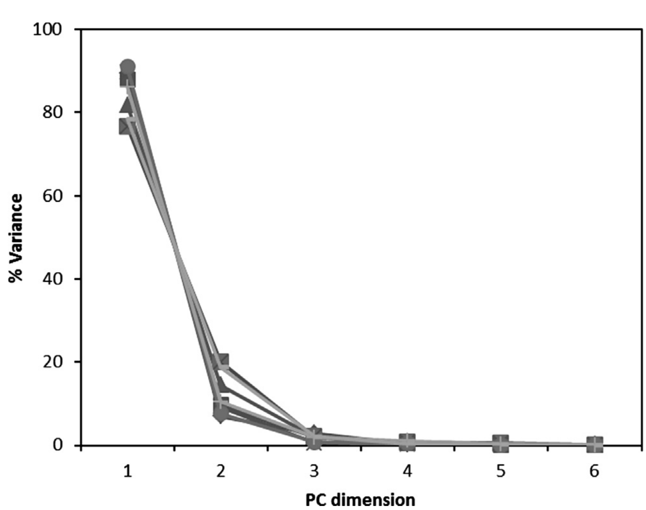

Fig. 3. Spectral signatures of the dominant vegetation species and soil types. Data were collected in the field using the CROPSCAN MSR5 spectrometer.

3.3.1. Spectral mixture analysis

Remote sensing images of arid and semi-arid environments contain pixels with several different components (e.g. vegetation, soil) resulting in mixed spectral information. SMA is based on the concept that the spectral information of each pixel is an integrated signature of the various components signal. The pure examples of these components serve as end-members –'pure' physical components of the area/scene that are not a mixture of other components. SMA was first proposed in the early 1970s (Horowitz, et al., 1971) to derive the proportions of land-cover components that compose a mixed pixel. As a result, this technique is very appropriate to monitor vegetation cover in the arid regions where vegetation is sparse (Collado et al., 2002). Vegetation cover as derived by remotely sensed imagery is defined as: "the green vegetated area, which is directly detectable by the sensor from any direction" (Purevdorj et al., 1998). Most studies involved in the unmixing of vegetation cover elements in arid regions have used multispectral un-mixing techniques, where vegetation fraction was quantified relative to the soil and rock fractions (Pech et al., 1986; Smith et al., 1990; Shoshany et al., 1996; Ustin et al., 1996).

The basic linear model was chosen. The linear SMA assumes that the electromagnetic energy interacts with a single 'pure' component before being reflected by the surface, resulting in a pixel which is a mixture of the 'pure' components (end-members) in proportion to the area that they cover within the pixel

$$\rho_{i,j,k} = \sum_{m=1,\rho} F_{i,j,k}\rho_{m\cdot k} + e_{i,j,k} \quad (1)$$

where $\rho_{i,j,k}$ is the reflectance of the i, j pixel in band k; $F_{i,j,m}$ is the fraction/weighted coefficient of the m component in that pixel for each of the ρ pure categories; $\rho_{m,k}$ is the reflectance of the pure cover m in the same band k; and $e_{i,j,k}$ is the error term for that pixel. Using a least-square approach to minimize the error, the best fit fractional covers (F) are determined.

Principle Component Analysis (PCA) was used to determine the number of end-members. PCA minimizes band to band correlation, resulting in a series of new bands (PCs) with diminishing variance. The accompanying Eigen-values distribution (Fig. 4) provides a quantitative measure for the number of end-members that represent the image mixing space (Small, 2004). Similar to Small (2004), the PCA and Eigen-values analysis demonstrated that over 98% of Landsat images variance is represented by three end-members: high albedo features, low albedo and vegetation. For desert environments these end-members correspond to sand, water, and vegetation.

The end-members spectral signature can be derived from the image (image end-members – pixels with 100% cover of a single land-cover type) (Elmore et al., 2000) or from spectra collected in

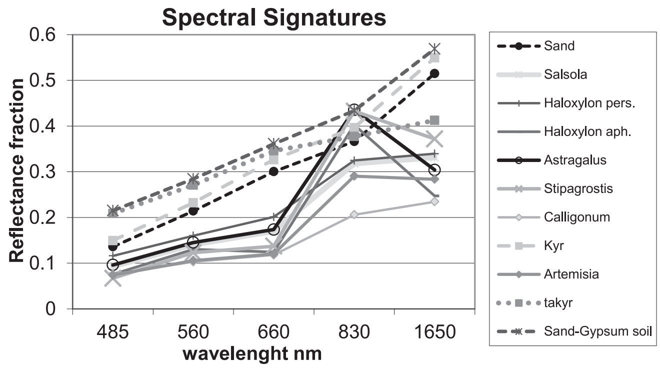

Fig. 4. Eigen-values for the 8 Landsat images used in this study. Analysis indicates that >95% of the variance is associated with the two primary principal components and that >98% can be described with three PCs.

the field/laboratory (field end-members). Given the sparse vegetation cover of the region, we used end-members derived from the spectra collected during the field campaign. Such end-members would represent a purer end-member spectrum and would possibly give a more accurate result compare to using image end-members. The field campaign indicated that the region can be divided into two sub-regions: the transition zone between the desert and oasis where water is present on the surface (canals, flooded areas) and the majority of the desert area where only vegetation and soil (sand) are present. For the northern part of the study area, where water and artificial planting are significant land-cover components, a three end-member model (sand – average vegetation signature – water) was used. The water end-member was used to inform us on the extent of flooded and waterlogged areas. For the natural pasture area of the Trans-Unguz Karakum Desert, the field campaign indicated that most pixels of an image consisted of two end-members – sand and vegetation. To maximize model performance and account for the variance between vegetation types, all possible model combinations of sand and the different vegetation types were considered. A combination of sand and the averaged vegetation signature was also included. The results from each model were compared to field data estimations, and the best fit model was used.

3.4. Change detection

To assess local and regional changes in the study area between 1988 and 2004, a post-processing image differencing method (Jensen, 1986) was applied to the WDVI and SMA products. The values for 1988 were reduced from the parallel images of 2004. The resulting difference images were classified based on their histogram statistics, i.e. mean and standard deviation. Following Volcani et al. (2005), a threshold of 1 standard deviation from the mean difference was used as the threshold value for change. Using histogram statistics allows us to assess both direction (negative/positive) and rate of change (Jensen, 1986).

Changes in vegetation cover were obtained by calculating the difference between vegetation fraction images. Previous assessments of vegetation degradation performed by the Turkmen National Institute for Deserts, Flora and Fauna (NIDFF) used a 2.5% change threshold (Babaev and Kharin, 1999). For consistency, our analysis used the same threshold. The resulting image consists of four change classes in each direction. An increase in vegetation fraction in the desert area points to rehabilitation processes, and *vice versa* (except in areas where the water logging and flooding processes take place – in such cases, the increase in vegetation fraction is considered as a desertification/degradation process) (Babaev and Kharin, 1999).

4. Results and discussion

4.1. Land-use changes

There are two main types of anthropogenic activities in the study area – irrigated agriculture and grazing. Using ArcGIS 9.0, we calculated the area of the oasis (cultivated and populated areas) in 1987 and 2004. The comparison of the Dashoguz oasis area in 1970s [taken from the Soviet literature sources – Nechaeva et al., 1977 and Nikolaichuk, 1985] and calculated during the present study shows that this area almost doubled in the last three decades. The most rapid increase took place between 1974 and 1987, coinciding with the former Soviet Union's development of large-scale irrigation in Central Asia for growing cotton (Fig. 5). After the collapse of the USSR in the early 1990s, the irrigated area continued to grow at the expense of adjacent pastures – at that time, mainly for growing wheat. The total pasture area in the north-eastern part of the province had shrunk by 4400 km^2 between 1974 and 2004.

Combined with official statistics, indicating an increase in livestock number from 5.6 million heads in 1991 to 15.5 million in 2004 (FAO, 2009), changes in land use can cause an increase in grazing pressure on remaining pastures. In addition, due to the outdated irrigation techniques (flooding and furrow irrigation), the ground water level is permanently rising and secondary salinization is taking place. As a result, many of these fields are abandoned, and new virgin lands previously used as pastures are being converted into irrigated fields. This is one of the most devastating processes for the pasture practices since the abandoned field rarely turns back into productive pasture without specific phytoremediation measures (Assessment Report, 2006).

4.2. Water logging and flooding

The processes of water logging and flooding take place mainly along the boundary area between irrigated fields and desert pastures. They occur as a result of water filtration from irrigation canals that is being constructed without waterproof isolation, excessive irrigation and washing of increased area of secondary salinized fields. Currently, an area of approximately 10 km^3 of drainage water is being formed in the Dashoguz and Khoresm oases annually. Part of this volume returns to the Amudarya River, while about 7 km^3

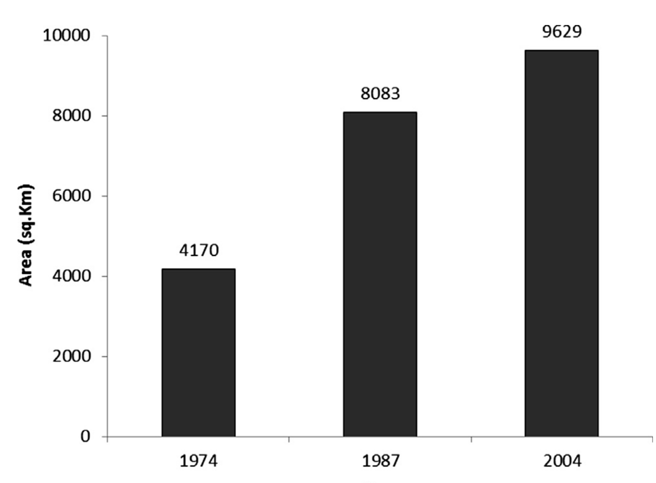

Fig. 5. The extent of the oasis area in Dashoguz province of Turkmenistan.

flows to the adjacent desert areas or is transferred to the desert depressions, where it evaporates, percolates or accumulates. The leakage from the irrigation and drainage canals, the chaotic flow of drainage water from the irrigated fields to the adjacent natural desert pastures and the diversion of drainage water to natural desert depressions lead to the formation of filtration lakes in the transition zone, and planned man-made lakes – collectors of drainage water – the largest of them, Sarykamish Lake.

The formation of marshes with hydrophilic vegetation communities has multiple effects: increasing biomass production, replacement of the palatable species by unpalatable or less valuable ones, as well as the formation of vast areas inaccessible by livestock and human population. Thus, in spite of an increase in vegetation cover and biomass around the filtration lakes and in waterlogged areas, this process is considered as a pasture's degradation. Both visual analysis and the Spectral Mixture Analysis show the increase of the flooded areas in the transition zone between the Trans-Unguz Karakum and the ancient Sarykamish delta from 93 km^2 in 1988 to 268 km^2 in 2004 (including canals) (Fig. 6). The Sarykamish Lake – the largest accumulator of drainage water in Central Asia – is constantly expanding. In 1973, its area was 888.7 km^2; it increased to 2446 km^2 in 1989 and was 3955 km^2 in 2006 (2994 km^2 in Turkmenistan territory) (Orlovsky et al., 2013). The expansion of the Sarykamish Lake carries significant implications because the western pastures of Dashoguz province had been preserved as a reserve source for livestock breeding (Nikolaev, 1989).

4.3. Land-cover changes

To fully evaluate changes in natural pastures, both vegetation condition and vegetation cover need to be considered. A previous study by Kharin (1994) describes most of the transition zone from irrigated area to desert as moderately degraded. In contrast to our initial assumption that the transition zone will remain the most affected area due to a continuing increase in population and livestock pressure, significant areas along the desert–oasis border show vegetation rehabilitation. A field survey in spring 2006 revealed a 5–7 km belt of artificially planted bushes of *Haloxylon aphyllum* covering 75% of the area. This growth, established in the 1980s to fight the active sand dune encroachment, is well preserved because the local population nowadays uses natural gas, free of charge, thus reducing dramatically the need for firewood. Beyond this belt, most pasture areas in the transition zone (up to 70 km from the irrigated oasis) show positive changes, with an average WDVI difference of 0.09 between 2004 and 1987. Based on histogram statistics (Volcani et al., 2005), a WDVI change detection map

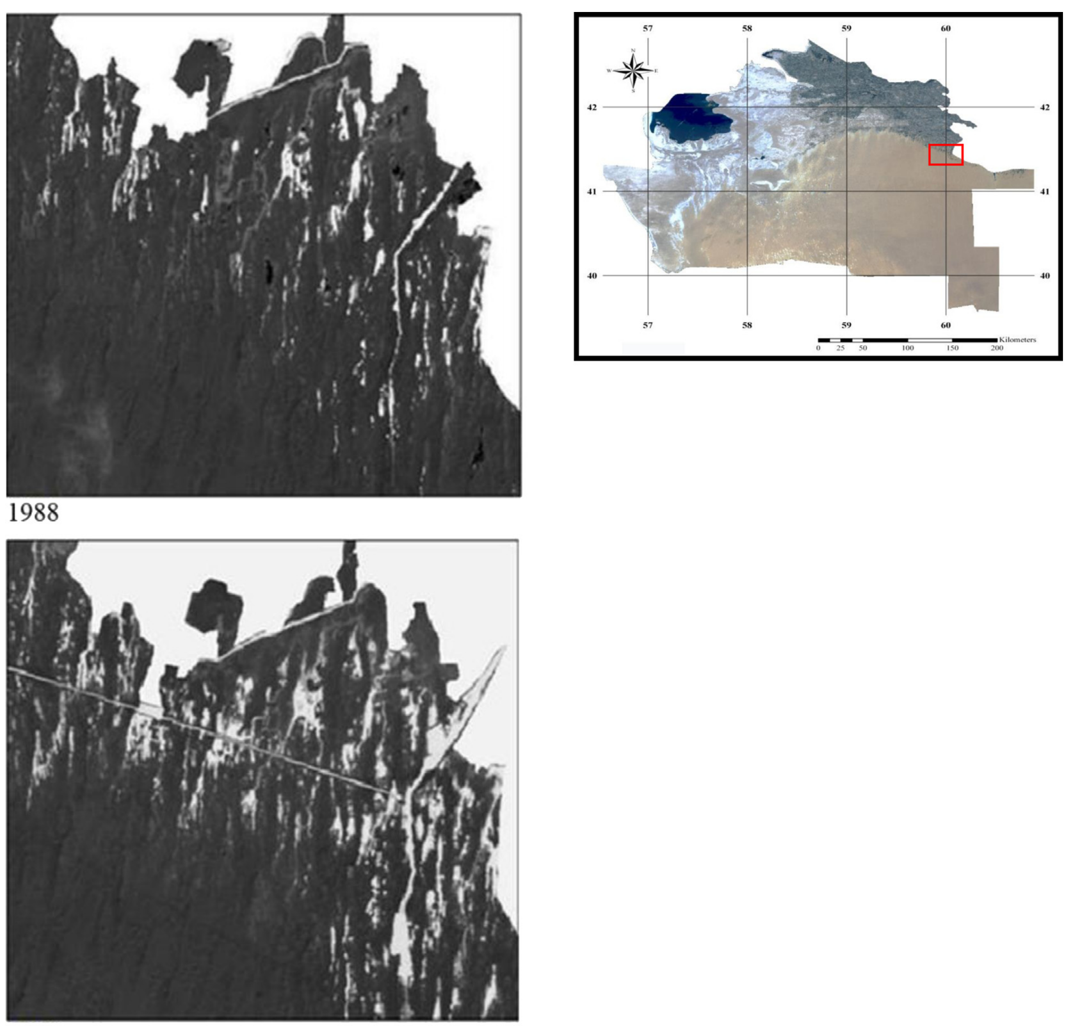

Fig. 6. Left: Water component in the transition zone between irrigation massif and the desert as identified by SMA. Brighter color represents higher water fraction. The main reason for the increase of flooded areas is the new, easily visible, irrigation canal (Turkmen-Darya) constructed in 1999–2000. Right: location of the transition zone within the study area.

was compiled (Fig. 7). Data within two standard deviations from the mean were classified as no change. Each additional class represents a 0.5 standard deviation additional step. Areas around watering points and other man-made features, such as near newly constructed canals, water- and gas-pipes remain severely degraded, showing negative changes (decrease in WDVI values).

Although official statistics indicate an increase in livestock number, local dwellers reported a reduction in livestock, which could explain the recovery of the transition pastures.

4.3.1. Vegetation cover: end-member selection and SMA application

Changes in the vegetation cover fraction over time indicate the magnitude of change (Hostert et al., 2003). The combination of spectra of sand and *Astragalus* was chosen because it showed the best fit ($R^2 = 0.74$) and provided the best discrimination of land covers. The result is not surprising given that the *Astragalus* signature (Fig. 3) follows more closely the vegetation signature, described by Small (2004), for the Landsat mixing space boundaries, thus minimizing the root mean square (RMS) error. The RMS error for the region around the Adjikui well (where two transects and two plots were taken) ranged from 0% to 3.8% (mean = median = 2.2%, standard deviation = 0.4%) for the 2004 ETM+ image and from 0% to 1.5% (mean = median = 0.7%, standard deviation = 0.3%) for the 1988 TM image. These results are consistent with the ones reported by Dawelbait and Morari (2012) for the savannah region of Sudan.

Fig. 8 shows the scatter plot correlation between the percentage of vegetation determined with SMA for the 2004 Landsat ETM+ image, combining both 3 and 2 end-member models, and field data. Generally, there is a good agreement between them with an R^2 of

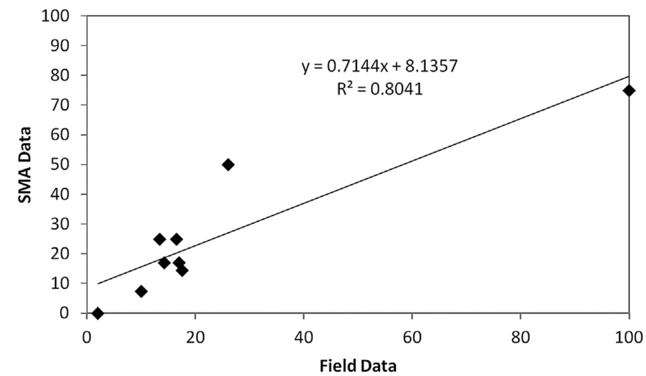

Fig. 8. Scatter plot correlation between measured and SMA estimated vegetation cover percentage.

0.8, but with an overestimation. Several sources of error can affect the correlation: the field data were collected two years after the image was taken. This, along with mis-registration of a multi-date scene and location of field sites, is potentially the largest source of error. Other sources of error can be related to the method used to fill the gaps in the ETM+ image, and accuracy of the field survey (Dawelbait and Morari, 2012).

Overall, the trends of the changes toward pasture rehabilitation revealed by the WDVI are confirmed by SMA change detection. The SMA vegetation cover results were able to discriminate between the different landscape associations (Fig. 9), i.e. dune slope, top of sand dune, and inter-ridge depression.

Most significant changes occurred in the inter-ridge depressions and the lower parts of the ridges' slopes, where vegetation cover

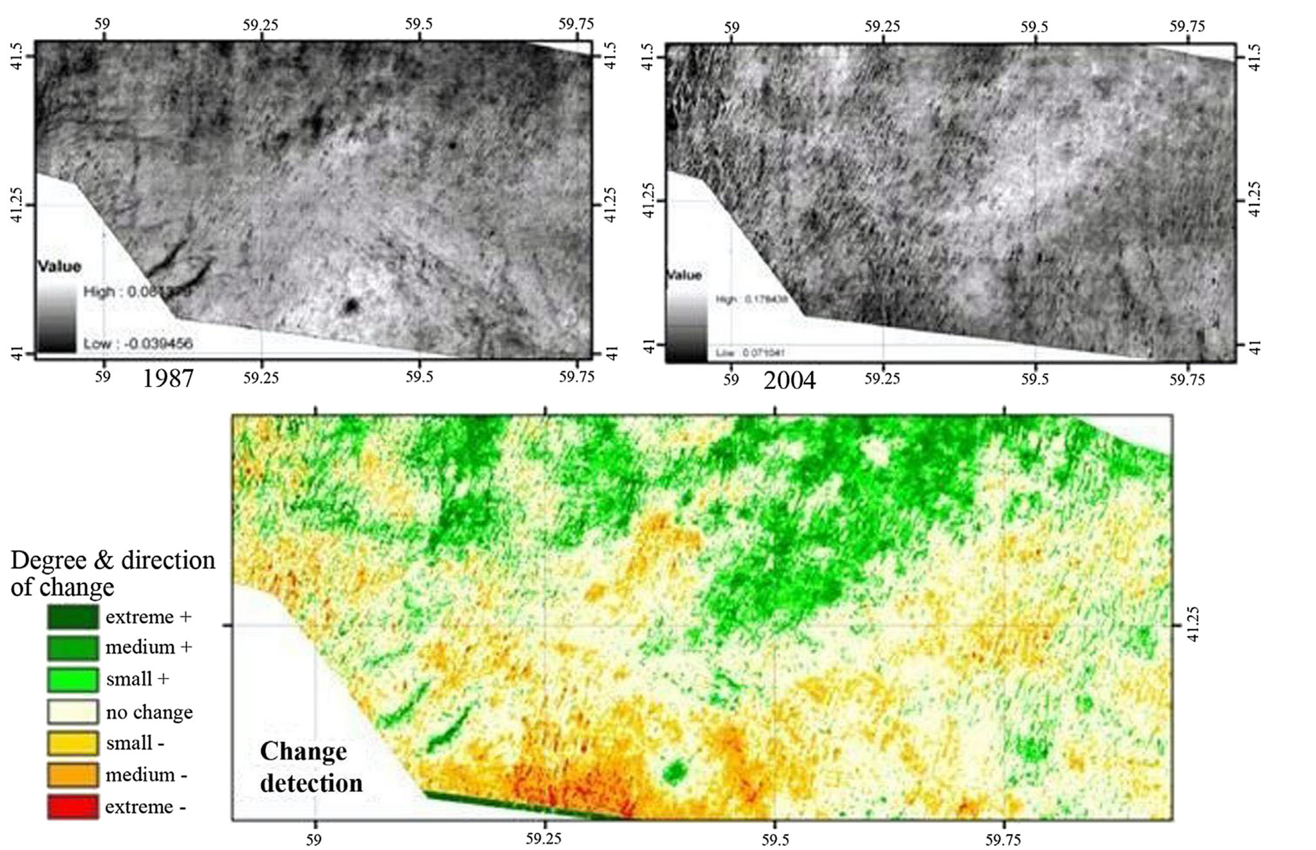

Fig. 7. WDVI and change detection results for the Trans-Unguz Karakum Desert. Green colors represent rehabilitation and orange-red colors represent degradation. The “no change” group is the size of 2 standard deviations − 1 from each side of the mean. All other groups are the size of 1/2 standard deviation each. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

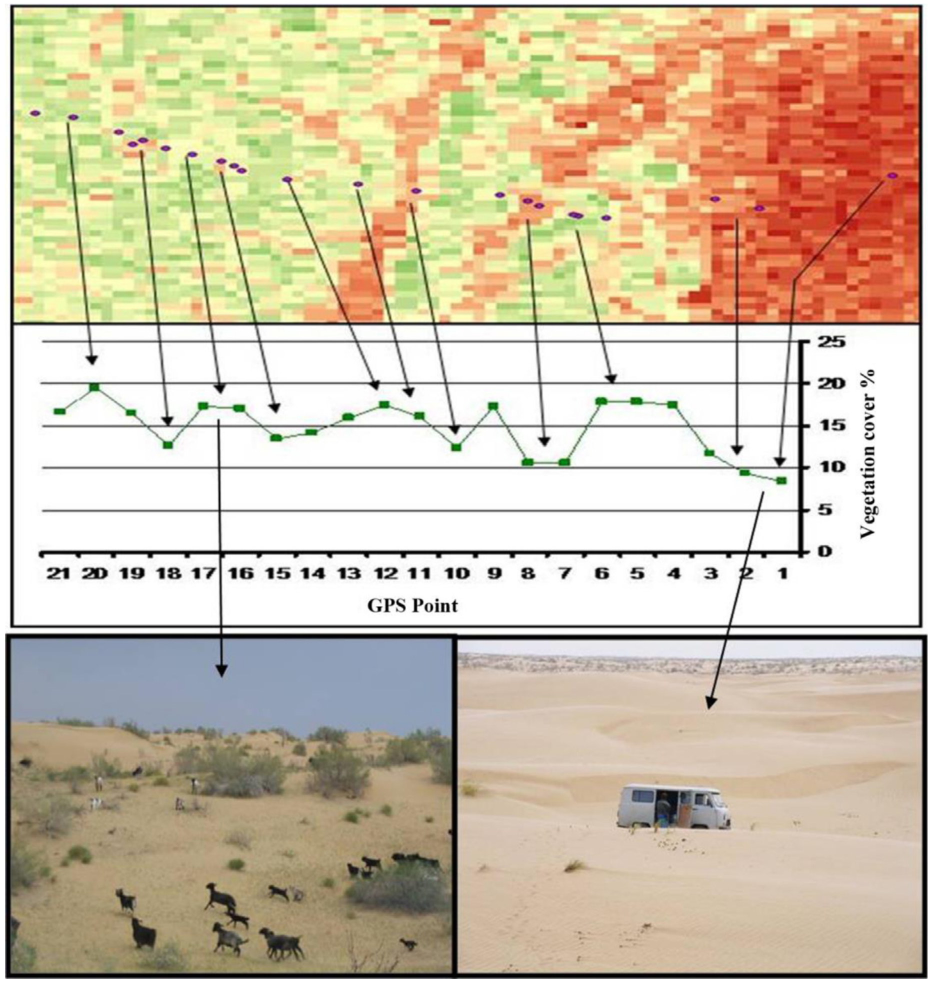

Fig. 9. Changes of vegetation fraction along different landscape associations. Dark colors represent bare sand and bright colors represent higher vegetation cover fraction.

has increased from an average of 19% in the 1987 to 27% in 2004. Some of the increase is attributed to ephemera (*C. physodes* – "*ilak*"). The '*ilak*' is one of the most significant plants for livestock nutrition, but due to its small size, spatial distribution within each pixel does not contribute to the vegetation signal. Fig. 10 shows the results of the change detection procedure for the vegetation fraction.

Biomass of herbaceous vegetation measured during the 2006 field survey made up 107 kg/ha versus an average of 77 kg/ha measured in this area during the field campaigns of the Turkmen Desert Research Institute in 1966–1974, reported by Nechaeva et al. (1977). The increase in biomass reduces the area each head of livestock needs to fulfill its nutritional demands to 8.2 ha compared to 11.4 ha previously. The reduction in needed grazing area supports the re-growth of vegetation. As we moved further into the desert, the amplitude of changes decreased. At a distance of 70 km from the irrigation–desert border, the changes have a negative trend, indicating degradation, with a decrease of up to 13% in the vegetation cover (Fig. 11).

Desertification spots around watering points and wells are still detectable, both in the transition zone and the distant southern areas of the Trans-Unguz Karakum Desert. Most watering points experience desertification within a radius of 5–7 km around them due to livestock trampling and grazing. Around Adjikui well, which surroundings have been studied during the field campaign, WDVI analysis indicates gradual rehabilitation of vegetation in the desertification spot up to 2 km from the well. The field survey supports these findings – the climax vegetation community was observed at a distance of 2 km from the well. Note that similar processes of vegetation rehabilitation are evident along water- and gas-pipes. Beyond 2 km, where WDVI and SMA analyses indicate moderate to severe degradation, field survey revealed the development of the soil biogenic crusts.

4.4. Soil biogenic crust

Field survey at the distance of 2 km from the "epicentre" of the desertification plot near the Adjikui well revealed developing biogenic crusts (local name – "*karakharsangs*") consisting of the moss *T. desertorum*, lichens and cyano-bacteria. This phenomenon indicates under-use of pastures, leading to vegetation degradation due to under-grazing (Orlovsky et al., 2004). In the absence of grazing by domestic livestock and wild ungulate, the developing biogenic crusts in the Karakum Desert reaches a thickness of 1–2 cm and start suppressing the higher vegetation, leading to disappearance of *C. physodes* and other palatable ephemera and even dying off the shrubs (*ibid*). Unlike biogenic soil crust reported in other arid regions such as the Negev Desert in Israel (Otterman, 1974; Karnieli and Tsoar, 1995), the crust in the Trans-Unguz Karakum is much thicker (up to 2 cm) and consists mainly of *T. desertorum* moss. The crust develops in the inter-ridge depressions and the lower slopes of sand ridges.

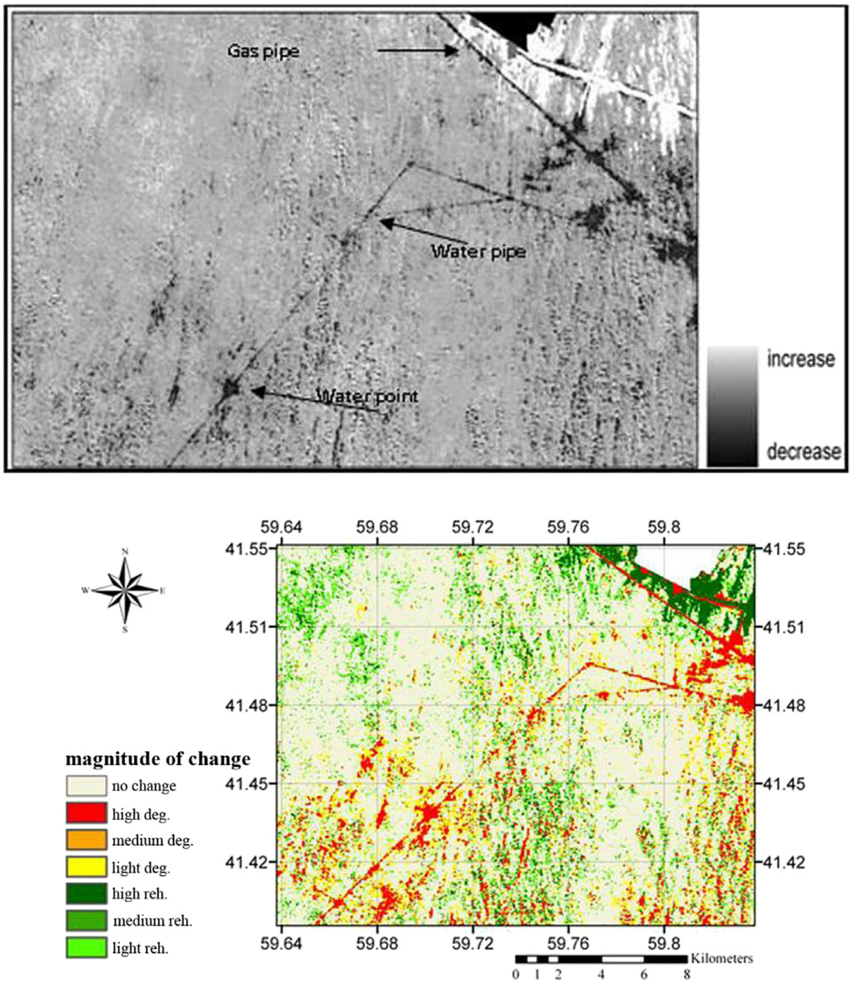

Fig. 10. Top: Change of vegetation fraction image. Brighter colors represent rehabilitation of vegetation and darker colors represent degradation. Bottom: Classified vegetation fraction change detection based on a 2.5% threshold value.

Results of BSCI, albedo images, visual analysis, and field data (Fig. 12) show that in areas with developing crust, the crust fractional cover reaches 50–80%, compared to 10–40% cover reported during the 1980–1990s by Kharin (1994) who used analog remote sensing data in his assessment. Biogenic crust biomass reaches 4426 kg/ha versus 66.4 kg/ha of herbaceous vegetation at the sandy inter-ridge depression 2 km to the west from the Adjikui water well; a dominance of the unpalatable weedy species *Cerathocephala falcata* and *Microcephala lamellata* and the presence of dead *H. persicum*, *Calligonum setosum* and *Ephedra strobilacea* is notable. The community was identified as the last stage of succession in the inter-ridge depressions. In the western Trans-Unguz Karakum, the crust biomass reaches 2460–2365 kg/ha, while the biomass of higher vegetation (grasses and bushes) varies from 41.6 kg/ha in a dry year to 98.4 kg/ha in a favorable year. This process of vegetation degradation can result from various mechanisms, including competition for water, inhibiting the seeds' germination and preventing the vegetative propagation of high nutritional value species such as *C. physodes* (Lavrov, 1965; Antonova et al., 1986; Dedkov et al., 1989; Zha and Gao, 1997; Orlovsky et al., 2004). Although further analysis is needed, our results indicate it is the areas with biogenic crusts that show the highest degree of degradation of higher vegetation.

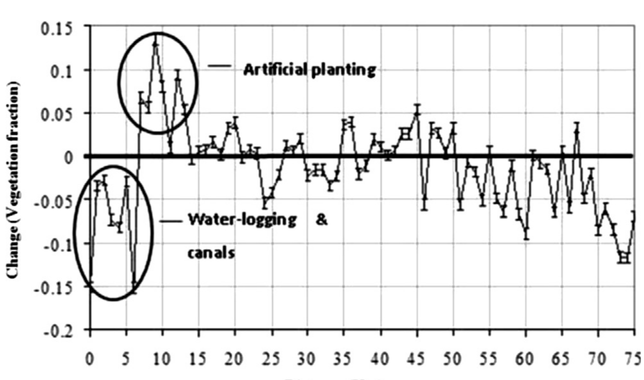

Fig. 11. Vegetation cover changes along the cross section from the irrigation massif to Adjikui well (41.0794 N, 59.3866 E). At first there is an increase of vegetation cover, resulting from artificial planting. As the distance from the irrigated massif increases the vegetation cover decreases.

5. Conclusions

The geopolitical and socio-economic changes that occurred in Central Asia during the last three decades, along with the site-specific interaction between natural processes and human activity play a significant role in land-use/land-cover changes in Northern Turkmenistan. Vegetation indices and Spectral Mixture

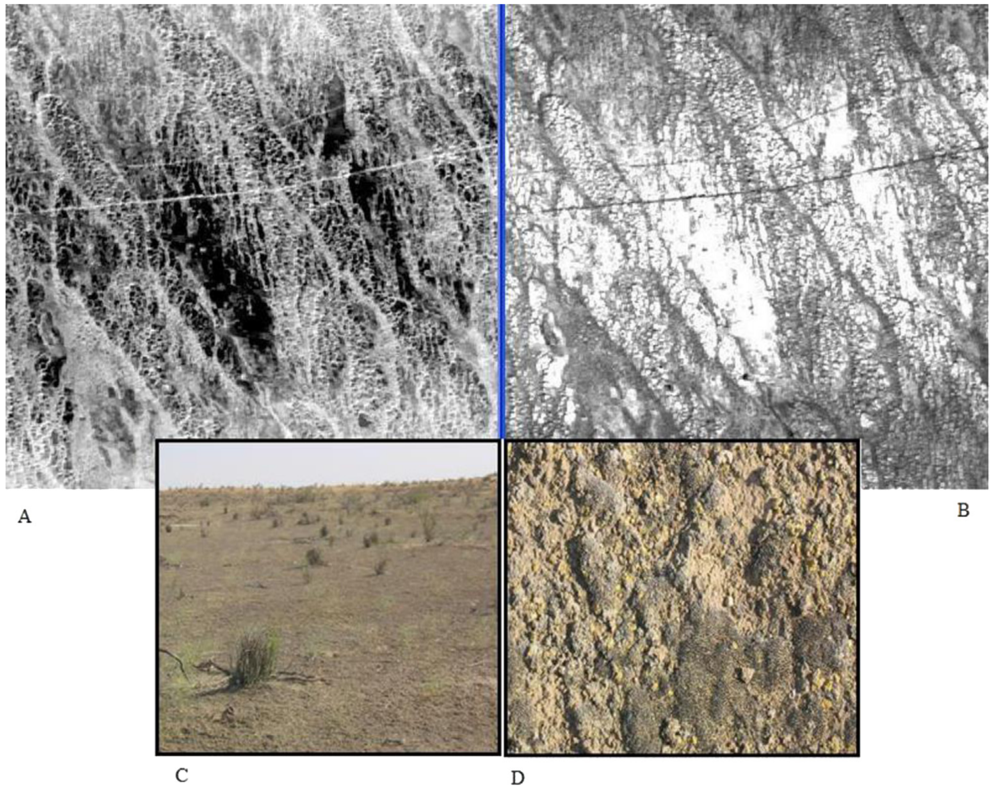

Fig. 12. Distribution of desert moss *Tortula desertorum*: A – Albedo; B – BSCI; C – Wide view of an area covered with crust; D – Close up of the crust.

Analysis (SMA) were selected to describe the spatial vegetation cover pattern at different times before and after the collapse of the Soviet Union. Special attention was given to the SMA since (1) it provides finer scale results compared to vegetation indices and (2) it enables both quality and quantity assessment of selected features, such as vegetation, water and soil. The SMA was found to be a suitable method for monitoring pasture vegetation cover from medium spatial resolution Landsat imagery.

Intensive land use with a highly variable and extreme climate subjects the arid and semi-arid Trans-Unguz Karakum to considerable stress. The first and most sensitive parameter to respond to that stress is the pasture natural vegetation, which is an important resource in this historic nomadic livestock breeding area. The geopolitical and socio-economic changes led to the expansion of irrigated oases, as well as to an increase in flooded and waterlogged areas, resulting in a 4575 km^2 reduction in the available pasture area in Dashoguz province, as well as disturbances in water supply to the desert pastures and maintenance of the watering points. However, in contrast to our initial assumption, vegetation rehabilitation trends were observed in the transition zone between the irrigated area and the desert. The rehabilitation trend is seen mainly in the sandy pastures and is attributed to less usage of the natural desert pastures due to a reduction in livestock numbers and the free gas supply which has dramatically reduced the cutting of trees and shrubs for firewood. Nevertheless, several degradation processes are still taking place, mainly flooding and water logging, resulting in vegetation degradation in the form of species replacement.

Two extreme degradation processes were identified: in the transition zone, the most devastating process is the so-called "technogenic desertification", which refers to a complete removal of the vegetation cover around man-made features (gas- and water-pipes, roads etc.); in the more remote pasture, the process of biogenic soil crusts development is believed to be responsible for the high degradation rate observed in the satellite imagery. It can be concluded that the crust development, in spite of its sand stabilizing effect, leads to vegetation degradation, and therefore, an additional factor of desertification can be defined: under-grazing.

Land-use and land-cover spatial and temporal changes were effectively identified by the indices and SMA change detection. This study illustrates the ability of Landsat imagery analysis to monitor changes caused by dramatic socio-economic changes as occurred in the Trans-Unguz Karakum Desert and, specifically, the suitability of the SMA for monitoring vegetation in arid regions. While most rehabilitation processes have taken place in the transition zone, close to the irrigated oasis, the more remote pastures have undergone degradation processes, surprisingly due to the same reason of reduced grazing pressure, emphasizing the role humans and their use of the land play in the ecosystem balance.

Acknowledgments

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