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SPATIAL TARGETING OF LAND REHABILITATION: A RELATIONAL ANALYSIS OF CROPLAND PRODUCTIVITY DECLINE IN ARID UZBEKISTAN

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With 4 figures, 4 tables and 1 photo
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Summary: Irrigated croplands in Central Asia are highly prone to land degradation due to their environmentally fragile physical settings and intensive agricultural practices. This study: (i) assesses the state of croplands in irrigated areas in northern Uzbekistan, based on the time series of MODIS-NDVI imagery; (ii) analyzes relationships between the identified trend of cropland degradation and soil quality, terrain characteristics, population density, and land use; and (iii) synthesizes the results which form the basis for recommendations on spatial targeting of land rehabilitation measures. The NDVI-based cropland degradation assessment revealed a significant decline of cropland productivity across 23% (94,835 ha) of the arable area in the study region between 2000 and 2010. We conclude that the degraded cropland identified within areas of high population density and with better quality soils, can be prioritized for rehabilitation measures. For degraded croplands located in sparsely populated areas with poorer quality soils, other alternatives (such as leaving cropland fallow) may be more effective depending on the severity of degradation and economic viability of rehabilitation options.

Zusammenfassung: Bewässerte Anbauflächen in Zentralasien zeigen eine starke Anfälligkeit für Bodendegradation. Ursachen hierfür sind physische Umwelteinflüsse sowie intensive Landwirtschaft. Diese Studie: (i) beurteilt den Zustand der bewässerten, landwirtschaftlich genutzten Fläche im nördlichen Usbekistan, aufgrund einer Zeitreihe von MODIS-NDVI Bildern; (ii) sie setzt die ermittelte Bodendegradationsentwicklung in Beziehung zu Bodenqualität, Geländeeigenschaften, Bevölkerungsdichte, Landnutzung und (iii) stellt die Ergebnisse so dar, dass Empfehlungen zu Bodenrehabilitierungsmaßnahmen für verschiedene Gebiete abgeleitet werden können. Eine NDVI-basierte Bewertung der Bodendegradation zeigte einen signifikanten Rückgang der Leistungsfähigkeit von Ackerflächen von 23% (94.835 ha) auf den Anbauflächen des Untersuchungsgebiets zwischen 2000–2010. Degradierte Ackerflächen, in Gebieten mit hoher Bevölkerungsdichte und Böden besserer Qualität, sollen für Rehabilitationsmaßnahmen vorgeschlagen werden. Für die degradierten Flächen, die in spärlich besiedelten Gebieten mit weniger guter Bodenqualität liegen, muss entschieden werden, ob die landwirtschaftliche Nutzung eingestellt wird. Dieses hängt von der Schwere der Degradation sowie der Wirtschaftlichkeit der Rehabilitationsmaßnahmen ab.

Keywords: Land degradation, population pressure, land restoration, remote sensing, MODIS-NDVI, Central Asia.

1 Introduction

Agricultural activities have significantly influenced the state of the earth's land, as the proportion of earth's habitable land area under agriculture has gradually increased to approximately 50% (Sivakumar and Stefanski 2007). Agriculture-induced land degradation is particularly alarming in dryland areas due to their lower natural resilience against anthropogenic pressure (Gao and Liu 2010). Approximately 30% of global food production currently takes place in irrigated drylands, and in some arid and semi-arid regions, such as Central Asia (CA), this forms the backbone of the national economies (Ji 2008). Globally, dryland degradation causes a loss of land productivity estimated at US$ 13–28 billion per year (Scherr and Yadav 1996). The alarming losses in economic revenues and agro-ecosystem services have revealed an acute need for monitoring of cropland degradation and analyses of its causes in order to advise decision makers on spatial targeting of land rehabilitation measures.

About 70% of the irrigated areas worldwide are located in Asia. Of these areas, the most heavily irrigated croplands are found in CA. During the 70 years of the Soviet Union, the agricultural sector in the five CA countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) was mod-

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ernized through extensive land use transformations, with the aim of increasing overall the arable land area and agricultural production (Glantz 1999). This process was primarily founded on the idea that it was not the amount of the irrigable land that was limiting the development of the agricultural sector in CA but rather the amount of irrigation water that needed to be diverted to the unexploited areas (Field 1954). From 1961 to 1999, the size of the irrigated area along the Amu Darya and Syr Darya rivers in CA tripled to about 7.9 Mha (Saiko and Zonn 2000). This made CA one of the largest irrigated zones in the world. The massive expansion of irrigated agriculture significantly increased food (wheat, rice) and fiber (cotton) production. Today in CA irrigated agriculture remains the economic foundation for approximately 60% of the rural population in the region – 41.8 million people (Ji 2008).

These large-scale irrigation systems, while supplying the “production factor” water for generating the increased crop yields, also drastically altered the environment, particularly in the downstream areas of the rivers. The ongoing Aral Sea desiccation is the most prominent example of such change (Martius et al. 2012). In addition, valuable natural ecosystems such as the riparian forests and wetlands in the Amu Darya River reaches have nearly disappeared (Krutov and Glantz 1999). Furthermore, irrigated land-use practices in the CA countries, inherited from the Soviet Union, have resulted in overexploitation and consequent degradation of croplands due to soil salinization. This has caused crop yields to decline as much as 30% (Létolle and Mainguet 1993). At present, a total of approximately 50% of the irrigated land in CA is affected by salinity, ranging from 11.5% of irrigated croplands in Kyrgyzstan to 95.9% in Turkmenistan (Saigal 2003). The entire region faces enormous challenges in preventing, mitigating and reversing the processes of land degradation. The economic costs of land degradation in CA are estimated to US$ 31 million annually (Ji 2008). In Uzbekistan alone, where agriculture accounts for 22% of GDP and employs 33% of labor, the abandonment of highly salinized croplands amounts to US$ 12 million yearly (WORLD BANK 2002). Considering also the predicted increasing scarcity of water due to the impact of climate change (Lioubimtseva and Henebry 2009) and population growth (Glantz 1999), the sustainable use of land resources is becoming critically important.

Despite the broadly recognized severity of land degradation, land managers in CA have insufficient information to implement land rehabilitation measures and sustainable land use practices (Dregne 2002). Concerns are also raised about the accuracy of available soil degradation maps, which are static and irregularly updated. These maps could be supplemented and improved by the use of satellite images and remote sensing techniques. In CA, there are few published studies assessing land degradation at both regional and local scales (Ji 2008). More attention has been paid to analyses of land use and land cover changes (LULC) in the region. De Beurs and Henebry (2004) assessed LULC changes in Kazakhstan, using a normalized difference vegetation index (NDVI) satellite time series (covering the periods of 1985–1988 and 1995–1999) from the Advanced Very High Resolution Radiometer (AVHRR) sensor system. Inter-annual changes in vegetation cover with relation to temperature and precipitation in CA were analyzed by Propastin et al. (2008). Spatial cropping patterns (Conrad et al. 2011) and cropland degradation trends (Dubovyk et al. 2013) have been studied in Northern Uzbekistan; these analyses, however, only describe in part the relations between the observed trends and potential causes. Still, understanding the fundamental processes of land degradation, including its relation to environmental factors of climate, soils, and topography along with socio-economic parameters such as population and land use, is critical for planning land rehabilitation and mitigation activities.

Degradation of croplands as manifested in the reduction of the land productive potential over time (Reynolds et al. 2007) can be detected through statistical trend analysis, employing a high temporal resolution series of NDVI images (Prince et al. 2009). Such analysis can separate seasonal and annual variations from long-term phenomena (Sonnenschein et al. 2011), and allow mapping of land productivity changes caused by degradation processes (Röder et al. 2008). High temporal resolution long-term satellite observation data, such as archives of remotely sensed images from AVHRR and Moderate Resolution Imaging Spectroradiometer (MODIS), have been shown to be suitable for the analyses of land degradation (e.g. Budde et al. 2004; Wessels et al. 2008).

In our study, negative trends in agricultural land cover were documented and related to land degradation; these were calculated based on a MODIS-NDVI time series (2000–2010) for a study region in the lower reaches of the Amu Darya river in Uzbekistan. In order to explain observed trends and their causes, the vegetation decline areas were analyzed in relationship to selected critical environmental and socio-economic parameters. These established relationships allowed us to develop spatially explicit recommendations for land rehabilitation.

2 Study area and data

2.1 Study area

The study area included the entire Khorezm Region and the southern part of Autonomous Republic of Karakalpakstan (SKKP) in northern Uzbekistan (Fig. 1). The area covers approximately 854,500 ha, of which 410,000 ha is arable irrigated cropland. The study area is included in the inner Aral Sea Basin and Central Asian semi-desert zone and is characterized by an extremely arid continental climate with an average annual precipitation of 100 mm, most of which occurs during the cold winter period (Tischbein et al. 2012). The Amu Darya River is the main source of irrigation water. Seasonal water delivery is controlled through the Tuyamuyun reservoir to Khorezm and Karakalpakstan as well as the Dashoguz province in neighboring Turkmenistan.

The two principal crops grown within the study area are irrigated cotton, which utilizes 60–70% of the arable land, and winter wheat, using 20–30% (Shi et al. 2007). The farmers follow a cotton/wheat

Fig. 1: Location of the study area, including the Khorezm region and the southern part of the Autonomous Republic of Karakalpakstan in Central Asia and Uzbekistan

production policy that allocates fixed land areas for cotton cultivation to achieve the expected yield targets based on a local soil production scale termed "*bonitation*" (Djanibekov et al. 2010). Following independence in 1991, winter wheat was introduced in an effort to attain national self-sufficiency in grain, and it is also assigned production quotas. After the June harvest of winter wheat each year, farmers cultivate maize, rice, fodder crops, vegetables, fruits and grapes; this practice also takes place on those remaining croplands that are exempted from state production orders (Conrad et al. 2007).

Irrigated agriculture is the principal source of employment and income for approximately 2 million inhabitants within the study area. However, regional irrigation and drainage networks are experiencing an accelerating decline (Tischbein et al. 2012), and virtually all of the irrigated croplands are affected by soil salinity (Ibrakhimov et al. 2007). These factors both negatively impact crop growth and yield. Some acutely degraded cropland areas have been abandoned by farmers, threatening the regional economy and people's livelihood (Martius et al. 2012).

2.2 Data sources and processing

The time series of 16-day NDVI composite images served as a principal data input for this analysis. This data set included the period of 2000–2010 and was derived from the MODIS MOD13Q1 product at spatial resolution of 250 m. MOD13Q1 datasets are composed of the best observations during each 16-day period with regard to spatial coverage and overall pixel quality, determined by parameters of aerosol content, low view angle, and absence of clouds and/or cloud shadows (Justice et al. 2002). The time series images are atmospherically corrected (Vermote et al. 2002). The images were also smoothed utilizing an adaptive Savitsky-Golay filter (Jönsson and Eklundh 2004). Image quality flags, as specified in MOD13Q1, were applied to weight the data in such a way that lower-quality pixels had relatively less influence on the curve fit during the smoothing procedure.

Environmental and socio-economic datasets were provided by the ZEF/UNESCO project database (http://www.khorezm.zef.de/) for the relational analysis of vegetation trends. All of these datasets were converted to the same geographic coordinate system (ED 1950 UTM Zone 41N) incorporating the same spatial extent and the 250 × 250 m cell size.

3 Methods

3.1 Trend analysis of satellite time series

Numerous studies have demonstrated that long-term changes in important ecological processes may be identified and described by employing trend analyses of remote sensing time series data. These processes include: vegetation productivity (e.g., Fensholt and Proud 2012; Sjostrom et al. 2011); land surface phenology (e.g., de Beurs and Henebry 2004; Verbesselt et al. 2010b); land cover (Lhermitte et al. 2011; Propastin et al. 2008); and land degradation (Bai et al. 2008; Budde et al. 2004; Paudel and Andersen 2010; Röder et al. 2008; Wessels et al. 2007). In arid and semi-arid environments, the sum of NDVI over the vegetation growing season (ΣNDVI) was strongly correlated with vegetation productivity including crop productivity (Hilker et al. 2008; Nicholson et al. 1998). Rasmussen (1998) demonstrated a high correlation between ΣNDVI and sorghum and millet crop yields in Senegal. A decreasing trend in ΣNDVI can therefore be used as an indicator of vegetation loss and may serve as an early indicator of the occurrence of land degradation (Tottrup and Rasmussen 2004; Wessels et al. 2004).

Methods commonly used to analyze time series satellite imagery include principal component analysis (Eastman and Fulk 1993), harmonic regression (Eastman et al. 2009), change vector analysis (Lambin and Ehrlich 1997), and Fourier transformation (Jeganathan et al. 2010). The trend analysis technique provides a clearly interpretable and consistent measure of change, regardless of area and time period under study (Fensholt and Proud 2012; Rigina and Rasmussen 2003; Verbesselt et al. 2010a). Moreover, in contrast to these other methods, the use of trend analysis allows for the quantification of gradual degradation processes within a single land-use class, thus allowing for monitoring subtle land cover changes caused by degradation (Röder et al. 2008).

In this study, ΣNDVI was calculated for each crop growing season (April–October) for the years 2000–2010 from a preprocessed NDVI time-series. The 250m MODIS imagery was chosen due to its higher spatial and temporal resolution compared to the other easily accessed remote sensing time series, which were available over longer time periods. The ΣNDVI MODIS images were also used as an input for the linear trend analysis. The trend coefficients, regression constant (a), and coefficient of linear regression (b) were calculated using a least-square fit for every pixel, according to:

$$f(x) = b \times x + a \qquad \text{(eq. 1)}$$

where $f(x)$ is a ΣNDVI over the crop growing season at year x.

The statistical robustness of the estimated trend was tested with a two-sided *T*-test for 90% confidence level. Taking into account the very dynamic nature of human-induced land degradation in the study area and according to several tests, this confidence level was considered sufficiently accurate.

A series of *in situ* field observations were conducted to validate the derived trend map. The 828 test fields, each larger in size than 6.25 ha, were randomly sampled during summer 2011. For this sampling, a simple binary classifier was utilized: The first class 'degraded land' represented significant negative slope of the NDVI trend; the second class 'other' represented any area not present in the degraded land class.

3.2 Relational analysis of land degradation and its factors

The areas that showed a significant negative vegetation trend were spatially correlated to ancillary datasets of population density, land use, soil quality, and terrain, in order to interpret the identified decline in vegetation productivity and to specify any remedial action. In the irrigated study area, vegetation cover fluctuates depending on the stage of crop growth, influenced by irrigation water availability, soil quality, and the intensity of land use. Population density and changes in land use were taken as a proxy for the variable of land use intensity (Bai and Dent 2009; Vlek et al. 2008). Irrigation overrides the usual strong relationship between vegetation productivity and precipitation which is observed in rain-fed agricultural and natural ecosystems (e.g., Wessels et al. 2007). Reduced irrigation water supplies have negatively influenced vegetation growth in the study region as experienced during the 2000–2001 cropping seasons and, to a lesser extent, in 2008 and 2011 (Tischbein et al. 2012). Other than these years, the annual water supply to the study region through the Tuyamuyun Reservoir remained stable between 2000 and 2010. Figure 2 shows the total amount of irrigation water used for cropland irrigation in Khorezm and SKKP between 2000 and 2010. In addition, the total size of the irrigated area hardly changed during the 2000–2010 period, while the principal crops of cotton and winter wheat were irrigated according to the standardized guidelines (Rakhimbaev et al. 1992).

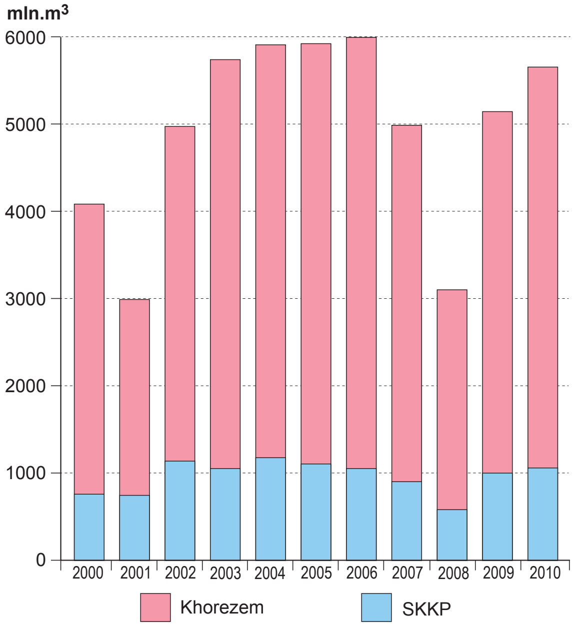

Fig. 2: Total irrigation water use in Khorezm and Southern Karakalpakstan during the vegetation periods 2000–2010

Natural soil fertility is an important factor to consider in the analysis of land degradation. It determines not only land suitability for agriculture, but it can also serve as an indicator for vulnerability to land degradation since low-quality soils are more prone to degradation. Soil *bonitation* is a measure of a relative quantitative assessment of land suitability for cropping, introduced in the Soviet Union and still used in many post-soviet countries (Ramazonov and Yusupbekov 2003). It is an aggregate of several parameters, varying from the physical soil characteristics (e.g., texture) to chemical soil properties (e.g., salinity) (Karmanov 1980). It ranges from 0 to 100 points, grouped in four fertility rate classes: Class VI 'low' (<40 points), Class III 'average' (41–60 points), Class II 'increased' (61–80 points), Class I 'very high' (81–100 points). To analyze how degraded cropland is distributed within these *bonitation* classes, each of the pixels, marked as degraded, was differentiated according to the corresponding *bonitation* class.

In a next step, spatial distribution of land degradation was analyzed with respect to slope. In general, terrain characteristics of elevation and slope also define land suitability for agriculture. For example, cropland with an elevation of more than 3500 m AMSL or slope >25° (ca. 47%) is considered unsuitable for cropping (e.g., Sheng 1990). The terrain of the agricultural study area is flat with elevation ranging between 85 m and 205 m AMSL and slopes of below 10%, except in the very north of SKKP, where slopes may reach up to 27%. On the other hand, the flat, low-laying terrain restricts the natural outflow of water, making it susceptible to soil salinization which is at present wide-spread in the study area (Ibrakhimov et al. 2007). Likewise, the supply of irrigation water and its distribution over the fields depends on terrain characteristics (Martius et al. 2012), eventually impacting crop growth.

The following analysis differentiated land degradation in relation to population density, as a proxy for population pressure, as recommended by the Global Assessment of Human-induced Soil Degradation (GLASOD) (Oldeman et al. 1990). The population densities were calculated per water user association, now called water consumer associations, within every district in Khorezm and SKKP in 2009–2010, since statistics were only available for this administrative level (UZSTAT 2010). The population densities were then reclassified into the four classes using a natural breaks algorithm: low density (0–2 pers/ha), medium density (2–17 pers/ha), high density (17–39 pers/ha), and very high density (39–79 pers/ha).In the study area, two agricultural land use periods can be distinguished: a spring season (October–June), dominated by winter wheat, and a summer season (April–October) dominated by cotton. The NDVI temporal profiles differ between spring and summer crops and among the summer crops (Conrad et al. 2011). Although the cropping pattern is largely consistent due to the cotton-wheat policy, a choice of the summer crop (after the harvest of winter wheat in June) or fallowing land can alter the NDVI trend. To avoid misinterpretation due to changes in cropping patterns, the negative NDVI trend map was cross-referenced with the land use data. The LULC maps for the years 2001–2009 (Machwitz et al. 2010) were used for this analysis. If the agricultural land use of particular pixels remained unchanged for six years between 2001 and 2009, they were defined as 'no change' areas. The same approach was used to derive a map of abandoned cropland which was defined as a land in fallow for at least six years within the monitoring period. Previous studies in Khorezm showed that land abandonment occurred mostly in areas that were least suitable for cropping due to low water availability, uneven terrain, infertile soils, shallow groundwater tables, and declining irrigation infrastructure (Dubovyk et al. 2012a).

4 Results and discussion

4.1 Spatio-temporal trend in vegetation decline

The mean seasonal NDVI and significant negative slope of NDVI trend over the years 2000–2010 are shown in figure 3. The maps revealed the overall correspondence between the low NDVI values (Fig. 3a) and areas of vegetation decline (Fig. 3b). The low vegetation cover, found along the southern border of Khorezm and in the north and north-west of SKKP (Fig. 3a), reflects the less intensive use of the cropland compared to the rest of the agricultural areas during the monitoring period (Dubovyk et al. 2012b).

Overall, approximately 40% (331,597 ha) of the study region experienced significant vegetation trends of differing magnitudes during 2000–2010. A pixel-wise trend of vegetation decline, expressed as a negative linear trend slope, highlights areas of significant and alarming vegetation cover loss and identifies land degradation (Fig. 3b, Photo 1). This decreasing trend was observed across 23% (94,835 ha) of the arable land in the study area, located mainly on the outskirts of the irrigation system near the borders of the Karakum and Kyzylkum Deserts. A large cluster of degraded cropland was identified in the western part of Khorezm, which coincides with an ancient riverbed of the Amu Darya River. Another cluster was detected on the northern and western part of SKKP, where the supply of irrigation water had reportedly been significantly limited during the observation period (Dubovyk et al. 2012a). An increasing trend in vegetation occurred in 19.6% (80,538 ha) of the arable land area, principally along the banks of the Amu Darya River and near irrigation canals. Vegetation cover was unchanged within 38% (156,225 ha) of the agricultural area (not shown here).

A number of studies (e.g., Prince et al. 2007) have raised issues related to the reliability of satellite based trend analysis for the detection of land degradation. Analyses have shown how differences in vegetation trends may be affected by several analytic and environmental variables. Analytic variables may include changes in the temporal domain of the time series, the timing and rate of degradation (Wessels et al. 2012), the particular data sources and methods used for a trend calculation (Fensholt et al. 2009). Significant environmental variables may include precipitation events (Tottrup and Rasmussen 2004), or atmospheric fertilization (Le et al. 2012). Additionally, management factors such as irrigation and fertilizer input practices occurring during agri-

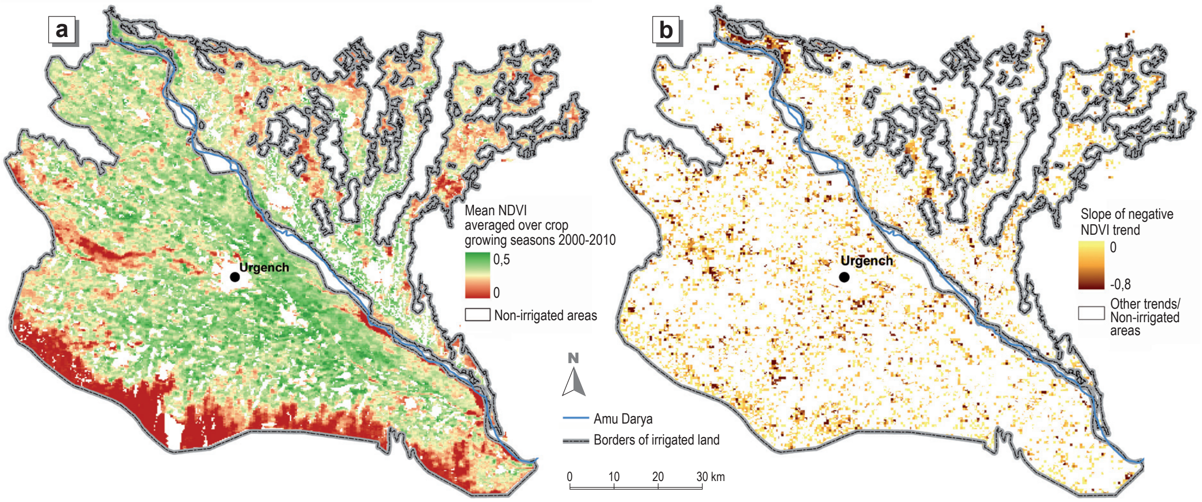

Fig. 3: Spatial distribution of mean NDVI values averaged over the crop growing seasons 2000–2010 (a), and negative significant linear trend of NDVI summed over the crop growing seasons 2000–2010 (b). White color represents masked out areas (a) and/or other trends (b)

Photo 1: Degraded highly saline cropland in the Khorezm Region (left) and degraded abandoned cropland in the southern part of Autonomous Republic of Karakalpakstan (right) during the crop growing season of 2010–2011 (Photo: O. Dubovyk 2010–2011)

cultural production and other ongoing land uses in the study region are likely to complicate the interpretation of satellite data.

As discussed previously, the accuracy assessment of the trend map was based on *in situ* field data. This procedure confirmed the validity of the analytic approach developed here. The validation results yielded an overall accuracy of 68%. The accuracy of the trend map derived in this study is in keeping with accuracies reported in related studies. Chen and Rao (2010) document an overall accuracy of 65% for their MODIS-based land degradation map in northeast China. The resulting degradation trend was also comparable with that observed in other studies in CA further suggesting reliable results. Dubovyk et al. (2012c) revealed a similar spatial pattern of a negative ΣNDVI trend for the same study area by use of a Mann-Kendall trend analysis of the 300 meter spatial resolution MERIS NDVI time series covering the years 2003–2011. The assessment by Propastin et al. (2008) of vegetation trends in CA, based on a 1 km AVHRR time series, previously identified the presence of a -10% to -20% negative linear trend within our study region during the 1982–2003 summer seasons.

The absence of reliable and spatially explicit information on irrigation water flows within the study region prevented the quantification of irrigation related effects on the degradation trend. However, a remote sensing based assessment is currently the only economically feasible and practical method for monitoring vegetation dynamics at the regional scale in this study area.

4.2 Spatial analysis of vegetation decline trend

4.2.1 Relationship with environmental factors

Spatial patterns of land degradation trend were overlaid with the maps of soil *bonitation* (Fig. 4a, Tab. 1) and slope (Fig. 4b, Tab. 2). Almost 50% of the degraded areas detected were found within the low *bonitation* classes III and IV. These areas are less suitable for agriculture due to soil quality constraints and require urgent attention of land managers to identify mitigation measures and cultivation techniques to forestall land degradation, or to decide whether to vacate land from cultivation (Vlek et al. 2008).

Approximately 14% of the cropland degradation present within the study site was observed in areas with the steepest slopes (2–10%). Local differences in the land relief play an important role in water distribution and management. When users can afford the costs of electricity, water pumping from the main irrigation canals into lower level channels is commonly practiced in the elevated areas on the southwestern border of Khorezm and north of SKKP (Dubovyk et al. 2012b). Dubovyk et al. (2013) applied logistic regression to analyze the spatial distribution of land degradation in Khorezm. This study determined that steep slopes, increasing groundwater table and groundwater salinity, and absence of cultivation had the strongest impacts on observed patterns of land degradation. Akramkhanov and Vlek (2012) employed neural network analysis to study impacts of environmental and management factors on the spatial patterns of soil salinity in the Khiva district of Khorezm. The authors point out the importance of micro-topographical features for soil salinity distribution on individual crop fields in their study area. In our analysis, we conclude that the small percentages of degradation observed within elevated areas in the study site are due to the fact that slopes steeper than 6% are found in only approximately 1% of the study area. The use of higher spatial resolution datasets may reveal additional details of terrain effects on land degradation distribution; these effects were partially concealed by the MODIS data product 250 m cell size. However, the field-level validation that was performed to evaluate the performance of our analysis verifies the utility of the relatively coarse MODIS data.

4.2.2 Relationship with socio-economic factors

The map in figure 4e shows clearly that most of the degraded areas are sparsely populated and constitute those marginal portions of the region having a limited carrying capacity (this can be observed by comparing figure 4a and 4e). Current cropping practices are not viable on such marginal lands, unless these areas are put under rice cultivation (Djanibekov et al. 2012). Ongoing agricultural practices are likely to aggreveate degradation processes, as generally observed in less resilient agricultural areas (Vlek et al. 2008). Approximately 3% and 19% of the degraded land was identified respectively within the areas of high and medium population density, principally along the right bank of the Amu Darya River and in central Khorezm (Tab. 3, Fig. 4e).

Up to 15% of the degradation trend was found within the areas of stable agricultural land use (Fig. 4c, Tab. 4), out of which about 7% were predominantly fallow lands (Fig. 4d, Tab. 4). The latter are

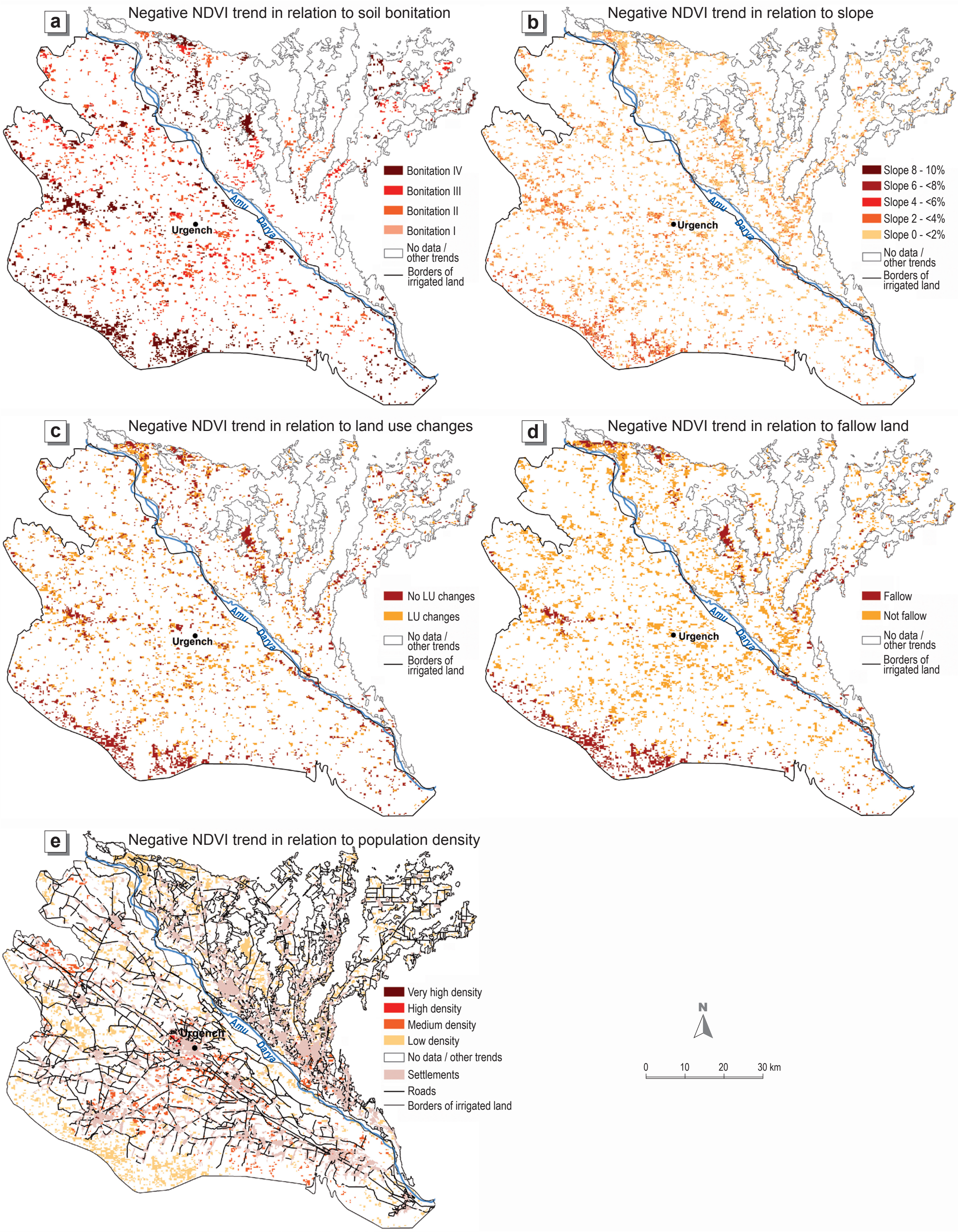

Fig. 4: Spatial distribution of degraded areas in relation to soil *bonitation* (a), terrain (b), land use (c, d) and population density (e). White color represents masked out areas and/or other trends

Tab. 1: Area of soil constraint (bonitation) classes calculated for the degraded land as identified by the negative ΣNDVI trend over 2000–2010

Bonitation class	Total degraded area [ha]	% of irrigated cropland	% of degraded land within bonitation class
Negative trend-*Bonitation* IV	27,762.50	6.77	29.27
Negative trend-*Bonitation* III	17,287.50	4.22	18.23
Negative trend-*Bonitation* II	13,181.20	3.21	13.90
Negative trend-*Bonitation* I	112.50	0.03	0.12
No bonitation data	36,491.20	8.90	38.48
Total	**94,834.90**	**23.13**	**100.00**

Tab. 2: Area of terrain constraint (slope) classes calculated for the degraded land as revealed by the negative ΣNDVI trend over 2000–2010

Slope class	Total degraded area [ha]	% of irrigated cropland	% of degraded land within slope class
Negative trend-Slope 0–2%	81,168.75	19.80	85.59
Negative trend-Slope 2–4%	12,941.15	3.16	13.65
Negative trend-Slope 4–6%	556.25	0.14	0.59
Negative trend-Slope 6–10%	168.75	0.04	0.18
Total	**94,834.90**	**23.13**	**100.00**

Tab. 3: Area of population density classes calculated for the degraded land as revealed by the negative ΣNDVI trend over 2000–2010

Population density	Total degraded area [ha]	% of irrigated cropland	% within population density class
Negative trend-Low density (0–2 pers/ha)	635,37.50	15.5	67.00
Negative trend-Medium density (2–17 pers/ha)	181,56.25	4.43	19.15
Negative trend-High density (17–39 pers/ha)	241,8.75	0.59	2.55
Negative trend-Very high density (39–79 pers/ha)	287,50	0.07	0.30
No data	104,34.9	2.55	11.00
Total	**94,834.9**	**23.13**	**100.00**

Tab. 4: Area of land use classes calculated for the degraded land as revealed by the negative ΣNDVI trend over 2000–2010

Land use class	Total degraded area [ha]	% of irrigated cropland	% within land use class
Negative trend-No LU changes	59,384.90	14.48	62.62
Negative trend-LU changes	35,450.00	8.65	37.38
Negative trend-Fallow	28,578.65	6.97	30.14
Negative trend-Not fallow	66,256.25	16.16	69.86

usually characterized by the low-*bonitation* values (compare Fig. 3a and Fig. 3d) and are often abandoned from cultivation particularly in drought years (Dubovyk et al. 2013). These areas have lost their protective vegetation cover (Photo 1) and should in the first place be a subject to rehabilitation measures that aims at establishing a healthy vegetation cover. This could be achieved by planting salt-tolerant crops, such as sunflowers (Gao and Liu 2010).

In irrigated land-use systems, the declining vegetation trend may also occur due to crop rotation and/or other management practices. During the last decade in Uzbekistan, agricultural land-use policies were maintained that persisted in limiting production to cotton and winter wheat; this explains the present predominance of these crops in the agricultural areas. The present studies of this region are subject to data constraints as well; data on the distribution of irrigation water is particularly limited. The analytical framework of this study, however, has been shown to be valid and can be reapplied when additional data is available.

4.2.3 Spatial targeting of rehabilitation of degraded cropland

We were able to accurately characterize the spatial dynamics of cropland degradation by integrating trend analysis of the MODIS-NDVI time series and spatial relational analysis of the mapped negative vegetation trends. These findings could, therefore, be used to support identification and targeting of appropriate and effective land management measures. If supporting corresponding policy decisions were implemented by Uzbek authorities, degraded areas identified and located in this study could be targeted for mitigation and rehabilitation measures. As an example, degraded croplands located within areas of high population density could initially be subjected to measures designed to halt ongoing cropland degradation while supporting the future livelihood of the people. Prompt actions are also necessary to restore croplands that have become least favorable for agriculture. These include poor quality lands located on elevated areas within zones of lower populated density. If such croplands remain under the present management approach, ongoing degradation could become irreversible or the required investments in soil improvement measures may no longer be economically viable (VLEK et al. 2008).

The rate of degradation has substantial impacts upon decisions regarding the suitability of cropland for further agricultural land use. Continuing cropping of severely degraded land is not profitable for farmers (DJANIBEKOV et al. 2012). A possible solution might involve releasing such lands from cropping and implementing alternative land uses, preferably uses that include remedial functions. Studies in Khorezm have documented successful rehabilitation of degraded croplands through afforestation efforts, using well adapted tree species that increased the productive and economic capacity of the land (KHAMZINA et al. 2012). In such cases, farmers should be offered additional incentives, such as payments for ecosystem services, to encourage the adoption of rehabilitation practices (THOMAS 2008).

The cost of corrective measures may be substantial, however compelling reasons remain for investing in sustainable land use measures, including the arguments of opportunity costs of farmers' foregone income. Delaying or postponing implementation of such measures will also increase the high costs of farmers' foregone income. If actions are not now implemented to reverse on-going land degradation, farming will require additional financial support or subsidies. Such future support would very likely exceed the present costs of implementing sustainable practices. It has been repeatedly demonstrated that the long-term benefits of soil protection practices such as yield stabilisation, yield improvement, and natural resources protection more than compensate for the costs of implementation. Additionally, convincing evidence is emerging that it is possible to adopt agricultural conservation practices that enhance agro-ecological restoration within this study region (KIENZLER et al. 2012).

The regional assessment presented in this study used medium resolution satellite data to identify "hotspot" areas; areas for which more detailed understanding of the cropland degradation process is required. Further steps toward this increased understanding could include on-site validations of results to enable development of site-specific recommendations for land rehabilitation and/or conservation measures. At the scale of individual fields, detailed information on the critical factors leading to degradation (such as soil salinization and soil nutrient loss) as well as land and water management practices should be identified and compiled. This would facilitate the development and introduction of the most appropriate restoration technologies to counter on-going cropland degradation - technologies that are economically viable, socially acceptable and ecologically sound (AKRAMKHANOV et al. 2011; LE et al. 2012).

5 Conclusions

Our analysis of the 2000–2010 MODIS-NDVI time series has identified a distinct trend of decreasing greenness values of vegetation signals within the image data set. This clear result was found to be useful in generating spatial information on the distribution of degraded irrigated croplands within our study area. Vegetation degradation maps which were developed as output products of our analyses can directly support the identification and prioritization of cropland areas best suited for remediation and restoration within the Khorezm Region and southern Karakalpakstan in Uzbekistan.

A suite of ancillary datasets were utilized to improve our understanding of the factors underlying the observed trends in vegetation degradation. The majority of the cropland degradation identified within the study area occurred in marginal agricultural areas. These marginal areas are typically characterized by poor quality soils and low resident population density. In addition, these degraded areas are commonly taken out of the regular cropping cycle and often abandoned. Those degraded croplands that are located within more densely populated areas and include higher quality soils may be appropriate areas for the introduction of more sustainable cropping practices. Marginal croplands, however, should be considered as candidate areas in which to implement appropriate rehabilitation measures. Such measures may include cessation of annual cropping and fallowing or vacating the land. This study clearly demonstrates the use of geospatial tools for land degradation assessment, and the resultant increased knowledge of the factors involved in land degradation can enable improved spatial decision support for planning rehabilitation measures.

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