LAND DEGRADATION MONITORING IN THE WEST MUUS, CHINA

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ABSTRACT:

This paper presents a study on land degradation monitoring focused in the west part of the MuUs Sandy Land in Ordos, one of the important dry areas in China, aiming to understand land degradation distribution in space and time and the role of anthropogenic action in such land surface processes at local level. Multi-temporal Landsat images (MSS 1978, 1979; TM 1987, 1989, 1991 and 2007; ETM+ 1999 and 2001) and SPOT images (HRVIR 2005 and HRG 2006) were used in this assessment. A combined processing algorithm: indicator differencing-and-thresholding and post-classification differencing was proposed. Meteorological data since 1960s were incorporated in the analysis to avoid the false alarm of the land degradation signal — change due to temporary fluctuation in climate. The results show that although local people and government agencies have undertaken widespread activities to combat desertification, for example, planting first herbs, shrubs and then trees in a network way in the degraded grassland, deserts and other sandy land in the study area, land degradation has still taken place, especially, in the non-controlled zones. Grassland patches in the marginal areas are being engulfed by deserts, which are extending mainly to southeast at an average rate of 11-21m/year; grassland degradation and reactivation of sand dunes caused by overgrazing and cultivation around water points/settlements and in the permitted rotation zones were also observed; and water-table has regionally declined due to over-pumping for agriculture, sand-control activity, and in particular, coal mining and oil and gas exploitation. Some aquifer has been locally destroyed due to land subsidence caused by unsustainable mining activity. For this case area, land degradation is produced by human activity, mainly overgrazing, land reclamation and overuse of the groundwater for agriculture and exploitation of oil, gas and coal mines, and intensified and extended by the general aridity of the area and dominant strong wind from northwest; the causes leading to land degradation in the recent three decades are multiple, but the underlying causes are culture and unreasonable land use policies. Under the "social capitalism system" there is indigenously the institutional deficiency with which the land property cannot be clearly defined. These factors exacerbate the negative impacts of policies and lead to land degradation. However, land degradation is not absolute and can be mitigated and even restored with the implementation of rational policies.

1. INTRODUCTION

1.1 Brief review of desertification and land degradation

Since Lampery reported the south advancement of the Sahara Desert at an average rate of 5-6km/year in the period 1958-1975 in the UNESCO/UNEP conference in 1975, "desert encroachment" or "desert advancing" or "desert marching" in Africa had drawn attention of a great number of institutions, individual scientists and governments and "desertification" has become one of the major subjects of dryland environmental research in the world in the past decades (Hellden 1988, Warren and Agnew 1988, Forse, 1989, Hellden 1991, Tucker *et al.* 1991, Thomas and Middleton 1994, Prince *et al*. 1998, Smith and Koala 1999).

A worldwide discussion and debate have been unfurled since then to understand the reality of "desertification", its reversibility, irreversibility and origins (climate variations and human activities). With the contribution of hundreds of scientists based on remote sensing studies and field investigation, it became clear that there is no desert advancing in Sahara.

The south marginal belt of the Sahara Desert can move not only to south but also to north. Such a to-and-fro movement, or rather, expansion and contraction of Sahara (Tucker *et al*. 1991) is a climate (rainfall) related phenomenon. Up to this time, "marching desert" was considered as a "myth" (Forse 1989, Thomas and Middleton 1994, Smith and Koala 1999). Lamprey's findings were challenged and criticized.

However, Lamprey's conclusion gained a lot of proponents from international community to national governments. Combating desertification has thus been raised as one of the major environmental managements and one of the national strategic priorities in some countries (Glantz and Orlovsky 1983, Hellden 1988). This has also become a rational pretension of some governments to get funding from the developed countries and international organizations, and the United Nations have thus invested billions of US$ for this activity (Forse 1989, Thomas and Middleton 1994). Despite this and other efforts, the UNEP concluded in 1991 that the problem of land degradation in arid, semi-arid and dry sub-humid areas had intensified, although there were "local examples of success". That was the reason to set up the United Nations Convention to Combat Desertification (UNCCD) in 1996[1].

However, a major confusion in the past decades and even today lies in the definition of desertification and its relation to land degradation. What was emphasized by Lampery's findings is in

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[1] http://www.unccd.int/convention/menu.php

fact the "spreading desert" (Warren and Agnew 1988). It is different from the original meaning given by Aubréville, which was used to describe a human-induced landscape transformation "from tropical forest to savannah and from savannah to desert-like region" (Aubréville 1949). A number of authors and institutions proposed their own definition and lead to a conception plethora and mal-communication among scientists, institutions and policy-makers (Glantz and Orlovsky 1983). The most recent definition by UNCCD (Article 1) is "desertification means land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities". De facto, the common problem in drylands is land degradation, which has the following symptoms according to Sheridan (1981): declining groundwater tables, reduction of surface waters, salinization, topsoil erosion, and the desolation of native vegetation. The authors agree on the opinion of Warren and Agnew (1988), we should respect the original meaning given by Aubréville and limit the usage of desertification to an extreme form of land degradation when it reaches desert-like condition. This is the baseline that needs to be clarified.

1.2 MuUs Sandy Land in Ordos

As one of the important arid areas in China, the MuUs Sandy Land (also called MuUs Desert) is located in the south part of the Ordos region in Inner Mongolia and adjacent with Shaanxi and Ningxia (figure 1). Geomorphologically, it is a part of the Ordos Plateau and bordered with the Loess Plateau on the south. The region is mainly a sandy agro-pastoral land embedded with desert patches. The vegetation consists of shrub, semi-shrub and perennial herb (Wu *et al*. 2005). The average annual precipitation is around 317 mm depending on the locations, 70% of which concentrates in the period July-September. Wind from northwest blows 230 days, among which the ones exceeding Beaufort Scale Force-8 (speed >17 m/s) occur more than 40 days per year. The hyper-concentration of rainfall and strong wind provoke soil erosion and water loss (Xu 1999). Furthermore, under this plateau, there is abundant good-quality coal resource as well as natural gas and oil reserve. In the recent years, Ordos has become one of the national energy bases under the mid-to-long term national strategy "To Develop the West". Long time human activity in grazing, deforestation and reclamation for agriculture, medicinal herbs and fuel wood collection and fossil fuel exploitation in the recent decades in the plateau has intensified land degradation (Jiang *et al.* 1995, Jia 1997, Wu 2003a).

Following to the Lamprey's conclusion, "desert invasion" in north China had been circulating in the Chinese media in 1980s. Especially, peoples started to note that dust-and-sand storms occurred more and more frequently and thus "desert spreading" was recurrent in the media in 1990s. It was said that the MuUs and Tengger Deserts (figure 1) were advancing to south and menacing the provinces Ningxia and Shaanxi. It is one the objectives of the Sino-Belgian Cooperation Project (1999-2001)[2] to verify whether such an invasion exists or not. Similar to the Sahara Desert, no significant advancing was found in north Shaanxi, a transitional belt between the MuUs Sandy Land and the Loess Plateau (Wu 2003a). This can be attributed to the success of sand-control by the local people and governmental agencies since 1950s (Wu *et al*. 2005).

For the land degradation problem in Ordos, some authors have carried out analyses on historical situation and degradation proximate and underlying causes (Jiang *et al*. 1995, Jiang 1999), degradation nature (Jia 1997), space-time distribution of degradation and sand-control (Wu *et al.* 2005), dust-storm and its relation to land use (Xu 2006). As to MuUs, Wang and Wang (1997), Chen and Gao (2001), Gao *et al*. (2001), Runnström (2003), Wu (2003a), Li *et al*. (2004) and Guo *et al.* (2005) have investigated rangeland use and biomass change including land degradation in the past decades by remote sensing.

Based on our previous study (Wu *et al.* 2005), this paper reveals a multi-temporal observation of land degradation in the west of MuUs by linking remote sensing with ground data to understand the role of human activity and natural factors in this process in the past 30 years.

2. METHODOLOGY

Remote sensing has been widely applied in monitoring land surface processes thanks to its grand advantage in multi-scale and multi-temporal/even time-series observation over the same area. As mentioned above, innumerous scientists have made contribution to land degradation and desertification study using this technology in the past decades (Hellden, 1988, Hanan *et al*.1991, Tucker *et al.* 1991, Hill 1993, Hill *et al*. 1995, Nicholson *et al.* 1998, Prince *et al.* 1998, Collado *et al*. 2002, Runnström 2003, Wu *et al*. 2005). This research makes use of this technology to analyze the land degradation, or rather, the biophysical feature change of the rangeland in response to different kinds of human activity in the West MuUs based upon a multiple change detection approach. The detail and procedure are unfurled as follows:

2.1 Data

As listed in table 1, multi-temporal Landsat and SPOT images were used. Meteorological data, especially, annual rainfall of the region from 1960 to 2007 were integrated.

2.2 Degradation discerning approach

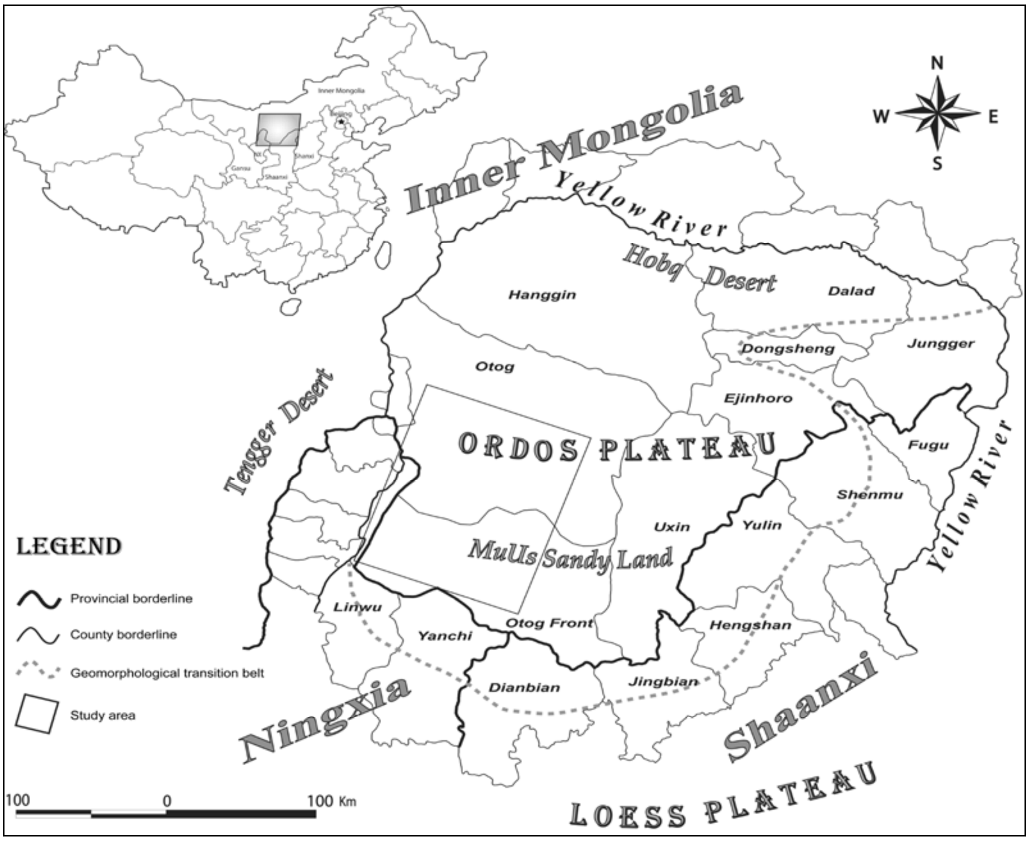
Land degradation is in fact one of the land surface processes, which physically shows an increase in soil bareness/brightness and a decrease in vegetation vigor or coverage extent that lead to eventually a reduction in land productivity. It can be thus distinguished through the spectral reflectance change of land cover in time. We can apply "change detection" techniques for discerning degradation.

At present, a number of change detection algorithms are available and they can be summarized in two groups: thresholding and non-thresholding approaches. *Thresholding* approaches include image or indicator differencing (Rifman 1975, Sabins 1978, Jensen and Toll 1982), ratioing (Todd 1977, Howarth *et al*. 1981, Nelson 1983), regression (Ingram *et al*. 1981, Jensen 1983, Singh 1989), change-vector analysis (Engvall *et al*. 1977, Malila *et al*. 1980, Colwell and Weber 1981, Lambin and Strahler 1994), cross-correlation (Koeln and Bissonnette 2000); and *Non-thresholding* techniques mainly contains delta data change detection (Anuta 1973, Weismiller *et al*., 1977), post-classification comparison (Swain, 1976, Weismiller *et al*. 1977, Gordon 1980, Howarth and Wickware 1981), post-classification change differencing (Mas 1999) or post-classification differencing (Wu 2008). For these change detection approaches, several authors (Singh 1989, Lunetta and Elvidge 1999, Mas 1999, Wu 2003b and Coppin *et al.* 2004) have reviewed their advantages, shortcomings and time scale

[2] http://www.geo.ucl.ac.be/Recherche/Teledetection/Projects/China1.html

applicability.

Although as many authors argued, the post-classification algorithm may produce huge error or unsatisfied results if each class is not well classified and validated compounded with mis-registration (Howarth and Wickware 1981, Lambin and Strahler 1994, Coppin *et al.* 2004), with the improvement of classifiers (such as Maximum Likelihood, Neural Network, etc.), advancing of computing technology and combined with some specific techniques, more and more successful change detection studies have been achieved with this algorithm (Tucker *et al.* 1991, Skole *et al.* 1993, Foody and Boyd 1999, Mas 1999, Pace *et al*. 2006, Wu 2008). It has become one of the most frequently applied approaches, especially, when we use different source and resolution data since each individual classification is undertaken independently. Another advantage is that there is no need to set thresholds to identify again the concrete change types as all classes have been defined during the classification procedures. The strict requirement for this method lies in the exactitude and high accuracy of each individual classification.



Note: the administrative unit shown in this figure in Inner Mongolia is Banner
("Qi" in Chinese pronunciation), which is similar to the unit "County" in other provinces.

Figure 1: Location of the study area and its administrative units

Captors	Scene frame	Acquisition dates	Spatial resolution	Total haze	Policy implementation
SPOT5 HRG SPOT4 HIVIR	**K-J: 262-272**	2006 Aug 15 2005 Aug 17	10 m 20 m		
Landsat 5 TM Landsat 7 ETM+ Landsat 7 ETM+ Landsat 5 TM Landsat 5 TM Landsat 5 TM Landsat 3 MSS Landsat 3 MSS	**Path-Row: 129-33**	2007 July 09 2001 Oct. 6** **1999 Aug.12*** 1991 Aug. 30 1989 Sep. 17* **1987 Sep. 20*** 1979 Oct. 09* **1978 Aug. 21**	30 m 30 m 30 m 30 m 30 m 30 m 56 m 56 m	30.07 31.06 85.54 13.13	**Period 3: 2000-2001,** "Herbs collection forbidden" and "Grazing-forbidden and -rotation policy" **Period 2: 1987-1988,** Deng's "Open and reform" and "Legalization of the private economy" **Period 1: 1979-1985,** Nationwide implementation of Deng's "Household land tenure policy" and issues of the Decree of Grassland

Note: (1) * images inherited from the Sino-Belgian Cooperation Project (1999-2001) at the University of Louvain, Belgium; ** provided by Dr C. Kunzer; two Landsat MSS 1978 and TM 1991 images acquired freely from Landsat.org; two SPOT images were provided by the EU (European Union) OASIS project; (2) the haze values in digital count (DC) derived from the 4th Tasseled Cap feature are used for atmospheric correction.

Table 1: Multi-temporal satellite images used in this study and policy implementation periods

Among the thresholding techniques, most algorithms necessitate a procedure to identify the concrete change types based on the first-hand data or knowledge about the study area as well as setting the thresholds to fix or highlight or label the changes. Since these techniques provide lower change detection errors when compared against other approaches, they are well employed in change detection in bi-temporal and time series spaces.

In view of the above considerations, both thresholding (indicator differencing) and non-thresholding (post-classification differencing) techniques were combined for labeling land degradation in this study. The procedures are shown as follows:

2.2.1 Image-to-image rectification: The Landsat ETM+ image dated Aug.12, 1999 was first geometrically corrected with topographic maps on the scale of 1/200,000 to 1/300,000 and field GPS points (totally 121 GCPs) in the datum WGS84 and projection UTM (Zone 48) using polynomial model (3^{rd} order) and nearest neighbourhood re-sampling. This image was used as reference to correct other images. The RMS error of the image-to-image rectification comes between 0.23 and 0.58 pixels.

2.2.2 Atmospheric correction: For the Landsat MSS, TM and ETM+ images, an image-based approach was introduced in this study, that is, the COST model proposed by Chavez (1996). A key point in this method is to determine the haze value to be removed. The traditional way to obtain the haze value is to measure the radiance in some deep clear water or shaded areas (dark-object) in image where the radiance in near infrared bands is zero or near zero. Any over-zero value is considered to be a result of scattering and path radiation. Such haze removal often produces over-correction and is not applicable to the image where dark-object does not exist (Chavez, 1996). In this study, the 4^{th} Tasseled Cap Feature (Kauth and Thomas 1976, Crist *et al.* 1984a, 1984b) was used to estimate the haze value (table 1). The scattering effect was removed from each band according to the improved DOS (dark-object subtraction) model (Chavez 1988) for Landsat images (MSS and TM), followed with the COST model to correct sun elevation and sun-earth distance effect and at the same time to transform the at-satellite radiance (DN) into the surface feature reflectance (more detail concerning this correction see Wu 2003b).

2.2.3 Multispectral transformation: The NDVI has been widely applied in land cover characterization and change detection. However, there are some concerns on the use of this index to infer vegetation and soil properties, especially, in dryland since the NDVI is influenced by brightness variations in canopy background (soils, litter, etc.). Moreover, there is a saturation effect of NDVI behavior over densely vegetated landscapes (Huete 1988 and Huete *et al*. 2002). The Atmospherically Resistant Vegetation Index (ARVI) proposed by Kaufman and Tanré (1992), the Soil Adjusted Vegetation Index (SAVI) developed by Huete (1988) overcome these shortcomings. The authors of the paper had once made use of the SAVI to assess land degradation in the Ordos region (Wu *et al.* 2005). Merely, we found that the dynamic range of SAVI is narrower than that of NDVI and ARVI after introducing the adjustment factor L, that is to say, the SAVI can reduce the soil influence meanwhile loses to a certain extent its sensitivity to varying vegetation vigor in dryland. In the improved version of SAVI, the Enhanced Vegetation Index (EVI), Huete *et al.* (1994, 1997 and 2002) introduced the blue band to diminish the atmospheric effect based on the idea of the ARVI (Kaufman and Tanré 1992). As Huete *et al* (2002) state, the EVI is resistant to both soil influence and atmospheric effects. Thus in this study, the EVI was employed to highlight the rangeland biophysical change through time. Mathematically it can be expressed as (Huete *et al.* 2002):

$$EVI = G \cdot \frac{\rho_{NIR-}\rho_{RED}}{\rho_{NIR} + C_1 \cdot \rho_{RED} - C_2 \cdot \rho_{BLUE} + L}$$

Where, ρ_{NIR} = Near Infrared reflectance;
ρ_{RED} = Red reflectance;
ρ_{BLUE} = Blue reflectance;
C_1 = Atmosphere resistance red correction coefficient (default = 6);
C_2 = Atmosphere resistance blue correction coefficient (default = 7.5);
L = Canopy background brightness correction factor (default = 1);
G = Gain factor (default = 2.5).

Unfortunately, the EVI is not applicable to the MSS and SPOT images, which do not contain the blue band. Thus, we transform again the NDVI and SAVI (L=1 for dryland), although with the above mentioned shortcoming, for all images to monitor the time trajectory of greenness (vegetation vigor) in the past 30 years.

2.2.4 Degradation extraction:

2.2.4.1 Indicator differencing-and-thresholding

A differencing processing was applied to the atmospherically corrected EVI between 1999 and 1987 and between 2007 and 1999 followed with a thresholding technique. Thus the negative change (vegetated cover decrease or vigor decrease) and positive change (vegetated surface augmentation or vigor increase) in the two periods were distinguished. This procedure allows us to extract the spectral reflectance change information in green vegetation cover. These positive and negative changes include a plenty of false change such as conversion from cropland to fallow land or from fallow land to farmland. These are not true changes and have to be excluded manually. For the period 1978-1987, we first tried to carry out a differencing on the SAVI. It was found that there is a difference of about 0.17 units between the mean SAVI values of 1987 (0.121) and 1978 (0.289), implying an inapplicability of differencing technique. That is the reason that we had to apply other discerning approach.

2.2.4.2 Post-classification differencing

With the failure of SAVI differencing algorithm probably due to the different resolution and captor features between MSS and TM images, we conducted the change detection by “post-classification change differencing” (Mas 1999) or “post-classification differencing” (Wu 2007).

The classification was carried out in a supervised way using Maximum Likelihood classifier. The training areas were selected in term of field observation, QuickBird images on Google Earth. Four major land cover types: Sand (desert), Vegetation (VGT, including agricultural patches, pastures and weak vigor grassland), Water and Bare Soil (with high reflectance is mainly dry salty crust or saline land occurring along rivers, around lakes and swamps). After aggregation, two major classes were eventually remained: Sand and Non-sand (VGT + Water + Bare Soil). The overall accuracy against the

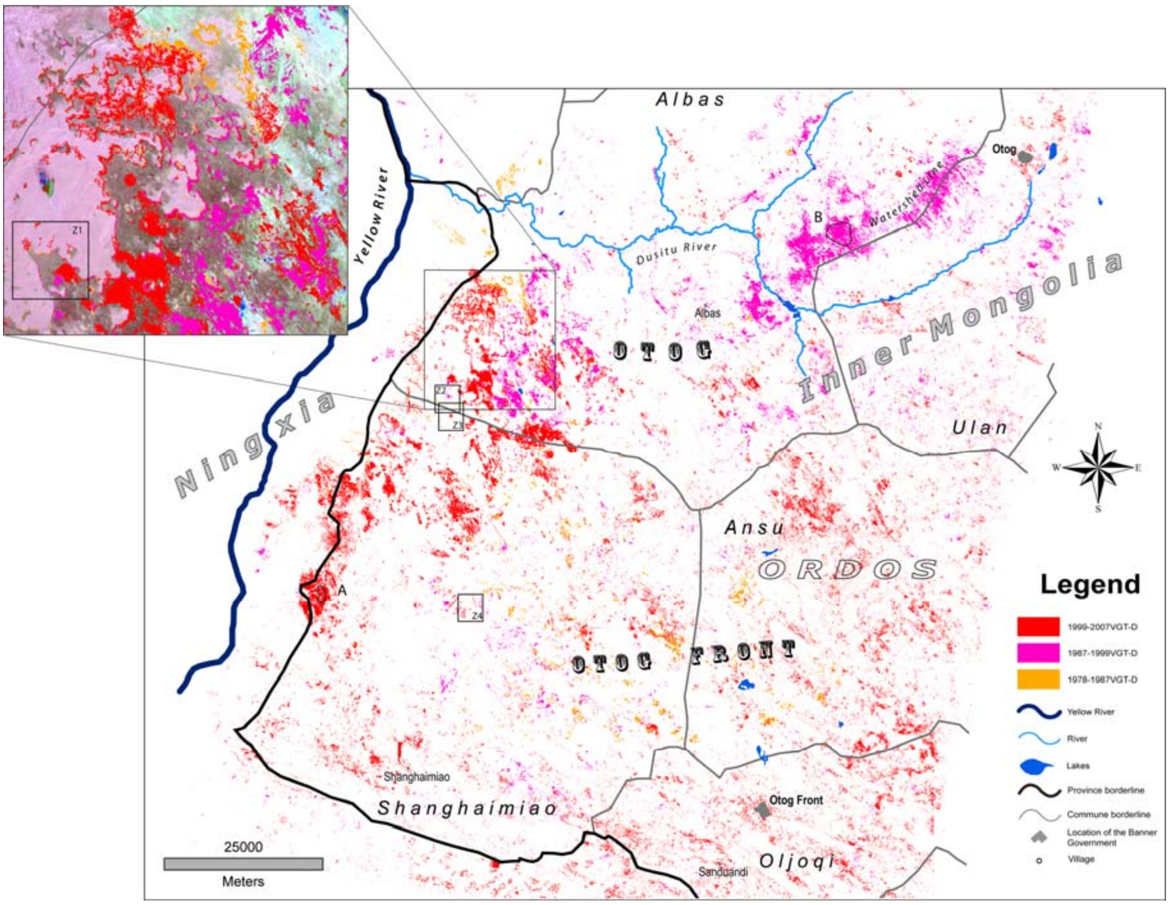
ground truth "regions of interest" and Kappa Coefficient of each individual classification are depicted below:
MSS 1978: Overall accuracy 98.4%, Kappa Coefficient 0.947
TM 1987: Overall accuracy 99.8%, Kappa Coefficient 0.995
Class-differencing produces extension or reduction information of the concerned class, for example, Sand1987 – Sand1978> 0, sand class has extended, on the contrary, it has contracted or reduced.

3. RESULTS

The remote sensing processing results are shown in figures 2, 3 and 4. It is noted that:

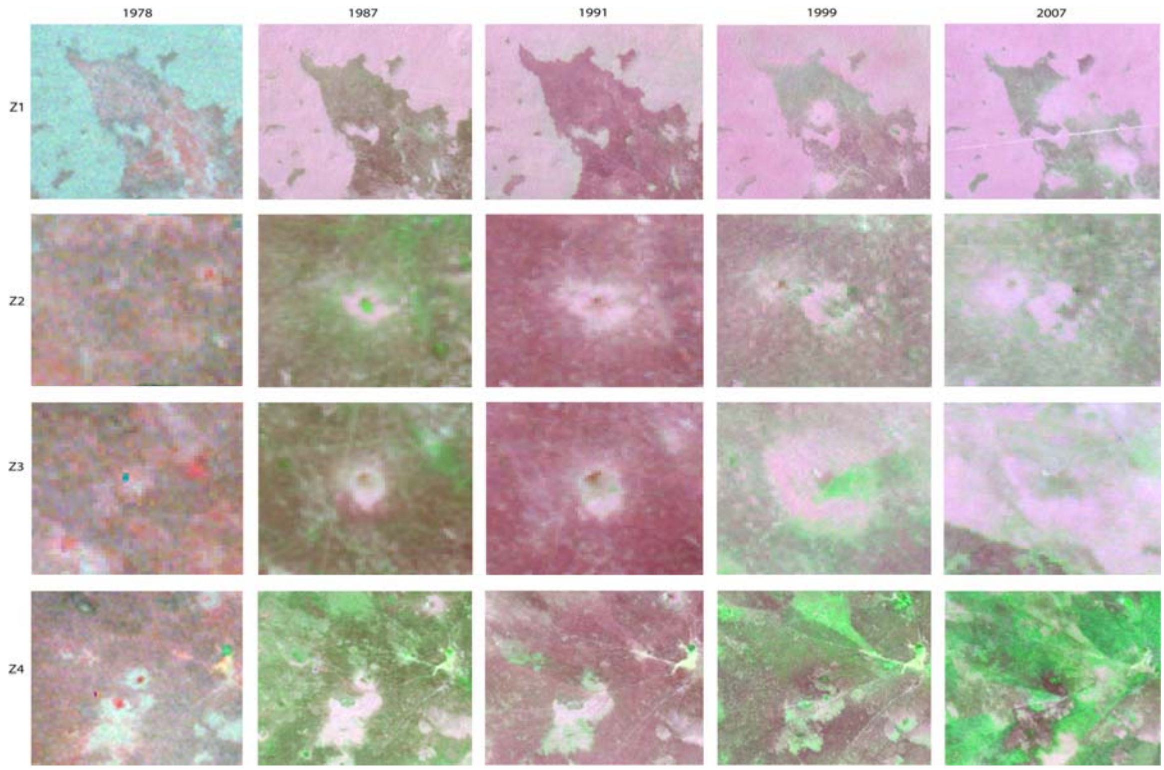
(1) Although the exaggerated "Menacing invasion of the MuUs Desert" as reported by the Chinese media in 1980s and 1990s was not observed in the study area, the desert patches, **especially, in the non-controlled zones** are truly in extension to the southeast not at a velocity of several km/year but 11-21m/year. More concretely, deserts and small patches of sand dunes extended respectively 4-8 pixels, 3-6 pixels and 2-5 pixels (1 pixel = 30m) in the periods 1978-1987, 1987-1999 and 1999-2007 and swallowed the grassland on their southeast margins where there is not enough shrubs (e.g., *Caragana Korshinskii Kom* and *Salix gracilior*) in their weak vegetation cover to block sand movement. We used the TM 1989, 1991, ETM+ 2001 and SPOT 2005/2006 to check the extension trend and found the deserts advanced respectively 1-2 pixels from 1987 to 1991 and from 1999 to 2001, and 2-3 pixels from 2001 to 2006. Clearly, this extension is due to the strong wind blowing from northwest, which occurs about 230 days per year. Driven by the wind, the deserts extended 240-570 m to the southeast in the past 30 years.

(2) As well as the desert extension, two kinds of vegetation degradation were observed: (a) around water points/settlements (patch diameter varying from 300 to 1600m depending on locations) and (b) in some grazing-permitted grassland, of which a part of such grassland had been previously controlled (figures 2 and 3). However, degradation does not always occur in the same place, that is, in one place in one period but elsewhere in the next one.



Note: figure showing (1) desert patches extending to the southeast (detail shown in the up-left zoom) and (2) grassland in degradation in the observed periods 1978-1987, 1987-1999 and 1999-2007. Site A (4146 pixels) reveals controlled grassland degradation after 1999 and site B (14467 pixels) shows a degradation in the period 1987-1999 and recovery in 1999-2007 (NDVI trajectory see figure 5). Zooms Z1, Z2, Z3 and Z4 show examples of vegetation cover changes around water points/settlements (see figure 3)

Figure 2: Land degradation in the West MuUs



Z1: patches of vegetation degradation started in the periods 1978-1987 and 1991-1999, degradation in extension; Z2: degradation patch occurred in 1978-1987 and after 1999 the 2nd one appeared in the adjacent area and almost coalesced with the 1st one; Z3: degradation extension around water point since 1978; and Z4: recovery of the previously degraded patches (degradation occurred before 1978).

Figure 3: Vegetation cover change around water points/settlements

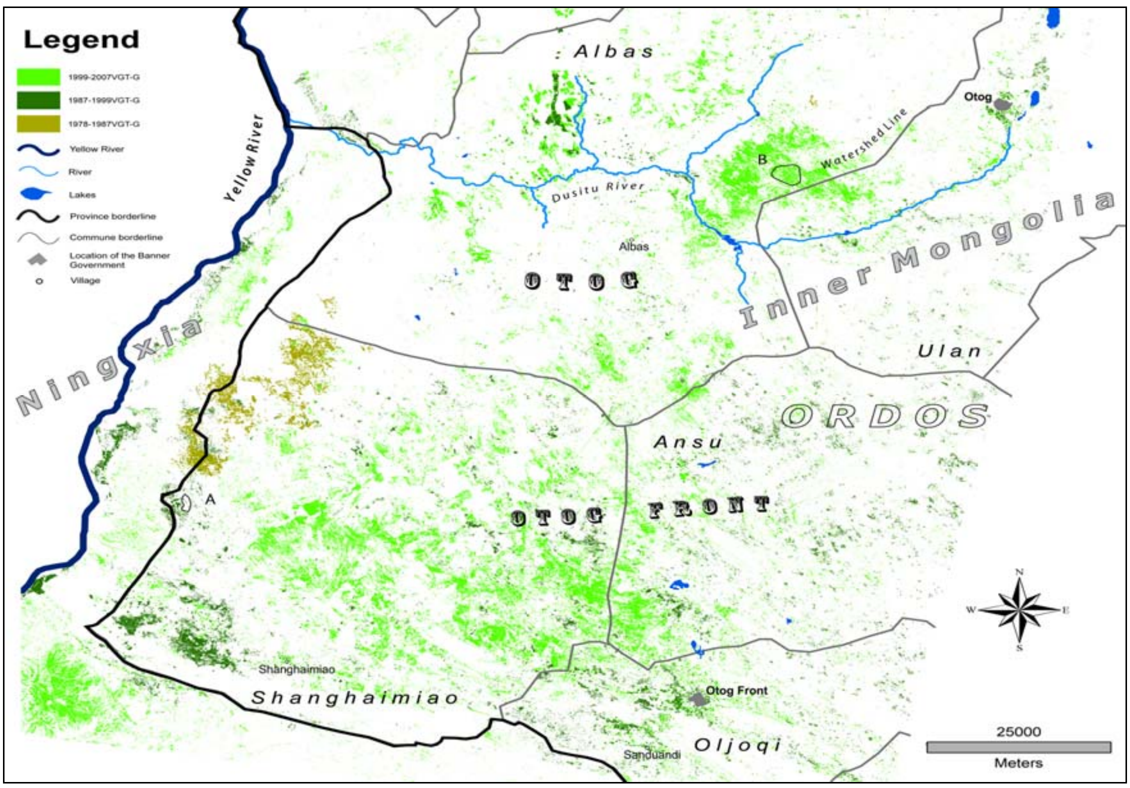
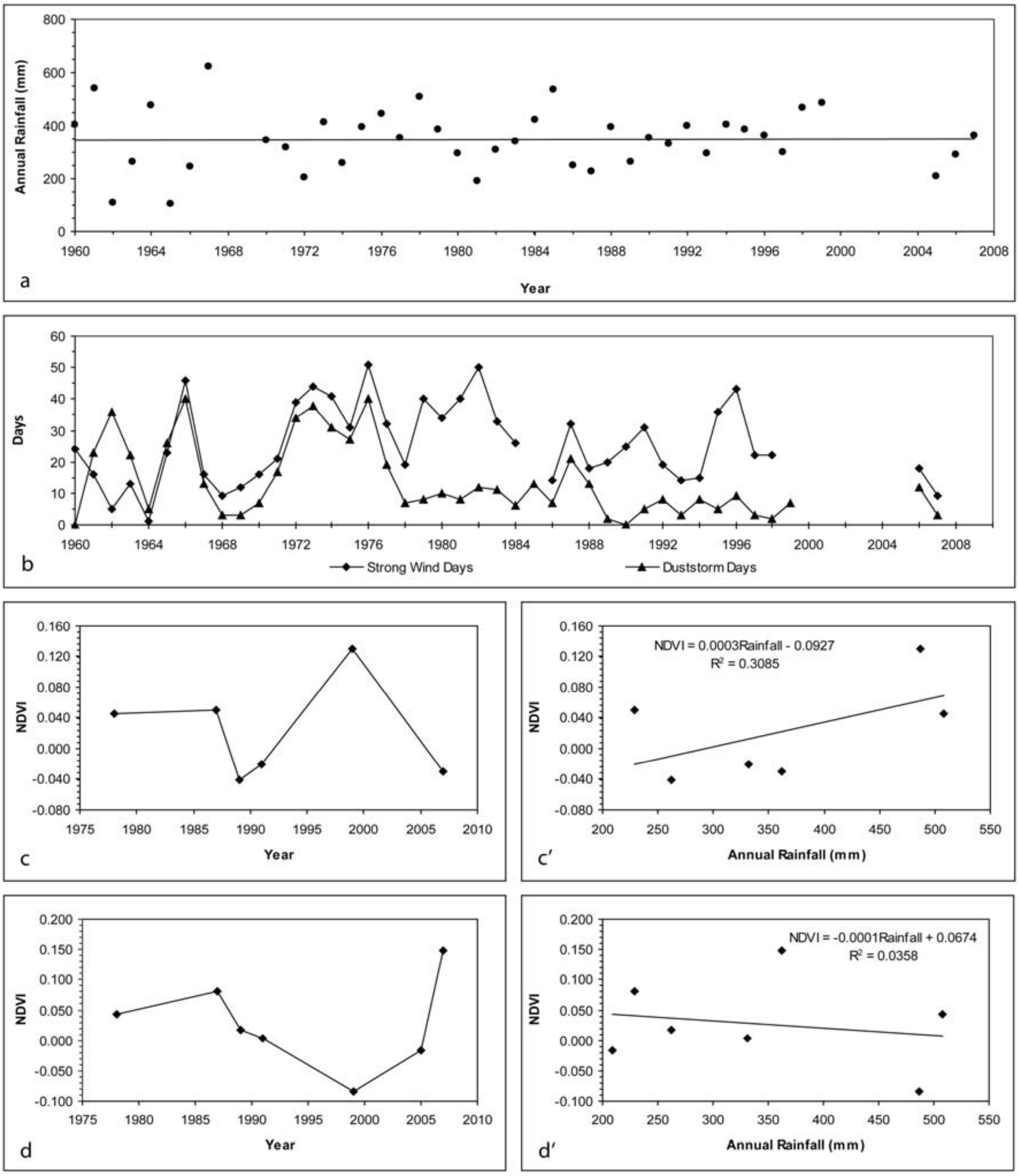


Figure 4: Vegetation recovery or vigor increase in West MuUs
(VGT-G: Vegetation growth or vigor increase)

(3) While occurs the vegetation degradation in some local places, vegetation vigor has gained a widespread increase (see figure 4), especially, in the recent decade due to the conversion from grassland to agricultural land (including farmland, plantations of economic plants such as ephedra, licorice, etc.) and from natural grassland into pasture/forage land irrigated with underground water. Sand-control (planting grasses, shrubs and trees in a network way) in the sandy land and desert patches has increased the land cover greenness. The degraded patches around water points/settlements having taken place in the previous periods have to a various extent restored although the green coverage in these patches has not yet reached to the level of the surrounding grassland after 20 even 30 years recovery (for example Z4 in figure 3).



Note: (a) annual rainfall and (b) duststorm days and strong wind days in the past four decades; (c) NDVI trajectory in site A: a controlled area in the 1987-1999 suffered a vegetation degradation in 1999-2007; (c') the relationship between the average NDVI value of site A (4146 pixels) in figures 2 and 4 and the mean annual rainfall; (d) vegetation cover degradation in the period 1987-1999 and recovery after 1999 in site B in figure 2 and 4, and (d') the relationship between the average NDVI of site B (14467 pixels) and the regional annual rainfall.

Figure 5: Annual rainfall and the relation between annual rainfall and NDVI

(4) Calibration with the meteorological data

To avoid the false alarm of rangeland degradation and resilience, it is necessary to combine the meteorological data for calibration. According to the research of Nicholson et al. (1990), Tucker et al. (1991), Davenport and Nicholson (1993), the NDVI has a log-linear or liner correlation with rainfall up to their geographical locations. In this study, the average annual rainfall of the study site in the past 40 years (1960-2007) was projected in figure 5a, it is not difficult to find that the annual rainfall interannually fluctuated in the past four decades but the mean value kept unchanged. The rainfall corresponding to the image acquisition was incorporated to calibrate the NDVI trajectories of the sites A and B (figure 5c' and 5d'). The R2 values are very low (0.3058 and 0.0358 respectively) implying that the correlation between the NDVI and annual rainfall is very feeble. That is to say, these changes in the NDVI trajectory might not be directly controlled by the rainfall fluctuation but a result of human activity in land use.

4. DISCUSSIONS

It is essential to be prudent in desertification and land degradation monitoring. Since the explosion of the myth: "desert spreading" of Sahara in 1990s, almost no one has dared to say any more "desert extension" or "desert advancing". For this issue, we should look at it dialectically. There is no "desert spreading" at a rate of 5-6km/year as Lamprey reported, but this does not mean that deserts are always stable. It is known that active sand-dunes move due to wind blowing. When they cross over the borderline between desert and non-desert, desert extends. As a matter of fact, local governments measured some sand-dune movement in the banners Otog Front, Otog, Hanggin and Uxin and reported the pace as 1.1 to 4.0m depending on the localities in the months from March to June in 2006[3]. Such velocities are compatible with what we have observed by remote sensing (11-21m/year). It is worthy of attention that no extension was sensed by satellites in most deserts where sand-control has been conducted inside and/or outside the patches, particularly, in the east part of the MuUs Sandy Land, for example, Ejinhoro and Yulin (Wu 2003a, Wu *et al.* 2005). Therefore, wind-driven desert extension is a local phenomenon and may not have constituted the sensational menace for the adjacent provinces.

It was observed in this study that vegetation degradation in the forms of a plenty number of round or quasi-round patches has taken place around water points/settlements in both banners Otog and Otog Front. Most of them appeared in the pre-1978 period, others occurred in the past three decades (e.g., 1978-1987, 1991-1999 or post-1999, see figure 3). This kind of degradation as sporadic rashes or points (Thomas and Middleton 1994) is related to the agro-pastoral activity of herdsmen, like cultivation and grazing. When vegetation cover in these rashes continuously reduces to certain level, for example, 25% (Warren and Agnew 1988) and the underlying sand deposit is reactivated, these rashes will extend and coalesce together forming larger desert patches. It is "desertification" (Thomas and Middleton 1994) and might be the origin of the deserts in MuUs and Hoboq. This result is different from that of Hanan *et al.* (1991), who employed the coarse resolution remote sensing data (AVHRR) of 1987 to assess desertification in West Africa (Senegal) and claimed that no desertification was found around deep wells. There were two limitations in their study: (1) the coarse resolution images (pixel size 1.1 km) are unable to reveal the total vegetation production variation in such small rashes or patches with a diameter of 300-1600m; (2) only one year of images (1987) are not enough for desertification assessment, in which normally multi-temporal or time-series images are required.

As well as the above two kinds of degradation, the third one — the major degradation type occurring in varying size from small to large patches (e.g., the large ones surrounding sites A and B in figure 2) seem to have a "mobility" in space, i.e., degradation appears in one place in one period and moves to elsewhere in other period. In terms of figure 5, such degradation might be unlikely a direct result of rainfall fluctuation, then what will be the causes of the major vegetation degradation in MuUs?

As Warren (2002) suggested, land degradation can not be judged independently of its spatial, temporal, economic, environmental and cultural context. That is to say, while analyzing land degradation in space and time, we have to consider not only the limitation of the natural conditions but also the roles of socio-economic and cultural driving forces. For the first two cases, desert extension and vegetation degradation around water points/settlements, it is not difficult to understand the change mechanism, or rather, the actions of the natural factor (e.g., aridity, wind blowing) and human activity (e.g., grazing and cultivation). But for the third ones, remote sensing encounters a difficulty to explain how and why they have taken place. We have to apply ground data for further interpretation.

It is generally believed that both natural factors and human activity have played a role in the process of land degradation. After analyzing the importance of these two groups of factors, Zhu and Liu (1989) point out the anthropogenic ones take up a quota of 94.5% in provoking desertification in China. Aside from the environmental limitation such as aridity (feeble precipitation), ecosystem vulnerability and limited water resources, recognized human factors include overgrazing, population growth, land reclamation, institutional defect, irrational policies, land property, market economy, water overuse, over-collection of fuelwood, over-excavation of wild medicinal and edible herbs, exploitation of fossil fuel (coal, oil and gas), over-hunting, culture and education (Jiang *et al*. 1995, Jiang 1999, Chen and Gao 2001, Erdunzhav 2002, Chen *et al*. 2003, Enkhee 2003, Wu 2003a, Gai 2007). Of course, not all of these socio-economic and cultural factors have been of the same importance in land cover change and degradation in history. In other words, only certain factors have taken a critical part in these processes in different historical periods. For example, the dominant culture (Jiang *et al*. 1995, Jiang 1999, Enkhee 2003) and policies (Chen and Gao 2001, Wu 2003a, Wu *et al*. 2008) which control land use (e.g., grazing and agricultural cultivation), market economy, development of new enterprises and other proximate causes like land reclamation, overgrazing, over-exploitation of the natural resources (medicinal herbs, wild vegetable, fossil fuel and underground water) may have been the underlying causes throughout the history in Ordos. In the agriculture dominant periods, grassland has been considered as "uncultivated land" or "wild land", land reclamation — a conversion from grassland to cultivated land driven by the national policies such as "Consolidating the frontier with immigrants from the interior of the country for reclamation" in Dynasty Qing, and "giving prominence to agricultural food production" in the period 1956-1974, occurred again and again, especially, in the last century. But rainfed land under the semi-arid and arid climate condition had feeble productivity and was often abandoned and exposed to soil erosion and desertification

[3] Ordos Government, 2007, Report on Climate and Eco-environment Monitoring 2006 (in Chinese), available at: http://www.ordos.gov.cn/zwgk/content/2007-01/17/content_13248.htm

after several years' cultivation (Chen and Gao 2001, Enkhee 2003, Wu 2003a). New land reclamation was conducted elsewhere for food production. Thus the procedure "reclamation — cultivation — abandonment" constitutes a malicious cycle leading to land degradation in the rangeland (Chen and Gao 2001, Wu 2003a). Nevertheless, as Enkhee (2003) emphasized, nomadic culture dominant periods, the grassland had been well protected and even degraded land had to certain degree restored.

In the recent decades, the function of policies can be more concretely checked. In the period 1979-1984, Deng's policy "Household responsibility for agricultural production" and the promulgation of the "Decree of Grassland" in 1985 had greatly aroused the enthusiasm of peasants and raised the agricultural production but left the grassland in a situation "collective grassland and private cattle" which lasts till today. To gain more personal profits and income, each herdsman will raise animals as many as possible in the public land, and this inevitably lead to "the Tragedy of a Commons" (Hardin 1968). This is the "institutional defect" (Erdunzhav 2002) and the consequence of "indefinite land property" (Gai 2007).

In 1987-1988, under the strategy "Invigorating the domestic economy and opening to the outside world", Deng's "Open and reform" policy and the decree on "Legalization of the private economy" were set into effect, hundreds of rural enterprises and companies were put up based on the agricultural and pastoral products like food, wool and natural resources (coal, oil, gas, kaoline, medicinal and edible wild herbs) in Ordos; new land reclamation for agriculture and economic plantation occurred again (see Albas and Shanghaimiao in figure 4); at the same time, an ecological construction enterprise composed of the local peasants and shepherds — "Sand-control" (planting ephedra, licorice, *Hedysarumleave*, *Caragana korshinski*, *Artemisia sphaerocephala* and *Artemisia ordosica*, sea-buckthorn, etc. in a network way to restore the degraded land and protect the sandy land from degeneration and simultaneously bring economic value for the local people) was spontaneously developed; no doubt, this activity has greatly produced positive impacts on environment.

After 1999, with the inauguration of the national middle-to-long term strategy "To Develop the West" in 1999, Ordos has become one of the National Energy Bases thanks to its abundant fossil fuel resources; with the exploitation of coal, oil and natural gas but without appropriate protection measure, in particular, for the private mining companies, pollution and land subsidence leading to a destruction of the original landscape, cultivated land, villages and a depletion of the underground aquifers have taken place in the mining areas, especially in the east MuUs (Fugu, Shenmu and Dongsheng). This mining related problem has made 3612 people homeless (number up to 2005) and Kuye River flow frequently intermitted[4]. As well as mining, agricultural and sand-control activities both consume a great deal of underground water. It was reported that there were about 800 motor-pump wells working day and night in the village Sanduandi, Otog Front in 2005 and the local government measured that this table had declined more than 1 m in this village in the period 2001-2005 due to the over-pumping for agriculture, so that some pieces of afforested areas around the village became withering. Besides Otog Front, water-table decline was also found in Yulin and Jianbian (2 m in the past five years)[5]. With the natural resources exploitation and agricultural activity, how to reasonably use and save water is a serious challenge.

In 2000-2001, with the awareness of serious land degradation and overlapping the "National order to forbid herbs collection" and the measure "Returning cultivated land to grassland", local governments of Otog and Otog Front implemented a "Grazing-forbidden and -rotation policy with a subsidy system" to treat grazing differently in different zones, biomass or greenness has clearly got an increase (see 1999-2007 VGT-G in figure 5) since large pieces of grassland were closed for recovery and parts of high productive grassland were converted into pasture cultivated with some aridity- and cold-resistant forage grasses such as alfalfa (*Medicago sativa*) and *Astragalus adsurgens* for breeding animals. Hence, the previously open grazing became indoor drylot feeding. An interesting fact noted is that with the implementation of these policies, not only the vegetation vigor and biomass but also the cattle number have increased (see table 2), which have led to an increase of household income of the local peoples. The average *per capita* income of the rural people has increased by 60.9% and 119.1% respectively in the banners Otog and Otog Front from 2000 to 2005 (Wu *et al*. 2008). Merely an undesirable aspect lies in that in the grazing permitted areas, grassland suffered even more grave destruction due to the overgrazing in the "Commons".

In the most recent years, a new impact on the local land use and resource exploitation is the globalization that influences local and national economic markets. With the participation in the WTO (World Trade Organization) in 2001, national and international supply and demand have exerted more and more pressure on the environment in Ordos, for example, exportation of the pastoral products from Ordos and helping the governments to make decision for oil and gas importation. With promising profits, animal husbandry may be augmented leading to more pressure on the rangeland and fossil fuel exploitation be accelerated provoking more serious land degradation.

In a word, a set of natural and anthropogenic factors play a role in land degradation. Culture and policy are the most important underlying causes in history since they predominate land use, market economy and other proximate driving forces directly exerted on the environment and lead to its degradation. Institutional deficiency and indefinite land property intensify such processes. In the recent decade, globalization starts to take a part in land cover change in Ordos. As Geist and Lambin (2004) summarized, dryland degradation is determined by different combinations of proximate causes and underlying driving forces in varying geographical contexts coupling socio-economic and biophysical factors. After understanding the mechanism of land degradation, reasonable policy can be made for degradation mitigation, better land management and sustainable natural resources exploitation. This study also shows that land degradation is not an absolutely irreversible land surface process but can be recovered by implementation of the policy taking into account the environmental protection consciousness.

5. CONCLUSIONS

This paper conducted a land degradation monitoring study in the West MuUs by linking biophysical feature change in land surface with anthropogenic action. The findings are depicted below:

[4] Liu, Q., 2005: Ecological Deterioration Related to the Last Defense Line of Human-being, *Ecological Protection News*, *Xinhua News Agency* (in Chinese), June 29, 2005 (available at: http://news.sina.com.cn/c/2005-06-29/09357076745.shtml)

[5] http://yudefu186.bokee.com/viewdiary.15081810.html

The sensational “desert advancing” as reported in the Chinese media in 1980s and 1990s was not observed, however, wind-driven extension of desert patches to the direction of southeast at a rate of 11-21m/year engulfing the marginal grassland does exist in non-controlled areas. In comparison with other land degradation this extension does not constitute the major menacing problem.

Other kinds of land degradation were clearly observed by remote sensing. Factors leading to the degradation are multiple. Culture and policy are the most dominant root causes. The impact of policy includes two aspects: positive and negative (Wu *et al.* 2008). In the “half-socialism and half-capitalism system”, institutional defect and indefinite land property may reduce the positive effect of the policy and aggravate the negative influence leading to the Tragedy of a Commons (Hardin 1968). When there is a contradiction between the policy and the short-term interest of herdsmen the degradation is inescapable. The importance of a policy lies in whether its implementation can bring economic profits for the local people while protecting the environment from further degradation. Nevertheless, land degradation is not an absolutely irreversible process but can be recovered by implementing the policy with environmental awareness. Nature has its own resilience.

Banner \ Year	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
Otog	1370	1363	1395	1261	1193	1119	1392	1562	1802
Otog Front	1077	1024	1008	1050	1020	1001	1245	1537	1856

Source: the Yearbooks of Inner Mongolia from 1998 to 2006 (Available at: http://www.nmqq.gov.cn/new/news/default.asp?cataid=59)

Table 2: Total cattle number in the study area in the past decade (1000 sheep unit)

Remote sensing is a powerful tool providing multi-temporal dynamic geospatial information of the land surface. But its application in land degradation research requires great care since land degradation is a subtle and continuous process that requires to be separated from the temporal climate phenomenon like drought. Furthermore, land use change assessment and land degradation monitoring need to be carried out in a holistic way by linking remote sensing with human activity in order to evaluate land use management options for sustainability or rehabilitation of the natural resource base.

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