Integrating MODIS-EVI and Gridded Rainfall/temperature Fields for Assessing Land Degradation Dynamics in Horqin Sandy Lands, Inner Mongolia (China)

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Abstract. Horqin Sandy Lands in NE-China represent a widely discussed case of ongoing land degradation which receives much attention in China and the outside world. Located in an area of strongly continental climate and extended sandy substrates, the region is undergoing substantial land use change dynamics, largely determined by political decisions and regulations issued by the central and regional governments. While climate data suggest for some stations an increase in annual precipitation during the past 10 years it appears mandatory to relate satellite measurements of biological productivity to corresponding changes in plant-available water over time. In the course of EU-funded research projects (LADAMER; DeSurvey) an approach based on ecological responses of vegetation to physical drivers (2dRUE) has been designed which is suited to more comprehensively characterize areas affected by desertification and transitional land use change processes. The concept departs from the assumption that Rain Use Efficiency, i.e. the ratio of net primary productivity to precipitation, decreases with land degradation. The approach is based on combining satellite-derived indicators of biological productivity (e.g. EVI, FAPAR) and spatially interpolated climate data; an important asset is that RUE is climatically de-trended for varying levels of aridity. The concept is currently applied to various study areas of the DeSurvey Project, one of which covers the Horqin Sandy Lands in Inner Mongolia (China). Results for this site are produced by integrating gridded climate station data and EVI time series acquired by MODIS for the time span 2001-2002, and are compared to a calibrated 20-year-time-series of Landsat-TM/ETM+ data (1987-2007).

Keywords. Land degradation, MODIS-EVI, rain use efficiency, DeSurvey Project

Introduction

Land degradation has long been recognized as a major threat to the global environment which directly impacts on human well-being and social welfare, particularly in in drylands, i.e. the arid, semiarid and sub-humid regions that cover more than 40 % of the Earth's terrestrial surface and are home of more than 30 % of the earth's population [1]. The driving processes are complex, not always completely understood, and diverse views exist on the relationship between climatic and anthropogenic causal factors of desertification. Climate surely sets important boundary conditions, but is not necessarily the major driver of dryland degradation because pulse-/event-driven dryland ecosystems share considerable resilience and recovery capacities. Degradation processes in drylands rather emerge from the human impact

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on the delicate balance between the demand for, and the supply of, ecosystem services (population pressure, socioeconomic and policy factors, land use practices, globalisation phenomena) [2, 3].

Designing and implementing sustainable land management strategies is a substantial endeavour – intrinsically tied to objective, repeatable and spatially distributed information on the state of ecosystems and available resources. The development of integrated assessment and monitoring concepts therefore remains an important challenge, as much as the improvement of environmental data bases and an efficient linkage of terrestrial and space-borne observation systems.

Starting from the perspective that land degradation may be defined as a long-term loss of ecosystem functions (i.e. its ability to provide goods and services) a range of geospatial approaches has emerged which conceptualize measuring degradation through assessing changes of net primary productivity. Earth observation satellite data were already successfully used for reconstructing green vegetation cover (as surrogate for NPP) over time spans of several decades which led to the identification of degraded vegetation resources on local scales [4]. These approaches have been complemented with additional elements of time series analysis and applied to regional scales based on continuous multi-annual time series from global environmental monitoring satellites (such as NOAA-AVHRR, VEGETATION and MODIS) [5].

Vegetation abundance itself interferes more or less directly with all water distribution processes at a site in order to maximise to a certain extent the local water availability for their own benefit (an optimisation process which involves several sub-processes and feedback mechanisms). Boer [6] has proposed a theoretical framework for land degradation assessments which relies on these vegetation functions for estimating the local water balance in terms of rainfall to evapotranspiration ratios. His approach has been modified with the objective to accommodate its use also under operational constraints in terms of limited spatial data availability [7]. Recently a similar but more simplified approach designed by [8] has recently been used to propose an updated global assessment of land degradation. Their results were substantially criticized, particularly because rainfall is not a limiting factor to net primary production NPP in more humid areas, and because RUE ratios largely correlate with rainfall and RUE trends thus merely reflect trends in precipitation [9].

In comparison, the approach of Del Barrio et al. [7], being developed and tested in the context of EU-funded research projects (LADAMER; DeSurvey[2]), relies on more elaborate expressions of 'Rain Use Efficiency' termed "2dRUE". The objective of this paper is to test and evaluate the 2dRUE concept in the context of a desertification-affected area in Horqin Sandy Lands, a dryland ecosystem with summer rainfalls in Inner Mongolia, China.

1. The Study Site

Desertification is an important issue in parts of Northern China [10]. While the region is less densely populated than Southern and Central China, densities are nevertheless very high, relative to the inherent low productivity of these arid and semi-arid zones. Horqin Sandy Lands (i.e. the Naiman Banner) are located in the agro-pastoral zone between the Inner Mongolian Plateau and the Northeast Plains in China (42°41'-45°45'N, 118°35'-123°30'E). Covering more than 42,000 km² it is one of the major sand areas in Northern China and an important part of Inner Mongolian grasslands. The vegetation consists predominantly of shrubs and perennial grasses, trees are found in places where water conditions are favourable. Climatically, the region is part of continental drylands with hot and short summers and very cold winters. Mean annual temperature minima and maxima range from -8.8°C in January to 30.4°C in July; mean annual precipitation is 375 mm with nearly 80 % concentrating in the months from June to September. An important characteristic is its irregularity: rainfall varied from 205 to 679 mm year-1 in the observation period from 2000 to 2008.

[2] http://www.ladamer.org/ladamer/ and http://www.desurvey.net/

The main aspect of degradation in this area is what Chinese authors term "sandy desertification" (including shifting sand dunes, sand dune reactivation, shifting sands spreading into grasslands, and wind erosion in dry farmland) which develops on sand sheets and fans of quaternary origin [11]. Although the role of drought is not exhaustively clarified yet most authors suggest that human activities and cultural change are key determinants of degradation processes [12]. Main drivers resulted from the transformation of the traditional Mongolian grazing society. Chinese immigrants brought with them a cultural tradition that is rooted in farming, a practice further promoted by the socialist regime [12, 13]. Reclaiming rangelands in areas of marginal rainfall and strong winds for agricultural production has caused the destruction and loss of topsoil, while the concentration of cattle in the remaining rangeland areas increased stocking rates above sustainability thresholds. Ever since, national policies, such as Deng Xiaoping's reform policies, but also decisions and regulations issued by the regional governments have encouraged both, new and intensified land use practises (expansive groundwater-based irrigation) as well as restoration and protection measures (enclosures of pastureland, grazing regulation, tree planting campaigns).

2. Material and Methods

The approach presented in this paper builds on consistent and reliable time series of satellite observations with high revisit capacity and coarse spatial resolution which can be used to produce proxies for net primary productivity (e.g. vegetation indices, green vegetation cover derived from spectral unmixing, or biophysical variables such as FAPAR). The dimensionality of the NPP equivalent is not important for the 2dRUE concept as quantities will be expressed as proportional values.

2.1. Satellite Data

In this study we used the MODIS Enhanced Vegetation Index (EVI) product (MOD13Q1) for the biennial period January 2001 – December 2002. EVI is a composite of daily bidirectional reflectance, available as 16-day-composite. Compared to other vegetation indices, EVI is less sensitive to soil atmosphere effects, minimizes brightness-related soil effects and is more responsive to canopy structural effects. The EVI time series resampled to monthly time steps for handling them equivalently to monthly temperature and rainfall averages.

In addition to the 2-year MODIS data series, a second time series of Landsat-TM and -ETM+ images over the core study area has been established which includes 12 satellite observations (1987-2007) from the same phenology period (August/September). This series of images has been corrected for atmospheric effects [14, 4] based on the latest calibration data [15]; the resulting reflectance images were then subject to spectral mixture analysis for generating abundance images for the endmembers "Photosynthetic Vegetation" (PV), "Active Sands" (AS) and "Water" (W). The PV time series was then used for analysing linear trends in NPP over the past 20 years.

2.2. Spatially Interpolated Meteorological Data

Meteorological data in tabulated form was received from the National Climatic Data Centre (NCDC) which holds the complete National Oceanic and Atmospheric Administration (NOAA) data and is the World's largest archive of weather recordings. For the Horqin area data are available from the 1950s onward; we used daily mean, minimum and maximum temperatures as well as precipitation from six stations inside and from additional seven stations outside the study area. The meteorological data were pre-processed by replacing missing values and outliers with the seasonal average of the period 1973-2008.

The 2dRUE-concept requires spatially explicit data layers. To generate equivalent temperature and rainfall fields the station data for the time interval 2001-2002 (condensed to monthly averages) were interpolated with a spherical Kriging procedure (where the spatial interpolation of temperature recordings was performed by using SRTM-derived altitude values as covariate).

2.3. The 2dRUE Land Degradation Assessment Concept

The reduction of plant biomass and Net Primary Productivity (NPP) below those of land not desertified under equivalent environmental conditions is proportional to land degradation impact. This is an accepted perception of land condition and the most closely related to the UNCCD definition of desertification [7]. Two ecosystem attributes are relevant for this assessment, annual average biomass and seasonal or inter-annual growth peaks. The first demonstrates the ecosystem's long-term capacity to sustain biomass, whilst the second concerns its resilience for recovering from disturbances, in particular, rainfall fluctuation. Both attributes are derived from a climatically de-trended expression of rain use efficiency (RUE).

Rainfall Use Efficiency (RUE) was originally defined as the ratio of NPP to precipitation (P) over a given time period [17], which can be interpreted as the fraction of rainfall released to the atmosphere through the vegetation cover; in this study monthly averages of MODIS EVI were used (as surrogate to NPP) for computing an "annual average RUE" layer. The interpolated rainfall and temperature fields together with extra-terrestrial solar radiation inputs provided the basis to generate a potential evapotranspiration (PET) map [16] which permits to establish an annual average aridity map based on the relationship PET/P (Figure 1). In parallel, the concept was used to generate maps of an "extreme observed RUE" (by the dividing the maximum monthly EVI by the accumulated rainfall over the three preceding months); the associated aridity index is derived by computing the ratio between the accumulated PET values by the accumulated rainfall figures from the same 3-month-period.

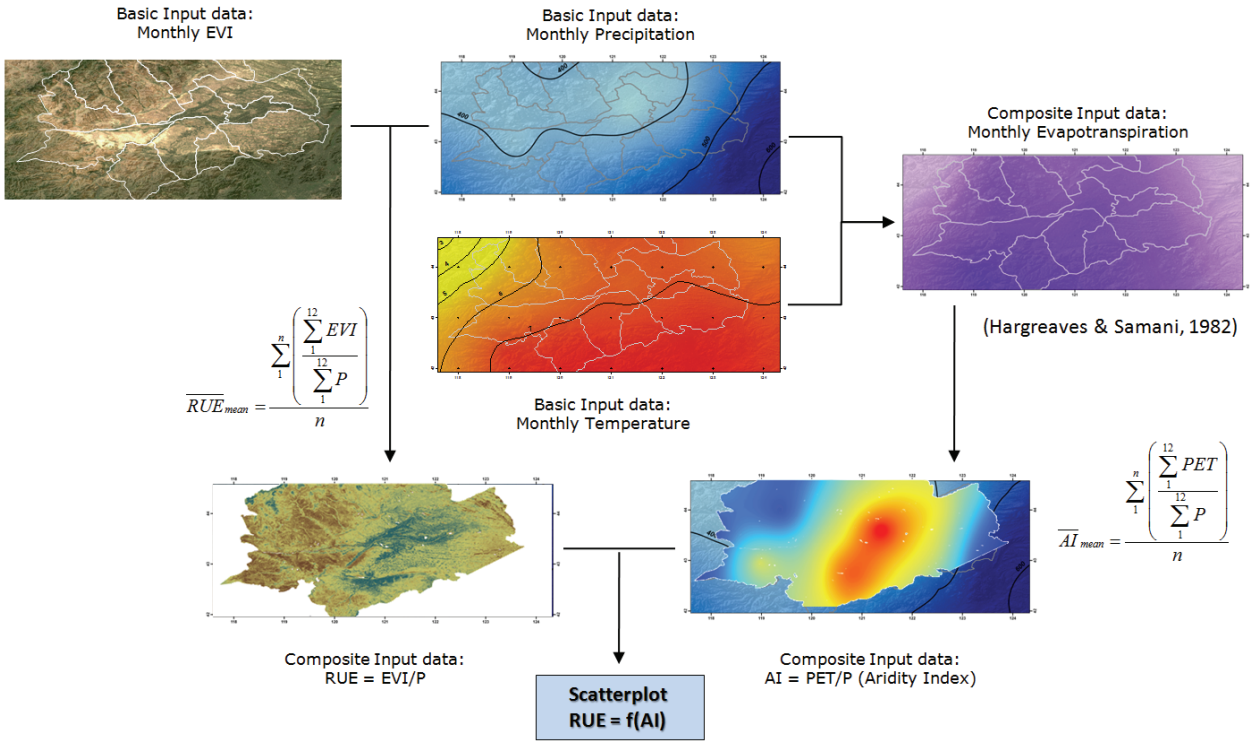


Figure 1. Input layers for the 2dRUE-based land condition assessment representative for the period 2001-2002

If RUE layers are computed over large areas with climatic gradients (as they exist between lowland and upland ecosystems in Horqin Sandy Lands) dry areas tend to account for the largest scores because of their very low P values. This effect renders a direct comparison between locations under different climates difficult, if not impossible (see also [9]). Del Barrio et al. [7] proposed a detrending concept where annual RUE values are plotted against the Aridity Index (AI) (Figure 2). The upper and lower boundaries of these scatter plots (here identified by fitting linear functions to the 5- and 95-percentiles) are considered representative for the maximum and minimum vegetation performance within a given aridity level. The final step was to compute a layer showing the relative position of the observed RUE within the range formed by the maximum and the minimum expected RUE. This relative RUE (rRUE) is assumed to reflect the vegetation condition as the observed performance (in terms of the satellite-derived vegetation index integrated over time) with respect to the minimum and maximum performance that can be expected for the particular climatic situation (defined in terms of AI). Pixels from irrigated vegetation (marked in blue) were not used for defining these upper and lower bounds (Figure 2).

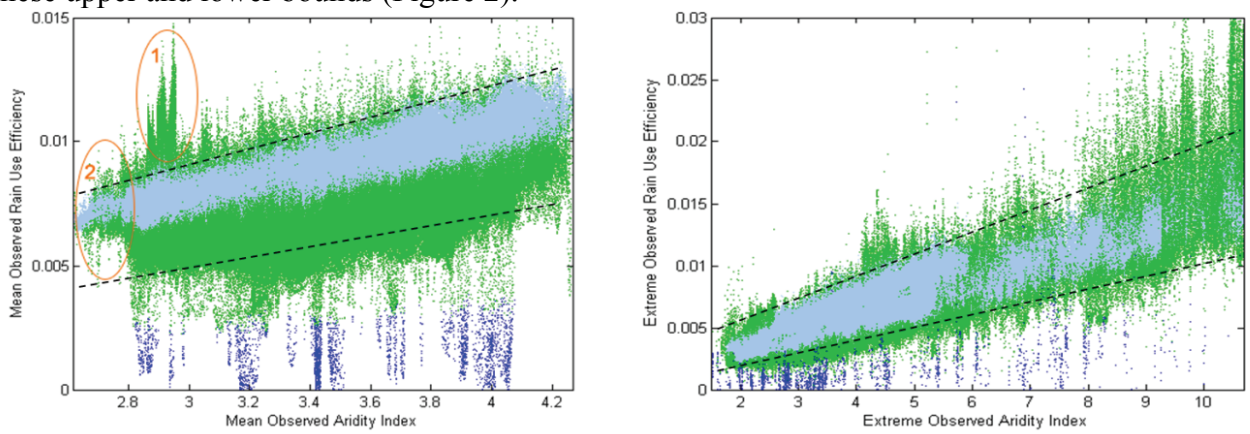


Figure 2. RUE vs. AI scatter plots used for defining the lower and upper vegetation performance range (5 - 95 percentiles) for long-term (left) and short-term response to rainfall

It is important to note that the definition of the **relative** (mean or observed extreme) RUE for each aridity level transforms the numerical scale into a common reference range from 0 to 1, where values close to one indicate high productivity, values around or below 0 more or less degraded areas. This relative assessment scale is a major justification for selecting a surrogate for NPP (here MODIS EVI) instead of quantified biomass model outputs.

3. Results and Discussion

The resulting relative RUE maps are shown in figure 3. Wherever any of the relative RUE estimators exceeds the stated range, it may be interpreted as a deviation associated with under- or over-performing vegetation in the respective component [7]. It is interesting to note that in the Horqin study area the highest relative mean RUE values are found in mountainous forests (Figure 3-top: 1) and agricultural areas which mainly extend along the river system (Figure 3-top: 2) or occur as isolated patches within the grasslands (Figure 3-top: 3); many of these agricultural areas are irrigated.

The short-term relative RUE maxima exhibit a modified distribution: in comparison to the vegetation communities in the mountainous areas (Figure 3-bottom: 1) and extended rangelands in the northeast (Figure 3-bottom: 2) only few agricultural areas (Figure 3-bottom: 3) arrive at high relative short-term RUE scores. This demonstrates that most agricultural areas are decoupled from rainfall and thrive on surplus water from irrigation systems, while it are primarily rangeland and forest ecosystems which are capable of responding quickly to rainfall events.

Combining both maps provides an attractive option to generate a map of ecosystem performance which reflects long-term productivity and the ability to react on surplus water for increasing productivity in the short run (2dRUE). This is achieved by dividing the both RUE-ranges for each aridity level into 5 discrete intervals (<0, 0-0.25, 0.25-0.75, 0.75-1, >1) and cross-tabulating the resulting RUE classes. This yields a 25-class table (figure 4), where the upper left quadrant represents situations where both, long- and short-term RUE responses are on high performance level (class 55, 45, 54, and 44); the lower right quadrant indicates adverse conditions, i.e. where short- and long-term ecosystem performance is in critical state (class 11, 21, 12, and 22). The remaining classes (36, 34, 53, 43, 31, 32, 23, and 13) represent intermediate (i.e. neutral) states; blue-coloured classes (25, 15, 14, 52, 51, 41) do not occur in the study area. Closer inspection reveals that the red areas (Figure 4: 1) represent active dunes and sand sheets with only occasional plant growth. The dark brown tones indicate unusually degraded land; contiguous areas of this type occur in the vicinity of active sand sheets, on extended rangelands north of the Xar Moron River (Figure 4: 3), and on erosion affected mountainous terrain (Figure 4: 2). Additional degraded areas occur in isolated patches.

This spatial pattern is in good agreement with field observations collected during several field trips. However, a systematic validation of such map products is an extremely difficult issue. Del Barrio et al. [7] related their RUE-based results to the Natura 2000 network Sites of Community Interest (SCI) in continental Spain and found that a majority of SCIs (i.e. protected areas with no or only limited disturbance) were positively associated with land in good condition and unusually good condition.

Since similar system of conservation sites or spatially distributed reference areas does not exist in Horqin Sandy Lands an alternative validation strategy is to consider the 20-year Landsat-TM/ETM+ time series as completely independent source of information and to compare how specific land condition classes are characterised in this data set. The underlying hypothesis is that areas in unusually degraded condition might already be under pressure for longer periods of time, and as such be characterised by decreasing trends in productivity. First results seem to support this assumption: rangeland areas with below average productivity (no. 3 in Figures 4 and 5) tend to coincide with decreasing vegetation abundance over the past 20 years, highly productive agricultural areas (no. 2 in Figures 4 and 5) typically exhibit inverse trends (increasing productivity over time), while some of the active dune fields and sand sheets (no. 1 in figures 4 and 5) appear invariant over this extended time span.

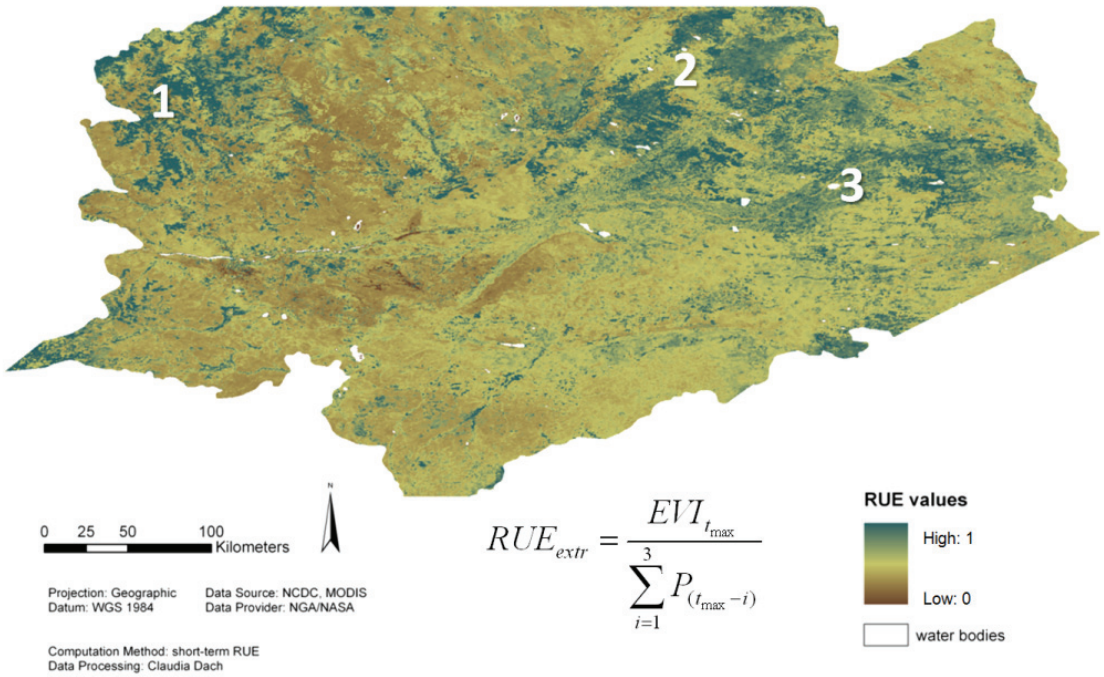


Figure 3. Maps of relative mean RUE (long-term ecosystem response, top) and relative extreme RUE (short-term ecosystem response, bottom) in Horqin Sandy Lands (2001-2002).

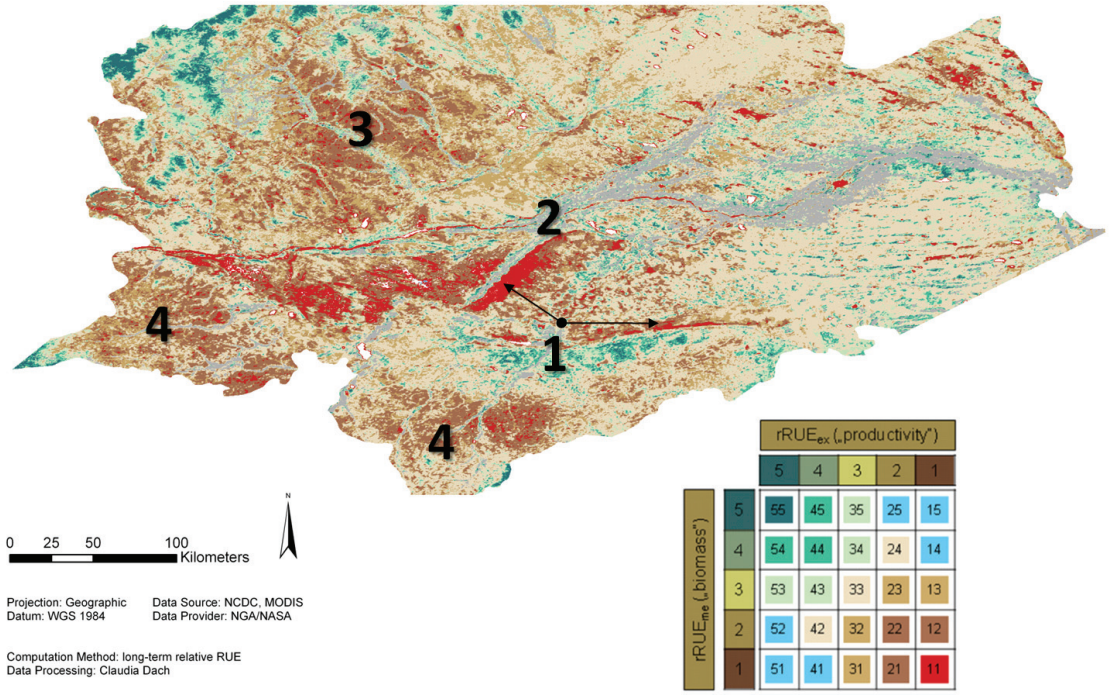


Figure 4. Integrated land condition assessment map (2dRUE) for Horqin Sandy Lands. The map is derived from cross-tabulating classified relative mean RUE and relative extreme RUE outputs; grey colours indicate irrigated agricultural areas

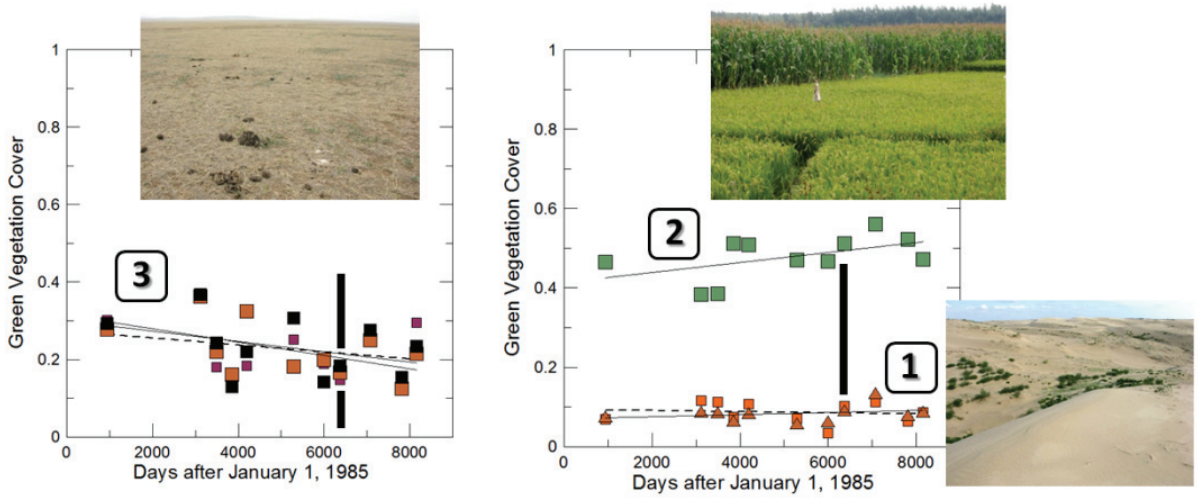


Figure 5. 20-year trends of SMA-derived photosynthetic vegetation abundance for active dune systems (1), an intensely farmed agricultural system (2) and degraded rangelands (3). The vertical bars represent the MODIS observation period (2001/2002) used in this study; numbers relate to Figure 4.

4. Conclusions

First results of applying the rRUE-based land degradation assessment concept to a marginal and desertification-affected area in Northeast China (low and irregular summer rainfall which coincides to the vegetation period) demonstrate that the method holds the potential to be applicable under a wider range of rainfall-temperature regimes under which it was originally developed. Making the RUE of any given location relative to its most probable range means that locations can be directly compared. The relatively modest data requirements (publicly available long-term climate recordings and multi-annual satellite observations of vegetation cover and biomass) constitute an important

advantage of this concept; in the absence of sufficiently dense station networks also meteorological satellites (e.g. Meteosat/MSG-1, TRMM) might be considered as alternative data sources.

However, care must be taken until a more systematic validation of the assessment results is available. Until now, only field observations and long-term cover/biomass trends derived from 20 years of calibrated Landsat-TM/ETM+ observations (1987-2007) have been evaluated for selected sites. Forthcoming work will focus on a systematic comparison between the Landsat-based trend analysis and the 2dRUE assessment maps at a common pixel size of 250 m. Additionally, the rRUE-based land condition assessment will be established for a second time step (2008-2009); comparison of both maps will not only reveal recent land condition changes but provide additional hints about the consistency of the approach.

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