Environ Earth Sci
DOI 10.1007/s12665-014-3926-x

ORIGINAL ARTICLE

Several challenges in monitoring and assessing desertification

Shulin Liu · Tao Wang · Wenping Kang · Mouat David

Received: 16 May 2014 / Accepted: 26 November 2014

Abstract Desertification is one of the most serious environmental and socioeconomic problems in the world. Desertification has got ever-increasing attention from scientists to policy makers worldwide. Monitoring and assessing desertification (MAD) has been a key and extreme important work, for combating desertification in threatened areas. Tremendous progress has been made in MAD during the last several decades, including multi-level indicator system, various kinds of extracting and assessing method of desertification information, etc. In particularly, Remote Sensing has become an important data source and technology in MAD due to its strength of macroscopic, synthesis, abundant information, quickly updated data, but it focused primarily on biophysical symptoms and involved some uncertainties challenging MAD. In this paper, several key challenges in MAD were reviewed and discussed. Some findings were given, mainly including: (1) the reference frame or baseline of desertification usually lacking of enough scientific support from environmental background reconstruction and ecosystem dynamics, (2) effective and readily accessible monitoring indicators of desertification usually lacking of reliability and scientific basis derived from bio-physics mechanism of desertification process, (3) underemphasized temporal and spatial scales of desertification and the scale effect, as well as (4) those extracting and assessing methods of real desertification information in need of improvement. Finally, some suggestions were put forward for advancing desertification research and providing authentic desertification information, including more distinct desertification connotation, addressing desertification research at multiple temporal and spatial scales, integrated application of multisource remote sensing data, closely combining MAD with field research work about desertification processes, establishing and protecting natural ecosystems' reserves with different climate types and vegetation types for desertification baselines, etc.

Keywords Desertification · Baseline · Indicator · Temporal · Spatial scale

S. Liu (✉) · T. Wang · W. Kang
Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences (CAS), No. 320 West Donggang Road, Lanzhou 730000, China
e-mail: liusl@lzb.ac.cn

T. Wang
e-mail: wangtao@lzb.ac.cn

M. David
Division of Earth and Ecosystem Sciences, Desert Research Institute, Reno, NV 89512, USA

Introduction

Desertification occurs in more than 110 countries and affects the livelihoods of one billion of people, especially in drylands (according to the UNCCD classification system). Global poverty, defined in almost any way, is disproportionately concentrated in the arid, semiarid, and dry sub-humid regions—the drylands—of the world (Verstraete et al. 2009). Due to its huge influence, desertification has got ever-increasing attention from scientists to policy makers worldwide, especially since the heavy drought that Sahel experienced in the 1970s (Batterbury and Warren 2001; Wang et al. 2011a; Peng et al. 2013).

According to Glantz' inventory, the word desertification had more than 100 definitions: a testimony to the complexity of the phenomenon (Mainguet 1991). The definition

Published online: 07 December 2014

of desertification generally accepted is "land degradation in arid, semi-arid and dry sub-humid areas, as a result of various factors, including climatic variations and human activities" (UNCCD 1994), where land degradation is defined, following the Millenium Ecosystem Assessment report (MA 2005), as the loss of biological or economic productivity. The desertification conceptual evolution can be tracked across three worldwide landmark projects that reveal a historical trend of increasing complexity in desertification assessment approaches, such as GLASOD in 1990, LADA in 2002, and Millennium Assessment in 2005 (Ibaneza et al. 2008). Herrmann and Hutchinson (2005) provide an excellent review of the different contexts in which this debate has taken place and summarize the evolution from a climatically driven concept of desert encroachment to a complex understanding of ecosystem services and their degradation, including both biophysical and socio-economic dimensions. A more explicit description about desertification and land degradation is that land degradation is qualified as a process of persistent reduction or loss of biological productivity, whose most extreme case is that of desertification (Vogt et al. 2011). Accordingly, an intrinsic problem is that not every reduction in productivity is land degradation, rather only a persistent reduction of biological and economic productivity can be defined as land degradation (MA 2005). Serious desertification ultimately results in long lasting and observable loss of vegetation cover and biomass productivity over time and in space, as well as a degradation and loss of water and soil resources and loss in vegetation quality (palatability and bio-diversity) (Helldén 2008). And then, a troublesome problem was produced to decouple environmental signals due to short-term climatic variance from real land degradation (Vogt et al. 2011). Moreover, the distinction among degradation, desertification and drought is not always clearly drawn (Prince et al. 1998). Because of its breadth, complexity and dynamism, desertification is difficult to monitor and assess (Eswaran et al. 2001). Another inherent problem about desertification is whether landscape will return to its previous state or not under climate or land use conditions return to their previous states, or some critical thresholds must have been crossed (Kurc 2008). This pendent problem showed that there is a big gap before achieving consensus about desertification connotation, as produced a big trouble for monitoring and assessing desertification (MAD).

Monitoring and assessing desertification is the most basic research to identify sensitive areas for combating desertification and evaluating the consequences of actions, and to develop early warning systems for readjusting land use planning and adapting adverse climatic variation, as well as for understanding desertification process and its dynamic mechanism (Wang et al. 1998). However, MAD is seriously deficient and lacks of scientifically robust (MA 2005). Remote sensing had been widely used and gradually become the foremost means in MAD (Mouat et al. 1997; Middleton and Thomas 1998; Wang et al. 2004a; Marini 2008; Jabbar and Zhou 2013; Hu et al. 2013; Kang and Liu 2014), due to its macro, periodic, and rich information from multi-sources, multi-bands and multi-temporal features. However, several issues and challenges in MAD still are expected to further discuss for better understanding desertification, including the reference frame or baseline, effective monitoring indicators, temporal and spatial scales of desertification and their scale effects, as well as those methods of extracting desertification information, etc. Inaccurate assessment of desertification is believed because of the result of two urgent problems: (1) uncertainty of baseline assessments and indictor systems and (2) misuse of remotely sensed data sources (Yang et al. 2005; Wessels et al. 2012; Amiraslani and Dragovich 2013). In addition, desertification monitoring and assessment approaches at supra-national and global levels have so far been largely empirical and focused primarily on biophysical symptoms (Vogt et al. 2011). In this paper, these aspects were further discussed for promoting future scientific monitoring and assessment of desertification.

Several key challenges in MAD

Baseline of desertification

Desertification is a land degradation process, as it involves a reference frame or baseline problem, serving as the starting point for evaluation and monitoring from which the land starts to degrade or improve. Without a scientifically robust and consistent baseline of desertification, identifying priorities and monitoring the consequences of actions are seriously constrained (MA 2005). Impacts of human activities (such as overgrazing) and climatic variables (such as inter-annual variability in rainfall and drought events) on vegetation productivity are difficult to distinguish. One example of this is the repeated droughts and famine in the Sahel region (Tucker et al. 1991; Thomas and Middleton 1994). Quantifying such impacts requires an established baseline of vegetation productivity against which changes can be assessed. Such a baseline is often not available and is further complicated by year-to-year and even decade-to-decade fluctuations (Millennium Ecosystem Assessment (MA) 2005). A distinction is made between the effects of drought that are relieved within a few years after rainfall returns and conditions that induce transitions between irreversible or very slowly reversible states. It is suggested that the term desertification be reserved for those changes in the vegetation that are induced by human actions, not natural fluctuations (Prince 2002). Incorrect estimates of the degree of degradation will be made if the choice of baseline year does not allow for climatic variation. This needs to define a meaningful baseline from which to measure change as well as accepted methods to detect change and analyze trends form the various types of measurements (Reed et al. 2011).

How to build the baseline of desertification? Scientists had made numerous attempts, mainly based on the following ideas. *First* is the systemic-dynamic idea that desertification will cross some critical threshold of land system, and land system will shift from one stable state to another (Kurc 2008; Bisaro et al. 2013; Reynolds et al. 2011). The climatic climax without human disturbance can be used as the baseline of desertification in specific area (Liu 1998). The boundary that once crossed cannot be reversed without considerable interference or management inputs (Archer 1989; Friedel 1991; Laycock 1991). The generic eight-equation dynamic model is proposed to evaluate structural long-term desertification risk in threatened areas (Ibaneza et al. 2008). A long-term time-series data are expected to estimate baseline of desertification in this idea. It was hypothesized that the boundaries of irreversibly degraded systems would not vary temporally but that the boundaries of healthy or at risk ecosystems would vary considerably (Eve et al. 1999). Sequential and high-quality NDVI dataset had been used as dynamic analysis for diagnosing desertification causes (Evans and Geerken 2004; Xu et al. 2010). *The second* is the discrete-contrastive idea that desertification can be detected according to change of some key indicators of land system, including: (1) Comparing land dynamic changes among different periods, taken land status at one presumptive-early epoch as relative baseline of desertification (Ding et al. 2004); For example, a vegetation-focused diachronic study to monitor and assess desertification processes in the southern Tunisian steppes was carried out between 1975 and 2000 (Hanafi and Jauffret 2008). (2) Comparing differences among different sub-regions in the same climate zone, assuming an aboriginal landscape area (such as some natural reserves or even those areas enclosed about several years) in the same climate region as baseline of desertification (Ding et al. 2004). Generally similar to this idea, desertification was classified into four levels of severity and detected with multiple satellite images during the last three decades (Liu and Wang 2007; Guo et al. 2010). A reference situation for degradation has also been derived spatially from areas with the same soils and climate (Wessels et al. 2008). Unfortunately, a natural reserve area in the same climate region usually is hard to find or already nonexistent due to human disturbances almost everywhere, as well as spatial and temporal heterogeneous of geographical landscapes at different scales. Furthermore, as many regions around the world have suffered degradation before 1981 and a ''non-degraded'' reference period does not exist within the satellite record, trend analysis methods cannot be expected to identify historically degraded areas (Wessels et al. 2008). A kind of inverted reference was put forward that local more stable desert is believed as the last stage of desertification, and the initial stage of desertification can be deduced backward in order (Zhang 1996). The lack of reference situations against which actual desertification could be compared is one of the future challenges for properly assessing desertification (Veron et al. 2006). The most important point is that those present presumptive baselines often were lack of scientific support, such as objective environmental conditions at different temporal and spatial scales in Quaternary research results, or accurate evaluation of those responses or feedbacks of local ecosystem change on climate variation or human activities.

Indicator systems in MAD

Desertification not only is a process of land degradation, but also is a result of land degradation (Mainguet 1991). To reveal the intrinsic characteristics of desertification, the assessment is ideally based on the identification of appropriate physical, biological and socio-economic indicators. For mapping desertification and risk analysis, many scientists and organizations put forward different indicator systems of MAD (Reining 1978; FAO/UNEP 1984; Zhu and Liu 1984; Berry and Ford 1997; Wang et al. 1998; Gao et al. 1998; Sommer et al. 2011). However, most indicator systems established are difficult to practically use in other regions, due to available and regional differences. Lack of agreement on the choice and application of indicators had been a major handicap in attempt to assess the status and trends of desertification, and some guide rules about desertification indicators were given (Mabbutt 1986). Later, fast and slow variables had been stressed in MAD by scientists (Smith and Reynolds 2003). Slow variables determine status of desertification, but they are not easily observed or monitored. Identifying and monitoring the key slow human and environmental variables are particularly important in drylands because high variability in “fast” variables masks fundamental change indicated by slow variables (Reynolds et al. 2007). Moreover, as mentioned in desertification definition, desertification indicators are often identified from natural, human and socio-economic conditions (FAO/UNEP 1984). The key point is that land can hardly be said to be desertified until the symptoms appear in the biophysical system, although social systems might be identified that predispose land to desertification (Prince 2002; Liu and Wang 2014).

Two major types of ecosystem biophysical state variables are often used to characterize desertification: vegetation and soils. Vegetation information was believed as very important indicator of desertification, because of the important ecological role of vegetation in land system and its protection of soil from erosion, especially reflecting loss of land biological productivity at certain degree. Vegetation indices have been used for desertification monitoring since the early days of remote sensing (Rouse et al. 1973). Because vegetation spectrum was affected by vegetation itself, environmental conditions, air conditions and other factors, vegetation indices possess obvious regional features and time effectiveness, and lots of vegetation indices were developed, such as Ratio Vegetation Index (RVI), Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), Transformed Soil-Adjusted Vegetation Index (TSAVI), Modified Soil-Adjusted Vegetation Index (MSAVI), Difference Vegetation Index (DVI), Greeness Vegetation Index (GVI), Perpendicolar Vegetation Index (PVI), etc. (Zhao 2003). However, vegetation in those places prone to desertification is usually sparse or strong depending on precipitation, and this creates difficulties in monitoring vegetation in at least two aspects. One hand, it is difficult to accurately reveal sparse vegetation change information by remote sensing (Leprieur et al. 2000; Li et al. 2009), due to the influence of background signal from the soil which deteriorates the classification accuracy (Edwards et al. 1999; Weiss et al. 2004). For weakening the effects of soil background on vegetation information, SAVI, TSAVI and MSAVI were introduced (Baret et al. 1989; Major et al. 1990). The other hand is the impact of precipitation on vegetation in desertification risk areas. For eliminating the effects of rainfall or precipitation on vegetation fluctuation, rain use efficiency (RUE) was used for detecting desertification (Prince et al. 1998), and another research work showed that functional modifications associated with vegetation structure caused by desertification can be captured with precipitation use efficiency (PUE) and precipitation marginal response (PMS) (Veron and Jose 2010). All these indicators such as vegetation cover, NDVI, NPP, RUE or PUE, and PMS only can be used as indicating vegetation status, but they do not directly denote whether desertification occurs or not (Wessels et al. 2007; Prince et al. 2007; An et al. 2014). Seasonal sums of multi-temporal NDVI are strongly correlated with vegetation production (Prince 1991; Nicholson et al. 1998), and it also be used to analyze degraded land (Wessels et al. 2004). It was stressed that the results of performed trend analysis of NDVI and rainfall z-scores cannot be used to verify any systematic generic land degradation/desertification trend at the regional–global level; on the contrary, a "greening-up" seems to be evident over large regions (Helldén and Tottrup 2008). Moreover, vegetation productivity derived from greenness can be linked to species composition, so spatial and temporal variations in species dominance are likely to add noise to the relationship between NDVI and biomass (Mbow et al. 2013). Field work also revealed that impact of drought on vegetation dynamics differed among species (Shinoda et al. 2010), as they further enhance difficulty to identify or diagnose desertification due to spatial heterogeneity of land system. Vegetation change, rangeland assessment or desertification modeling in drylands using remotely sensed image acquisition normally ignores long-term rainfall as a key criterion in image acquisition (Amiraslani and Dragovich 2013). In the view of vegetation pattern, spatial heterogeneity (Schlesinger et al. 1990) and spatial vegetation patterns were believed as an important indicator which may be a warning signal for the onset of desertification (Prince 2002; Kéfi et al. 2007). The landscape leakiness index, for remotely monitoring changes in the health of land, takes important aspects of landscape structure and function into account by focusing on the potential for landscapes to lose or 'leak' (not retain) soil sediments (Ludwig et al. 2007a). However, deviations from a patch size distribution characterized by a power law are not directly related to desertification (Maestre and Escudero 2009). The selection of methodology is crucial when using power-law models to detect changes in vegetation patterns. Using a binning-based method to analyze our dataset, the patch-area relationship deviated from a power law to a truncated power-law model with increasing grazing pressure, while the truncated power law was a better fit than the power law for all plots when binning was not used. A strong nexus between the vegetation spatial pattern and the desertification associated with heavy grazing was revealed and information incorporated about vegetation spatial pattern in future monitoring desertification processes should be considered (Yang et al. 2010). Hence, it still needs to be further studied in MAD that the important role of vegetation information based on remote sensing might be highly related to spatial scale or spatial heterogeneity of vegetation.

Soil properties usually are another key indicator of desertification because of soil productivity, mainly including these indicators of soil mechanical components, soil organic content and soil moisture content. In an integrated mapping method, soil moisture can compensate for the weakness of vegetation indices in areas of sparse vegetation cover (Saatchi et al. 1994). Vegetation parameters were more sensitive not only to grazing but also to temporal variation of precipitation between 2006 and 2008 in northern China, while soil parameters were primarily affected by grazing and resistant against climatic variations (Wiesmeier et al. 2012). Chen et al. (2000) used remotely sensed imagery to evaluate surface soil organic matter at landscape scale. Omuto and Shrestha (2007) showed that it is useful in rapid diagnosis of soil physical degradation in large areas, by the combined application of digital image analysis techniques, diffuse spectral reflectance of soils, especially with limited measurements of physical properties to aid understanding. Although significant success has been achieved under controlled laboratory conditions using Imaging Spectroscopy, lots of research work need to be done for studying soil properties in large spatial domains, because of those problems such as dealing with data having a low signal-to-noise level, contamination of the atmosphere, large data sets, the BRDF effect and so on (Ben-Dor et al. 2009). Accurate soil properties about desertification obtained by remote sensing were restricted at smaller spatial scale.

With the development of Remote sensing data sources and computing techniques, other some large-scale indicators (such as Albedo, LST and TVDI, etc.) are also used for desertification monitoring and their advantages are increasing (Liu et al. 2007). The desertification difference index (DDI) as powerful one for desertification assessment was produced, which combined information contained in the Albedo-NDVI space, and which is easy to use and possess biophysical properties of the land surface (Zeng et al. 2006). However, those comprehensive desertification indexes or indicators are usually short of the specific biophysical meanings about desertification information which bring troubles for comparison of desertification status. At the same time, choosing of critical thresholds in MAD are subjective and lacking of reliability and scientific basis derived from bio-physics mechanism. Moreover, indicators based on remote sensing in MAD have been not strictly associated with real desertification, hence some big uncertainties still exist in them.

Some scientists had attempted to find several sensitive indicators of desertification, such as in the northern Chihuahuan Desert (de Soyza et al. 1998), Hunshandake Sandy Land (Zhang et al. 2005). Recent research has identified some possible early warning signs of desertification, which can be used as indicators of resilience loss and imminent shift to desert-like conditions, such as changes in grass community composition, seed bank abundance and viability and changes in soil properties (e.g., soil nutrient content, water holding capacity or infiltration), etc. (D'Odorico et al. 2013). However, these indicators are difficult to obtain at the large scale. It will be one of the research trends to combine remote sensing monitoring at large scale and soil sampling in field sites.

Temporal and spatial scales of desertification

Multi-level or multi-scale problems exist in desertification. Lots of research work targeted to desertification had been carried out at different spatial scale: global, continental, regional, national and local. A conceptual model based on hierarchy theory is used to clarify the relationship of desertification to causative factors at a finer scale and state variables at coarser scales (Prince 2002). In assessment of desertification severity and its causes, scale-effect problems often were ignored or underestimated. Climate change is a main control factor for the formation and development of desertification in north China in the view of geo-chronologic period (Li et al. 2007). Desertification in China is likely to be controlled by climate change and geo-morphological processes, even though human impacts have undeniably exacerbated their effects (Wang et al. 2008). However, it was emphasized that desertification occurs in the human historical period, especially the most recent one hundred years (Wang et al. 2011a), and the dominant role of human activities in desertification was emphasized (Wang et al. 2004b). Assessment at longer temporal scales may average the characteristics when it is assessed at shorter scales. Scale-dependent characteristics must be considered when evaluating the causes of desertification (Xu et al. 2010). The exact time slice under examination has a very large influence on trends. For example, adding 3 years to an assessment period can completely change the trend (Wessels et al. 2012). In China, different scientists holding the geological-historical viewpoint discussed the problem of desertification based on different temporal and spatial scales, resulting in the confusion of the national desertification area statistics, and the area difference of the both can reach up to 3–4 times (Wang et al. 2011a). At the different spatial scales, desertification change trends can have obvious differences (Zuo et al. 2009). Multilevel statistical modeling results suggest that main driver factors are different for desertification at different spatial scales. Rural population density, the density of livestock, and accessibility to markets all have significant effects on desertification reversion at the local level, while changes in precipitation and land use policies are important at the regional level in Uxin Qi of Inner Mongolia in China (Zhang et al. 2013). The cumulative impact of human activities on desertification was in relatively short-time scale, while the cumulative impact of natural activities was in middle-short time scale (Aru and Yang 2007). Landscape ecology provides new theoretical frameworks and methodologies for understanding complex ecological phenomena at multiple scales. Scaling is a hot topic in studies of landscape ecology because it is critical in understanding the ecological processes at various scales (Fu et al. 2011).

Indicators also have scale features (Reynolds et al. 2007). The scaling effects were interlinked with landscape processes that operated simultaneously and interactively with different proximate desertification drivers (Oba et al. 2008). However, in the case of desertification, the process is relatively slow and occurs at the decade to century (or longer) time scales; long-term observations and monitoring of dryland ecosystems over these temporal scales are rare (D'Odorico et al. 2013). As a result, it is difficult to assess desertification due to such scale features. So temporal and spatial scales of desertification must be carefully considered and be closely associated with desertification processes and their interaction mechanism.

Approaches in MAD

Traditional desertification assessment methods have evolved from classic field survey methods for soil and vegetation mapping and land suitability evaluations to the later ecological approaches, landscape leakiness index (e.g., Ludwig and Tongway 1992; Mouat et al. 1992; Ludwig et al. 2007a). These ground-based methods score low for most of the practical requirements, but when based on broad field experience, they may yield very accurate results in relatively small areas. During the last 30 years, many extracting methods or technologies of desertification information based on remote sensing data also have gradually developed, from the man–machine interactive interpretation technique (MMIT), the technique based on vegetation index, the technique based on spectral mixture analysis (Smith et al. 1990), the technique based on landscape leakiness index (Ludwig et al. 2007a, b), and the technique based on integrated multi-index, to the technique based on landscape ecology theory (Wu and Peng 2009), Decision tree hierarchical classification and Artificial neural network method, etc. (Kang and Liu 2014). Although the MMIT approach usually can achieve a higher interpretation precise, it has obvious shortcomings such as labor-consuming, time-consuming and stronger subjectivity greatly depending on experts. The other approaches to monitor desertification still are at the initial grope or development stage.

Assessing desertification has put emphasis on desertification severities and its quantitative grades. The existing problems in all kinds of methods of assessing regional sandy desertification status were summarized, such as incapability to compare regional sandy desertification severities with the same desertification area, and ill-consideration for the ecological significance and impacts of spatial distribution of different desertified land types on regional desertification severities (Kang et al. 2005). Landscape pattern feature also is introduced to desertification monitoring and assessment (Chang 1997; Kang et al. 2007; Ludwig et al. 2007a). The desertification was classified and evaluated based on the land use point of view and the evaluation index system based on land use was set up, and quantitative remote sensing information model on the basis of the pixel was developed (Wu and Peng 2010). The precision of the desertification assessment RSIM (Remote Sensing Information Model) lies on the data-acquired precision and the current methods on desertification assessment that is to say whether the appraisable indexes are rationale and scientific or not and whether the weigh and the grade criteria that the experts provide are objective or not (Fan 2002).

Uncertainties in MAD

Uncertainties in MAD are mainly originated from two aspects. One is that the desertification definition (UNCCD 1994) widely adopted by scientists today is not very clear. This definition only indicates that desertification is a kind of land degradation, but it did not define what land degradation is. This problem has resulted in ambiguities (Vogt et al. 2011). For example, Kurc (2008) pointed out that some critical threshold must have been crossed in desertification process, while Vogt et al. (2011) only stressed that desertification is the most extreme case of land degradation. This inkling involved what should be preferentially consisted of indicator systems in MAD, fast variables or slow variables (Reynolds et al. 2007), as well as desertification reversibility (Archer 1989; Friedel 1991; Laycock 1991; Hill et al. 2008), and what can really characterize land degradation instead of just fluctuation with disturbances from climate variation or human activities. Land degradation is generally reversible unless damage is very severe or soils are shallow (Dregne 1995). Longer observation periods provided an increasing probability which includes 'equilibrium phases' that allow the identification of long-term degradation processes and showed that degradation processes are reversible (Miehe et al. 2010). Some transition-prone ecosystems are surprisingly resilient (Bestelmeyer et al. 2013). Qualifying desertification as a persistent reduction of biological productivity in the drylands may resolve difficulties in addressing desertification, though no agreement exists as to what degree of degradation and its reversibility properties would qualify as desertification (Safriel 2009).

The other one is about the methods in MAD. On one side, although longer time series dataset had been used in MAD, it is still too short to examine ecosystem changes, especially for diagnostic change. For example, AVHRR NDVI curves for those training sites were used to classify and map the irreversibly degraded rangelands in southern New Mexico, but it was stressed that such assessment requires understanding productivity patterns and variability across the landscapes of the region and careful selection of the years from which imagery is chosen (Eve et al. 1999). At shorter time scales of few decades, natural systems fluctuate to a certain extent in a non-systematic manner without necessarily changing equilibrium. Finding a systematic model that describes this behavior on large spatial scales is certainly a difficult challenge (Ivits et al. 2013). On the other side, there is a big uncertainty only adopting several individual images to detect desertification change trend, and different imaging time may result in bigger difference in desertification identification (Li and Yang 2010). For example, according to the interpretation results of remote sensing data in 1975, 1990, 2000, 2005 and 2010, Aeolian desertification in northern China was quickly developing during the several decades before 2000, and it is obvious rehabilitation trend occurred only since 2000 (Wang et al. 2004a, 2011b). However, Zhong (1999) compared aerial photos in 1950s and Landsat TM images in 1990s and revealed that mobile dunes and semi-fixed dunes gradually transformed toward fixed dunes.

Conclusion and suggestion

Desertification is a very complex phenomenon, which include its dynamic features, its change forms, its reversibility, its driving causes, and its temporal and spatial scale problem, etc. Although MAD had made great progress during the last several decades, several big and imperative challenges still need to be met, such as the reference frame or baseline of desertification, effective and readily accessible monitoring indicators of desertification, temporal and spatial scales of desertification and the scale effect, as well as those extracting and assessing methods of desertification information.

For improving MAD, some findings and suggestions were put forward. Firstly, an agreement about the rigorous expression and its intension about what is desertification should be reached as soon as possible in different communities over the world. This will be helpful for decreasing uncertainties in MAD and facilitating indicators selection, diagnosing means and assessing rules, etc., and thus producing far-reaching influence on desertification science development and combating desertification. Secondly, those presenting presumptive baselines usually were lack of scientific support, such as proofs derived from objective environmental conditions at different temporal and spatial scales in Quaternary research results, or accurate evaluation of those responses or feedbacks of local ecosystem change on climate variation or human activities. At the same time, natural reserves should be established and protected in ecosystems with different climate types and vegetation types, for scientific comparison or desertification baseline and diversity protection. Thirdly, choosing of some desertification indicators, especially critical thresholds in MAD, is subjective and lacking of reliability and scientific basis derived from bio-physics mechanism of desertification process. Many indicators based on remote sensing in MAD have been not strictly associated with real desertification, hence some big uncertainties still exist in them. Application of remote sensing in MAD should be closely combined with field research work about desertification processes, including short-term field investigation or test, and long-term in situ observation of ecosystem structure and function. Fourthly, temporal and spatial scales of desertification must be carefully considered and be closely associated with desertification processes and their interaction mechanism. Desertification research should be orderly conducted at multiple temporal and spatial scales, such as from smaller biological community, ecosystem to bigger landscape at the different spatial scales, and from years, decades to centuries at the different temporal scales. Fifthly, the pattern-process-scale theory or ideas in landscape ecology should be given special attention. The ability of extracting desertification information using long time series of remote sensing images in the view of system dynamics and the ability of using high-spectral data identifying plant composition change should be enhanced. In addition, data sharing should be further promoted in the world, especially various earth observation data.

Acknowledgments This research is supported by the Western Light Talents Training Program of Chinese Academy of Sciences, the National Basic Research Program of China (2009CB421308), the National Natural Science Foundation of China (40801003), and Science and Technology Program of Gansu Province (1308RJZA314). The authors are grateful to several reviewers for their valuable comments and advices to improve the manuscript.

References

Amiraslani F, Dragovich D (2013) Image acquisition for detection of vegetation change based on long-term rainfall in an arid rangeland in Western NSW, Australia. Environ Earth Sci 70(1):83–95. doi:10.1007/s12665-012-2105-1

An YZ, Gao W, Gao ZQ (2014) Characterizing land condition variability in Northern China from 1982 to 2011. Environ Earth Sci 72(3):663–676. doi:10.1007/s12665-013-2987-6

Archer S (1989) Have southern Texas savannas been converted to woodlands in recent history? Am Nat 134:545–561. doi:10.1086/284996

Aru H, Yang C (2007) Cumulative impacts of driving factors on desertification in Duolun Country, inner Mongolia. J Desert Res 27(6):936–941

Baret F, Guyot G, Major DJ (1989) TSAVI: a vegetation index which minimizes soil brightness effects on LAI and APAR estimation. IGARSS'89: 1989 international geoscience and remote sensing symposium: quantitative remote sensing: an economic tool for the Nineties, Vancouver, 10–14 July, 1989. The institute of electrical and electronic engineers (IEEE), New York, pp 1355–1359

Batterbury S, Warren A (2001) The African Sahel 25 years after the great drought: assessing progress and moving towards new agendas and approaches. Global Environ Chang 11(1):1–8. doi:10.1016/S0959-3780(00)00040-6

Ben-Dor E, Chabrillat S, Demattê JAM, Taylor GR, Hill J, Whiting ML, Sommer S (2009) Using imaging spectroscopy to study soil properties. Remote Sens Environ 113(Supp. 1):S38–S55. doi:10.1016/j.rse.2008.09.019

Berry L, Ford RB (1997) Recommendations for a system to monitor critical indicators in areas prone to desertification. In: Worcester M (ed) Program for international development. Clark University, Clark

Bestelmeyer BT, Duniway MC, James DK, Burkett LM, Havstad KM (2013) A test of critical thresholds and their indicators in a desertification-prone ecosystem: more resilience than we thought. Ecol Lett 16:339–345. doi:10.1111/ele.12045

Bisaro A, Kirk M, Zdruli P, Zimmermann W (2013) Global drivers setting desertification research priorities: insights from a stakeholder consultation forum. Land Degrad Dev. doi:10.1002/ldr.2220.Wiley

Chang XL (1997) The application of lacunarity index on desertification research. J Desert Res 17(4):351–354

Chen F, Kissel DE, West LT, Adkins W (2000) Field-scale mapping of surface soil organic carbon using remotely sensed imagery. Soil Sci Soc Am J 64:746–753

Ding GD, Zhao TN, Fan JY, Du H (2004) Analysis on development of desertification assessment indicator system. J Beijing For Univ 26(1):92–96

D'Odorico P, Bhattachan A, Davis KF, Ravi S, Runyan CW (2013) Global desertification: drivers and feedbacks. Adv Water Resour 51:326–344. doi:10.1016/j.advwatres.2012.01.013

Dregne HE (1995) Desertification control: a framework for action. Environ Monit Assess 37(1–3):111–122. doi:10.1007/BF00546884

Edwards MC, Wellens J, Al-Eisawic A (1999) Monitoring the grazing resources of the Badia region, Jordan, using remote sensing. Appl Geogr 19(4):385–398

Eswaran H, Lal R, Reich PF (2001) Land degradation: an overview. In: Scherr SJ, Sombatpanit S, Bridges EM, Hannam ID, Oldeman LR, Penning de Vries FWT (eds) Response to land degradation. Science Publishers Inc, Enfield, pp 20–35

Evans J, Geerken R (2004) Discrimination between climate and human-induced dryland degradation. J Arid Environ 57(4):535–554. doi:10.1016/S0140-1963(03)00121-6

Eve M, Whitford WG, Havstadt KM (1999) Applying satellite imagery to triage assessment of ecosystem health. Environ Monit Assess 54(3):205–227. doi:10.1023/A:1005876220078

Fan WY (2002) Hyperspectral remote sensing information model for disertification degree assessment. Sci Silvae Sin 38(2):61–67

FAO/UNEP (1984) Provisional methodology for assessment and mapping of desertification. FAO, Rome

Friedel MH (1991) Range condition assessment and the concept of thresholds: a viewpoint. J Range Manag 44(5):422–426. doi:10.2307/4002737

Fu BJ, Liang D, Lu N (2011) Landscape ecology: coupling of pattern, process, and scale. Chin Geogr Sci 21(4):385–391

Gao SW, Wang BF, Zhu LY, Wang JH, Zhang YG (1998) Monitoring and evaluation indicators system on sandy desertification of China. Sci Silvae Sin 34(2):1–10

Guo JA, Wang T, Xue XA, Ma SX, Peng F (2010) Monitoring aeolian desertification process in Hulunbir grassland during 1975–2006, Northern China. Environ Monit Assess 166(1–4):563–571. doi:10.1007/s10661-009-1023-5

Hanafi A, Jauffret S (2008) Are long-term vegetation dynamics useful in monitoring and assessing desertification processes in the arid steppe, southern Tunisia. J Arid Environ 72:557–572. doi:10.1016/j.jaridenv.2007.07.003

Helldén U (2008) A coupled human-environment model for desertification simulation and impact studies. Global Planet Change 64:158–168

Helldén U, Tottrup C (2008) Regional desertification: a global synthesis. Global Planet Change 64:169–176. doi:10.1016/j.gloplacha.2008.10.006

Herrmann SM, Hutchinson CF (2005) The changing contexts of the desertification debate. J Arid Environ 63:538–555. doi:10.1016/j.jaridenv.2005.03.003

Hill J, Stellmes M, Udelhoven T, Rder A, Sommer S (2008) Mediterranean desertification and land degradation mapping related land use change syndromes based on satellite observations. Global Planet Change 64(34):146–157. doi:10.1016/j.gloplacha.2008.10.005

Hu GY, Jin HJ, Dong ZB, Lu JF, Yan CZ (2013) Driving forces of aeolian desertification in the source region of the Yellow River: 1975–2005. Environ Earth Sci 70(7):3245–3254. doi:10.1007/s12665-013-2389-9

Ibaneza J, Valderramab JM, Puigdefabregas J (2008) Assessing desertification risk using system stability condition analysis. Eecolog Modell 213:180–190. doi:10.1016/j.ecolmodel.2007.11.017

Ivits E, Cherlet M, Sommer S, Mehl W (2013) Addressing the complexity in non-linear evolution of vegetation phonological change with time-series of remote sensing images. Ecol Ind 26:49–60

Jabbar MT, Zhou JX (2013) Environmental degradation assessment in arid areas: a case study from Basra Province, southern Iraq. Environ Earth Sci 70(5):2203–2214. doi:10.1007/s12665-013-2290-6

Kang WP, Liu SL (2014) A review of remote sensing monitoring and quantitative assessment of Aeolian desertification. J Desert Res 34(5):1222–1229

Kang XW, Wu SH, Yang QY, Xia FQ, Ma X, Liu ZQ, Yang PG (2005) Research progresses, problems and analyses of the evaluation on regional sandy desertification. Arid Land Geogr 28(3):330–335

Kang XW, Ma X, Wu SH (2007) Model construction of regional desertification degree assessment based on landscape pattern analysis. Geogr Res 26(2):297–304

Kéfi S, Rietkerk M, Alados CL, Pueyo Y, Papanastasis VP, Elaich A, de Ruiter PC (2007) Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. Nature 449(7159):213–217. doi:10.1038/nature06111

Kurc S (2008) Extreme makeovers: crossing critical thresholds into desertification. Arid Lands Newslett 60:4–11

Laycock WA (1991) Stable states and thresholds of range condition on North American rangelands: a viewpoint. J Range Manage 44:427–433. doi:10.2307/4002738

Leprieur C, Kerr YH, Mastorchio S, Meunier JC (2000) Monitoring vegetation cover across semi-arid regions: comparison of remote observations from various scales. Int J Remote Sens 21(2):281–300. doi:10.1080/014311600210830

Li HW, Yang XP (2010) Advances and problems in the understanding of desertification in the hunshandake sandy land during the last 30 years. Adv Earth Sci 25(6):647–655

Li ZP, Yue LP, Guo L, Liu SY, Wang M, Nie HG, Yang LR, Sun H, Wang FY (2007) Holocene climate change and desertification in Northern China. Northwest Geol 40(3):1–29

Li YY, Yang XC, Zhu XH, Xu B (2009) The application of remote sensing technology to land desertification monitoring. Prog Geogr 28(1):55–62

Liu YP (1998) Theoretic framework for desertification assessment. J Arid Land Res Environ 12(3):74–83

Liu SL, Wang T (2007) Aeolian desertification from the mid-1970s to 2005 in Otindag sandy land, Northern China. Environ Geol 51(6):1057–1064. doi:10.1007/s00254-006-0375-1

Liu SL, Wang T (2014) Aeolian processes and landscape change under human disturbances on the Sonid grassland of inner

Mongolian Plateau, northern China. Environ Earth Sci 71(5):2399–2407. doi:10.1007/s12665-013-2640-4

Liu AX, Wang CY, Wang J, Shao XM (2007) Method for remote sensing monitoring of desertification based on MODIS and NOAA/AVHRR data. Trans Chin Soc Agric Eng 23(10):145–150

Ludwig JA, Tongway D (1992) Monitoring the condition of Australian arid lands: linked plant-soil indicators, In: McKencie DH, Hyatt DE, McDonald VJ (eds) Ecological indicators. Proceedings of an international symposium, Fort Lauderdale, Florida, USA, Oct 16–19, 1990, Chapman and Hall, London, pp 765–772

Ludwig JA, Bastin GN, Chewings VH, Eager RW, Liedloff AC (2007a) Leakiness: a new index for monitoring the health of arid and semiarid landscapes using remotely sensed vegetation cover and elevation data. Ecol Ind 7:442–454

Ludwig JA, Bastin GN, Wallace JF, Mcvicar TR (2007b) Assessing landscape health by scaling with remote sensing: when is it not enough? Landsc Ecol 22:163–169

Mabbutt JA (1986) Desertification indicators. Clim Change 9:113–122. doi:10.1007/BF00140530

Maestre FT, Escudero AN (2009) Is the patch size distribution of vegetation a suitable indicator of desertification processes? Ecology 90(7):1729–1735. doi:10.1890/08-2096.1

Mainguet M (1991) Desertification: natural background and human mismanagement. Springer, Berlin, pp 1

Major DJ, Baret F, Guyot G (1990) A ratio vegetation index adjusted for soil brightness. Int J Remote Sens 11:727–740

Marini A (2008) Talbi M. Desertification and risk analysis using high and medium resolution satellite data: training workshop on mapping desertification, Springer

Mbow C, Fensholt R, Rasmussen K, Diop D (2013) Can vegetation productivity be derived from greenness in a semi-arid environment? Evidence from ground-based measurements. J Arid Environ 97:56–65. doi:10.1016/j.jaridenv.2013.05.011

Middleton NJ, Thomas DSG (1998) World atlas of desertification, 2nd edn. Edward Amold, London, p 182

Miehe S, Kluge J, Wehrden HV, Retzer V (2010) Long-term degradation of Sahelian rangeland detected by 27 years of field study in Senegal. J Appl Ecol 47:692–700. doi:10.1111/j.1365-2664.2010.01815.x

Millennium Ecosystem Assessment (MA) (2005) Ecosystems and human well-being: desertification synthesis. World Resources Institute, Washington

Mouat DA, Fox CA, Rose MR (1992) Ecological indicator strategy for monitoring arid ecosystems. In: McKencie DH, Hyatt DE, McDonald VJ (eds) Ecological indicators. Proceedings of an international symposium, Fort Lauderdale, Florida, USA, October 16–19, 1990, Chapman and Hall, London, pp 717–737

Mouat D, Lancaster J, Wade T, Wickham J, Fox C, Kepner W, Ball T (1997) Desertification evaluated using an integrated environmental assessment model. Environ Monit Assess 48:139–156. doi:10.1023/A:1005748402798

Nicholson SE, Tucker CJ, Ba MB (1998) Desertification, drought, and surface vegetation: an example from the West African Sahel. B Am Meteorol Soc 79:1–15

Oba G, Weladji RB, Msangameno DJ, Kaitira LM, Stave J (2008) Scaling effects of proximate desertification drivers on soil nutrients in northeastern Tanzania. J Arid Environ 72(10):1820–1829. doi:10.1016/j.jaridenv.2008.04.009

Omuto CT, Shrestha DP (2007) Remote sensing techniques for rapid detection of soil physical degradation. Int J Remote Sens 28(21):4785–4805. doi:10.1080/01431160701260357

Peng J, Xu YQ, Zhang R, Xiong KN, Lan AJ (2013) Soil erosion monitoring and its implication in a limestone land suffering from rocky desertification in the Huajiang Canyon, Guizhou, Southwest China. Environ Earth Sci 69(3):831–841. doi:10.1007/s12665-012-1968-5

Prince SD (1991) Satellite remote sensing of primary production: comparison of results for Sahelian grasslands 1981–1988. Int J Remote Sens 12:1301–1311

Prince SD (2002) Spatial and temporal scales for detection of desertification. In: Reynolds JF, Stafford Smith DM (eds) Global desertification: do humans create deserts?. Dahlem University Press, Berlin

Prince SD, De Colstoun EB, Kravitz LL (1998) Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. Global Change Biol 4(4):359–374. doi:10.1046/j.1365-2486.1998.00158.x

Prince SD, Wessels KJ, Tucker CJ, Nicholson SE (2007) Desertification in the Sahel: a reinterpretation of a reinterpretation. Global Change Biol 13:1308–1313

Reed MS, Buenemann M, Atlhopheng J, Akhtar-Schuster M, Bachmann F, Bastin G, Bigas H, Chanda R, Dougill AJ, Essahli W, Evely AC, Fleskens L, Geeson N, Glass JH, Hessel R, Holden J, Ioris A, Kruger B, Liniger HP, Mphinyane W, Nainggolan D, Perkins J, Raymond CM, Ritsema CJ, Schwilch G, Sebego R, Seely M, Stringer LC, Thomas RJ, Twomlow S, Verzandvoort S (2011) Cross-scale monitoring and assessment of land degradation and sustainable land management: a methodological framework for knowledge management. Land Degrad Dev 22:261–271. doi:10.1002/ldr.1087

Reining P (1978) Handbook on desertification indicators. AAAS Publication No, Washington, pp 78–79

Reynolds JF, Smith DM, Lambin EF, Turner BL, Mortimore M, Batterbury SP, Downing TE, Dowlatabadi H, Fernández RJ, Herrick JE, Huber-Sannwald E, Jiang H, Leemans R, Lynam T, Maestre FT, Ayarza M, Walker B (2007) Global desertification: building a science for dryland development. Science 316:847

Reynolds J, Bastin G, Garcia-Barrios L, Grainger A, Janssen M, Jürgens N, Scholes B, Stafford S, Veldkamp M, Verstraete T, Von Maltitz M, Zdruli P (2011) Scientific concepts for an integrated analysis of desertification processes. Land Degrad Dev 22:166–183

Rouse JW, Haas Jr RH, Schell JA, Deering DW (1973) Monitoring the vernal advancement and retrogradation (green wave effect) of natural vegetation. Prog Rep RSC 1978-1, Remote Sensing Center, Texas A&M Univ., College Station, p 93

Saatchi SS, Levine DM, Lang RH (1994) Microwave backscattering and emission model for grass canopies. IEEE Trans Geosci Remote Sens (ISSN 0196-2892); 32(1):177–186. DOI:10.1109/36.285200

Safriel UN (2009) Status of Desertification in the Mediterranean Region. In: Rubio JL et al (eds) Water scarcity, land degradation and desertification in the Mediterranean region, NATO science for peace and security series C, environmental security. Springer, Berlin, pp 33–73

Schlesinger WH, Reynolds JF, Cunningham GL, Huenneke LF, Jerrell WM, Virginia RA, Whitford WG (1990) Biological feedbacks in global desertification. Science 247:1043–1048. doi:10.1126/science.247.4946.1043

Shinoda M, Nachinshonhor GU, Nemoto M (2010) Impact of drought on vegetation dynamics of the Mongolian steppe: a field experiment. J Arid Environ 74:63–69. doi:10.1016/j.jaridenv.2009.07.004

Smith MS, Reynolds JF (2003) The interactive role of human and environmental dimensions in the desertification debate. Ann Arid Zone 42(3&4):255–270

Smith MO, Ustin SL, Adams JB, Gillespie AR (1990) Vegetation in deserts: i. A regional measure of abundance from multispectral images. Remote Sens Environ 31:1–26

Sommer S, Zucca C, Grainger A, Cherlet M, Zougmore R, Sokona Y, Hill J, Della Peruta R, Roehrig J, Wang G (2011) Application of indicator systems for monitoring and assessment of desertification from national to global scales. Land Degrad Dev 22:184–197. doi:10.1002/ldr.1084

Soyza DAG, Whitford WG, Herrick JE, Van Zee JW, Havstad KM (1998) Early warning indicators of desertification: examples of tests in the Chihuahuan Desert. J Arid Environ 39(2):101–112. doi:10.1006/jare.1998.0391

Thomas DSG, Middleton NJ (1994) Desertification: exploding the myth. Wiley, Chichester

Tucker CJ, Dregne HE, Newcomb WW (1991) Expansion and contraction of the Sahara desert from 1980 to 1990. Science 253:299–301

UNCCD (1994) International convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa

Veron SR, Jose M (2010) Desertification alters the response of vegetation to changes in precipitation. J Appl Ecol 47:1233–1241. doi:10.1111/j.1365-2664.2010.01883.x

Veron SR, Paruelo JM, Oesterheld M (2006) Assessing desertification. J Arid Environ 66:751–763. doi:10.1016/j.jaridenv.2006.01.021

Verstraete MM, Scholes RJ, Smith MS (2009) Climate and desertification: looking at an old problem through new lenses. Front Ecol Environ 7(8):421–428. doi:10.1890/080119

Vogt JV, Safriel U, Von Maltitz G, Sokona Y, Zougmore R, Bastin G, Hill J (2011) Monitoring and assessment of land degradation and desertification: towards new conceptual and integrated approaches. Land Degrad Dev 22:150–165. doi:10.1002/ldr.1075

Wang T, Wu W, Wang XZ (1998) Remote sensing monitoring and assessing sandy desertification: an example from the sandy desertification region of northern China. Quaternary Sciences 2:108–118

Wang T, Wu W, Xue X, Han ZW, Zhang WM, Sun QW (2004a) Spatial-temporal changes of sandy desertified land during last 5 decades in northern China. Acta Geogr Sin 59(2):203–212

Wang T, Wu W, Zhao HL, Hu MC, Zhao AG (2004b) Analyses on driving factors to sandy desertification process in Horqin region, China. J Desert Res 24(5):519–528

Wang XM, Chen FH, Eerdun HS, Li JC (2008) Desertification in China: an assessment. Earth Sci Rev 88:188–206. doi:10.1016/j.earscirev.2008.02.001

Wang T et al. (2011a) Deserts and Aeolian desertification in China. Elsevier

Wang T, Song X, Yan CZ, Li S, Xie JL (2011b) Remote sensing analysis on Aeolian desertification trends in northern China during 1975–2010. J Desert Res 31(6):1351–1356

Weiss JL, Gutzler DS, Coonrod JEA, Dahm CN (2004) Long-term vegetation monitoring with NDVI in a diverse semiarid setting, central New Mexico, USA. J Arid Environ 58:248–271

Wessels KJ, Prince SD, Frost PE, van Zyl D (2004) Assessing the effects of human-induced land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-series. Remote Sens Environ 91(1):47–67

Wessels KJ, Prince SD, Malherbe J, Small J, Frost PE, Vanzyl D (2007) Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa. J Arid Environ 68:271–297

Wessels KJ, Prince SD, Reshef I (2008) Mapping land degradation by comparison of vegetation production to spatially derived estimates of potential production. J Arid Environ 72:1940–1949

Wessels KJ, van den Bergh F, Scholes RJ (2012) Limits to detectability of land degradation by trend analysis of vegetation index data. Remote Sens Environ 125:10–22

Wiesmeier M, Kreyling O, Steffens M, Schoenbach P, Wan HW, Gierus M, Taube F, Kolbl A, Kogel-Knabner I (2012) Short-term degradation of semiarid grasslands results from a controlled-grazing experiment in Northern China. J Plant Nutr Soil Sci 175(3):434–442. doi:10.1002/jpln.201100327

Wu J, Peng DL (2009) Advances in researches on desertification evaluation technology based on remote sensing. World For Res 22(5):34–39

Wu J, Peng DL (2010) Remote sensing information model for sandy desertification assessment in Duolun based on land use. J China Agric Univ 15(3):114–121

Xu DY, Kang XW, Zhuang DF, Pan JJ (2010) Multi-scale quantitative assessment of the relative roles of climate change and human activities in desertification—a case study of the Ordos plateau, China. J Arid Environ 74(4):498–507. doi:10.1016/j.jaridenv.2009.09.030

Yang X, Zhang K, Jia B, Ci L (2005) Desertification assessment in China: an overview. J Arid Environ 63:517–531. doi:10.1016/j.jaridenv.2005.03.032

Yang L, Han GD, Zhao ML, Chang SX (2010) Spatial vegetation patterns as early signs of desertification: a case study of a desert steppe in Inner Mongolia, China. Landsc Ecol 25(10):1519–1527

Zeng YN, Xiang NP, Feng ZD, Xu H (2006) Albedo-NDVI space and remote sensing synthesis index models for desertification monitoring. Sci Geogr Sin 1:75–77

Zhang YX (1996) Evaluation of desert and desertification degree. Arid Zone Res 13(2):77–80

Zhang D, Ding GD, Ma SL, Ma YH (2005) Research on indicator system of early-warning of desertification damages in hunshandake sand. Res Soil Water Conserv 12(6):79–82

Zhang J, Niu JM, Tong LG, Zhang XF (2013) A multilevel/multiscale analysis of the impact of land use drivers on desertification: a case study of Uxin Banner, Inner Mongolia, China. J Desert Res 33(6):1–11

Zhao YS (2003) The principle and method of analysis of remote sensing application. Science Press, Beijing, pp 366–412

Zhong DC (1999) The dynamic changes and trends of modern desert in China. Adv Earth Science 14(6):229–234

Zhu ZD, Liu S (1984) The concept of desertification and the differentiation of its development. J Desert Res 4(3):2–8

Zuo XA, Zhao HL, Zhao XY, Chang XL, Guo YR, Zhang JP, Li JY (2009) Changes on landscape pattern of sand dunes at different scales in Horqin sandy land. J Desert Res 29(5):785–795