

Several challenges in monitoring and assessing desertification

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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 particular, 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

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

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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 Millennium 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 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 indicator 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 from 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), Greenness Vegetation Index (GVI), Perpendicular 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 (Bendor 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.

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