Ecological responses of vegetation and environmental factors to the reversal of sandy desertification and soil-vegetation relationships

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Zusammenfassung

Die Vegetation des innerasiatischen, kontinental geprägten Trockengebiets wird verschiedenen Steppentypen, den Halbwüsten und den Wüsten zugeordnet (Terminologie nach Pott 2014). Die Grenzen zwischen den verschiedenen Vegetationstypen werden dabei durch Niederschlagsgradienten geprägt und sind oft fließend. Im Norden Chinas sind Hochgrassteppen – zumeist dominiert von *Stipa*-Arten – auf dem Lößplateau, vor allem in Waldsteppenmosaiken der Randbereiche der Ordos und der südlichen Gobi anzutreffen (Liu et al. 1999a, b). Östlich der Linie Altai-Tian Shan kommen Niedriggrassteppen in der hochkontinentalen, extrem winterkalten zentralasiatischen Steppenregion vor (Lavrenko et al. 1993), in der die Vegetationszeit auf wenige Monate begrenzt ist. Hier dominiert das C_4-Gras *Cleistogenes squarrosa* zusammen mit anderen Horstgräsern, die an das Klima und Beweidung angepasst sind.

Die innerasiatischen Ökosysteme werden unter anderem im Norden Chinas verstärkt von Menschen genutzt, was zur Zerstörung der natürlichen Steppen- und Wüstenvegetation geführt und das Entstehen großer Wanderdünen gefördert hat. Die damit verbundene Ausbildung von Wüstenflächen (Desertifikation) ist ein großes Problem. Auf SRTM (Shuttle Radar Topography Mission)-Daten basierende Kartierungen haben allerdings gezeigt, dass in jüngster Vergangenheit neben der Desertifikation in einigen Gebieten auch die teilweise Regeneration von anthropozoogenen Wüsten zu Halbwüsten- und Steppenformationen (Desertifikation reversal) stattgefunden hat. Die damit verbundenen Prozesse auf der Ebene von Pflanzengesellschaften, -morphologie und -physiologie sowie Pflanze-Boden-Wechselwirkungen sind allerdings noch weitgehend unbekannt. Diese Arbeit vergleicht die Zusammensetzung von Pflanzengesellschaften, morphologische und pflanzenphysiologische sowie Bodenparameter unterschiedlicher Regenerationsstadien im Norden Chinas. Während auf Sträucher und Halbsträucher wie *Artemisia ordosica* eine wichtige Rolle bei der initialen Wiederbesiedlung offener Sandflächen spielen, werden diese und annuelle Arten wie *Agriophyllum squarrosum* in späteren Regenerationsstadien durch ausdauernde Pflanzen und vor allem Gräser wie *C. squarrosa, Pennisetum centrasiaticum* und *Leymus secalinus* ersetzt, was mit einem Anstieg an Bedeckungsgrad und Biodiversität verbunden ist. Für die beiden letztgenannten Arten werden zudem deutliche Veränerungen in Physiologie und Morphologie zwischen den Regenerationsstadien festgestellt, die beim C_3-Gras *L. secalinus* im Vergleich zum C_4-Gras *P. centrasiaticum* deutlich stärker ausgeprägt sind. Mit der Vegetationsregeneration sind zudem starke Unterschiede in der Korngrößenzusammensetzung, Dichte, Nährstoffversorgung und Enzymaktivität des Bodens verbunden. Über Regressionsmodelle werden mobiles Kalium, Gesamtstickstoff, pH-Wert und Proteaseaktivität als die wichtigsten die Vegetation beinflussenden Bodenparameter identifiziert. Diese Studie stellt dabei eindeutig die starken Wechselwirkungen und gegenseitigen Einflüsse zwischen Vegetations- und Bodenparametern bei der Regenation von Steppen heraus und liefert wichtiges Grundlagenwissen zur zukünftigen Restauration anthropozoogener Wüstenböden.

Stichwörter: Restauration von Wüstenböden; Wüstenpflanzen; Pflanzengesellschaften; Vegetationseigenschafte

Abstract

The vegetation at the margins of the inner Asian continental region is characterized by different steppe types, semi-deserts and deserts (classified after Pott 2014). Their boundaries are controlled by precipitation gradients and transitions are often gradual, which makes them highly sensitive to anthropogenic disturbances. In Northern China, tall grass steppes with many perennials and C_3 grasses, commonly *Stipa* species exist on loess plateau, especially at the margins of Ordos and southern Gobi Deserts in the form of forest steppe (Liu et al. 1999a, b). East of the line Altai-Tian Shan, in the highly continental steppe region with extremely cold winters where the vegetation period is reduced to few months (Lavrenko et al. 1993), small grass steppes can be found, which are often dominated by the C_4-grass *Cleistogenes squarrosa* and other bunch grasses that are resistant to the climatic conditions and grazing.

The Asian continental ecosystems are increasingly subjected to anthropogenic activity, mainly overgrazing, which has led to the disturbance and devastation of the natural desert and steppe vegetation and the formation of large shifting sand dunes. Especially in northern China, desertification represents a severe problem. Observations, mainly based on SRTM (Shuttle Radar Topography Mission)-data, have shown that in recent times not only ongoing desertification, but in some (smaller) regions also the partially regeneration of anthropogenic deserts back to semi-desert and steppe formations (desertification reversal) took place. The related processes on plant community, plant morphology and plant physiology level plus plant-soil-feedbacks are, however, largely unknown. This study compared plant community, morphological and physiological characteristics as well as environmental (mainly soil) parameters in areas belonging to different regeneration stages in Yanchi County, Northern China. While at plant community level shrubs and sub-shrubs as *Artemisia ordosica* seemed to play an important role in the initial recolonization of open areas, during the desertification reversal these and annual herbs as *Agriophyllum squarrosum* were replaced by perennial herbs and especially grasses as *C. squarrosa*, *Pennisetum centrasiaticum* and *Leymus secalinus* with an increase in biodiversity and plant cover. For the latter two species our results showed changes in physiology and morphology during the desertification reversal, which seemed to be stronger in the C_3-grass *L. secalinus* than in the C_4-grass *P. centrasiaticum*. We further detected strong shifts in grain size composition (fining), bulk density (decrease), nutrients (increase) and enzyme activities (increase) of the soil with the reversal of desertification. By regression models, soil available K, total nitrogen, pH value, and protease activity were identified as the most important factors related to vegetation characteristics. This study especially highlights the strong interactions and mutual influences between soil and vegetation parameters during the regeneration of heavily anthropogenic disturbed semi-desert and steppe formations. This research is supposed to serve as a knowledge base for the future restoration management of anthropogenic deserts.

Key words: Restoration of desertified soil; Desert plants; Plant community; Vegetation characteristics

Abbreviations

AF	annual forb
AG	annual grass
AK	soil available potassium
AN	soil available nitrogen
AP	soil available phosphorus
A. ordosica	*Artemisia ordosica*
A. squarrosum	*Agriophyllum squarrosum*
B	total plant aboveground biomass
BJ	Badain Juran Desert
BD	soil bulk density
C	plant cover
CAT	soil catalase activity
C_i	intercellular CO_2 concentration
CLS	clay and silt
CS	course sand
C. squarrosa	*Cleistogenes squarrosa*
Chl	Chlorophyll
D	plant species diversity
DV	dominance value
DW	Durbin-Watson value
E	plant species evenness
EC	soil electrical conductivity
FS	fine sand
G	dry weight of the soil sample
G_s	Stomatal conductance
H'	Shannon - Wiener index
INV	soil invertase activity
IV	species importance value
J'	Pielou index
K-S test	Kolmogorov- Smirnov test
LD	Light desertification
L. secalinus	*Leymus secalinus*
MD	moderate desertification
Mu	Mu Us Sandy Land
N	Nitrogen
NDVI	normalized difference vegetation index
NPP	net primary production
Or	Ordos Plateau
P. centrasiaticum	*Pennisetum centrasiaticum*
PD	potential desertification
PF	perennial forb

Abbreviations

PG	perennial grass
PHO	soil phosphatase activity
PL	perennial legumes
Pn	photosynthetic rate
PRO	soil protease activity
PS	perennial sub-shrub
R	plant species richness
RA	relative abundance
RH	relative height
RC	relative cover
RF	relative frequency
S	the number of plant species
SD	severe desertification
SH	Shrub
SOC	soil organic carbon
SRTM	shuttle radar topography mission
SW	soil water content
T	Tengger Desert
TK	soil total potassium
TN	soil total nitrogen
TP	soil total phosphorus
Tr	transpiration rate
UNCCD	United Nations Convention to Combat Desertification
URE	soil urease activity
V	Volume
VFS	very fine sand
VSD	very severe desertification
W	wet weight of the soil sample

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1 Introduction

1.1 Background and goal

Desertification is a global eco-environmental problem occurring in more than a quarter of the total terrestrial area (Allington and Valone 2010), influencing a large amount of people: more than 250 million people are influenced directly by desertification (Adger et al. 2001; Millennium Ecosystem Assessment 2005). Desertification is becoming a serious social-economic-environmental problem worldwide (UNCCD 1994; Zhou W. et al. 2013). Desertification is therefore a problem that needs a global attention and an important topic for intensive research.

China is a country severely suffered from desertification. There are several large deserts or sandy lands in China, like Taklamakan desert and "Mu Us Sandy Land". Desertification causes many problems including land resource destruction and ecosystem service reduction in China (Li and Xie 2013). This phenomenon is threatening the survival and development of human beings in those areas suffering from desertification (Wang et al. 2012).

It is believed that human efforts can promote desertification reversal effectively (Li et al. 2013). Desertification reversal is becoming an important field to study. Sciences of desertification reversal, especially the processes and mechanisms of the reversal, are helpful for ecological restoration in arid and semiarid regions.

Studies on desertification reversal can provide the scientific basis for land management, which is important for policy making and land regulation in China. A systematic study of responses of soil physical and chemical properties, soil enzyme activities, micrometeorological indices, plant physiological traits, vegetation characteristics to the reversal of sandy desertification, and soil-vegetation relationships is needed to provide detailed information and better understanding of the process of sandy desertification reversal.

To study the reversal of sandy desertification systematically, we posed the following questions. (1) Do common species get some adaptive changes to desertification reversal and what factors are related to these changes in plant attributes? (2) How does each ecological factor, such as vegetation characteristics, soil properties, and micrometeorological indices respond to the reversal of sandy desertification? (3) What are the relationships between soil and vegetation characteristics in the process of desertification reversal and what are the implications of these relationships on the reversal of sandy desertification?

1.2 Progress in studies of desertification

Numerous studies have been conducted on desertification, especially on the mechanisms, including effects of natural factors such as climate change, herbivory, and fire (Neary 2009), and also anthropogenic disturbances such as grazing (Bo et al. 2013; Ibáñez et al. 2007; Manzano and Návar 2000; Schlesinger et al. 1990), cultivation, and wood cutting (Helldén 1991).

A study of large spatial scale (Zhu and Wang 1990) showed that the desertification in China increased at the rate of 2100 km^2 y^{-1} from 1970s to 1980s. Desertification developed quickly during that period in China. "Mu Us Sandy Land" is a major anthropogenic desert in China, and is located in north central China (Fig. 1). It is on the border of Inner Mongolia, Shaanxi Province, and Ningxia. It covers nine districts of these three provinces (Autonomous regions) (Wu and Ci 2002) . The total area of "Mu Us Sandy Land" is about 40,000 km^2. Yan and Wu (2013) showed that although the desertification in "Mu Us Sandy Land" declined in general from 1977 to 1999, the area of shifting sandy land (Fig. 2) increased obviously from 1977 to 1999; however, the total area of shifting sandy land and semi-fixed sandy land (Fig. 3) decreased apparently from 1999 to 2010 (Tab. 1), showing a clear reversal of desertification in "Mu Us Sandy Land" in this period (Fig. 4) (Yan and Wu 2013).

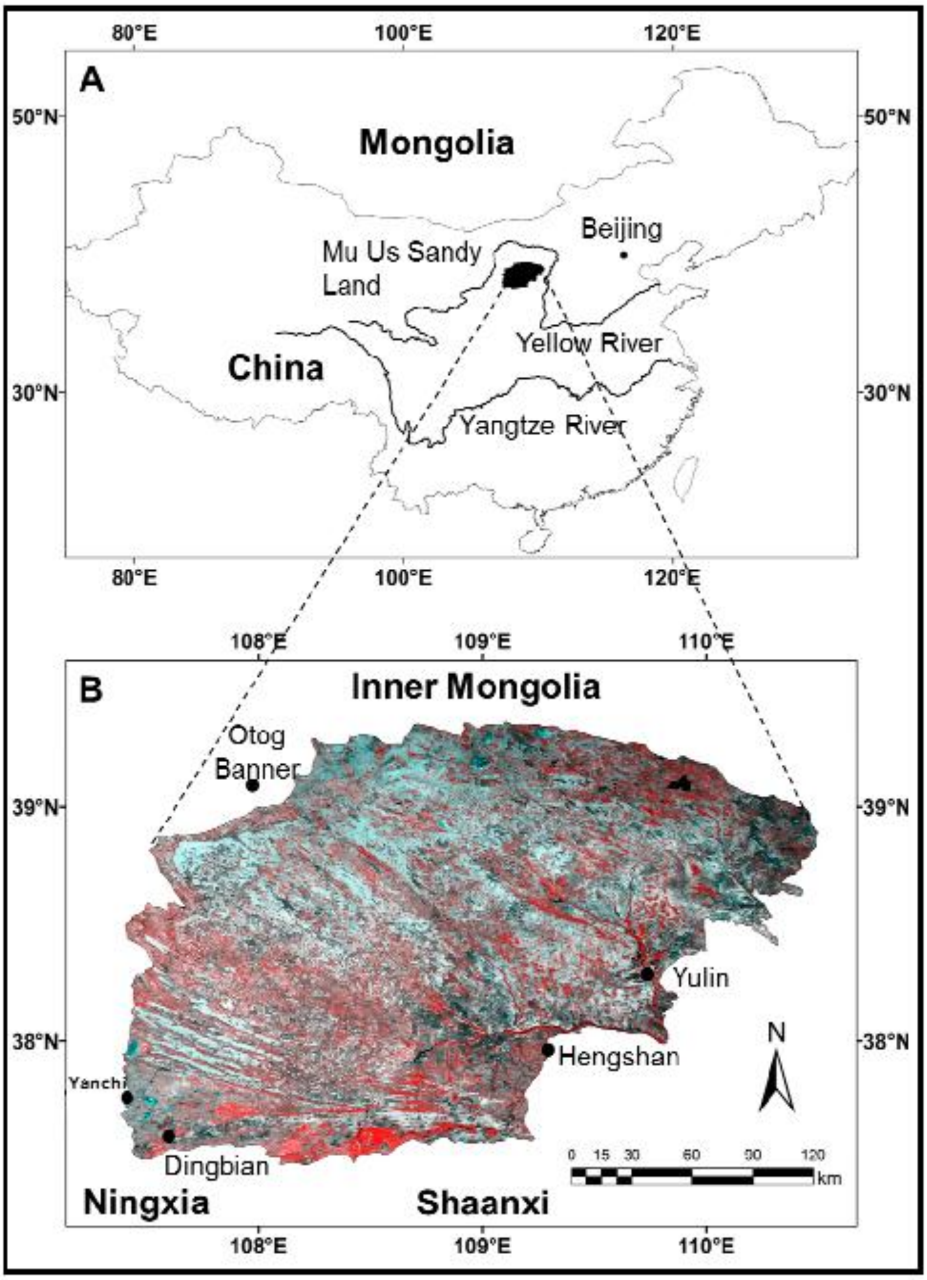

Fig. 1: Map showing the location of "Mu Us Sandy Land" (A), and the image of Landsat took in 2007 for Mu Us Sandy Land (B); the combination of Band is: RGB: 5, 4, 3 (from Karnieli et al. (2014), changed)

Fig. 2: Photo of shifting sandy land in southern "Mu Us Sandy Land"

Fig. 3: Photo of semi-fixed sandy land in southern "Mu Us Sandy Land"

Tab. 1: Changes in the area of shifting sandy land, semi-fixed sandy land, and their total area in Mu Us Sandy Land from 1977 to 2010 (from Yan and Wu (2013), changed).

Year	Shifting sandy land (km^2)	Semi-fixed sandy land (km^2)	Total area (km^2)
1977	15445.4	16638.6	32084.0
1988	16462.6	12119.1	28581.7
1999	18811.1	10765.2	29576.3
2010	9157.8	16889.5	26047.3

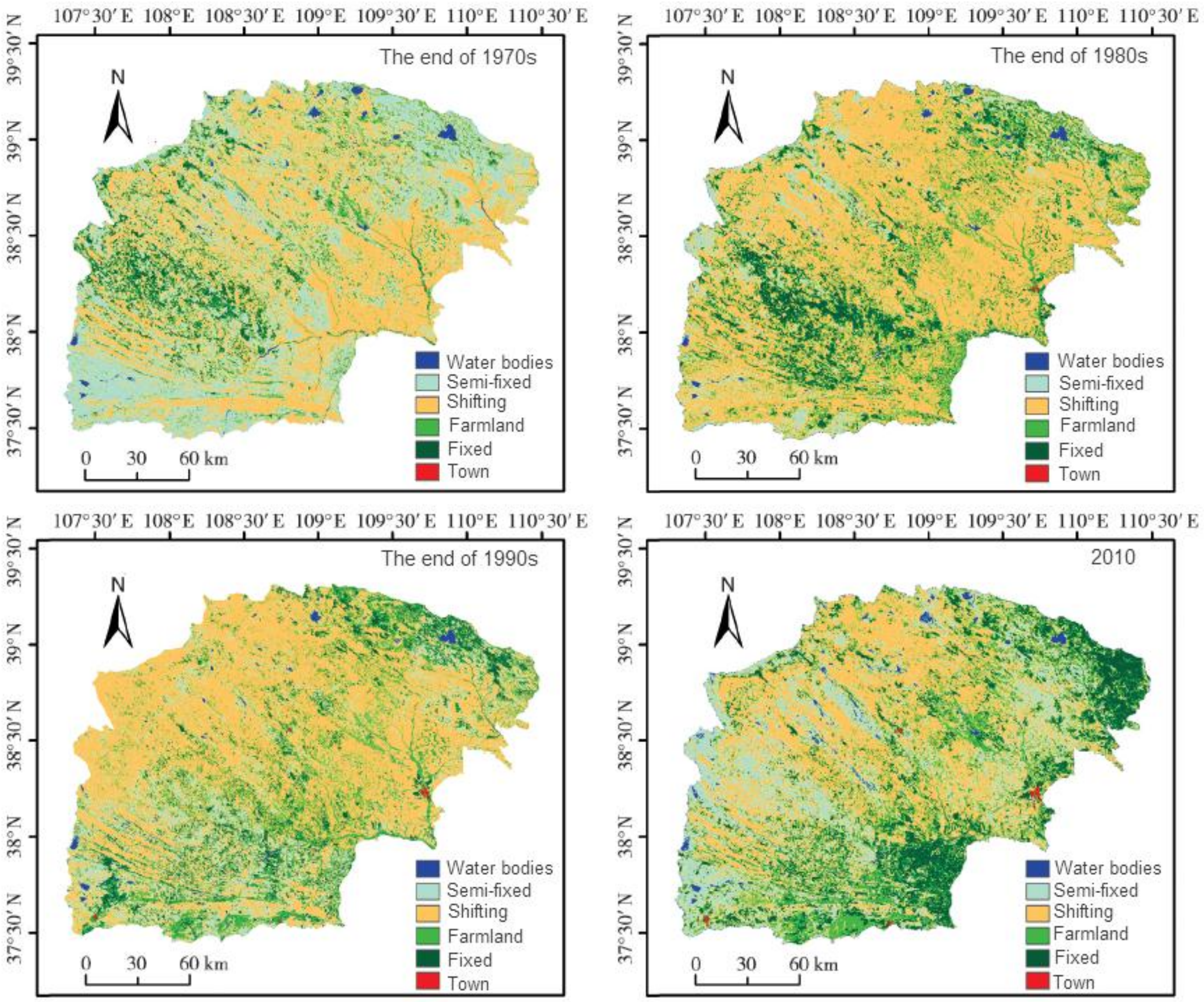

Fig. 4: Changes in land cover of "Mu Us Sandy Land" during the period from 1977 to 2010. Semi-fixed: semi-fixed sandy land; Shifting: shifting sandy land; Fixed: fixed sandy land (from Yan and Wu (2013), changed).

This kind of study is useful for the periodical monitoring of desert expansion and desertification development. Land use dynamics are also analyzed in many studies (Gilruth et al. 1990; Gilruth et al. 1995; Imagawa et al. 1997; Lambin and Ehrlich 1997; Reenberg 1994), which are helpful to indicate the mechanisms of desertification on a regional scale. Based on a long term monitoring, these studies are also valuable to predict the trend of desertification development in those regions which are sensitive to desertification. Using satellite images (Fig. 4) is favorable due to the convenience to store and retrieve at any time. Studies based on satellite images have therefore great advantages. However, this method has also some limitations. For examples, the satellite images for a specific region in a specific time are not always available. What happened exactly to the soil, vegetation, and other ecological factors still need a field survey.

1.2.1 Concept of desertification

The concept of "desertification" was first introduced by André Aubréville in 1949 and depicted as a shift of fertile land into ecological desert resulting from erosion, deforestation, and climate change (Aubréville 1949; Katyal and Vlek 2000). Although there are some other definitions by scholars all over the world, the definition provided by the "United Nations Convention to Combat Desertification" (UNCCD) is the most commonly used.

Desertification is defined by the UNCCD as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UNCCD 1994), thus containing both natural and anthropogenic factors (Reynolds et al. 2007). It involves in the steps from steppe to desert. UNCCD further defines the terms in the definition above: (1) "land degradation" refers to decrease or loss in the productivity of biology or economy, and in the complexity of cropland, pasture, woodland, and forest, in arid, semi-arid and dry sub-humid areas. It is caused by land uses or by a process or combined processes like human activities and habitation patterns, including soil erosion, soil properties deterioration and long-term loss of natural vegetation (UNCCD 1994); (2) "arid, semi-arid and dry sub-humid areas" refers to areas where the ratio of annual rainfall to potential evapotranspiration is between 0.05 and 0.65 (i.e. $0.05 \leq \frac{\text{Annual rainfall}}{\text{Annual potential evapotranspiration}} \leq 0.65$). These areas do not include polar and sub-polar zones (UNCCD 1994).

1.2.2 Temporal dynamics of desertification

The investigation of the temporal dynamics of desertification is an important part of desertification studies. Related study have often used satellite images (Fig. 4) to analyze the development of desertification in the past decades (Tucker et al. 1991; Wu and Ci 1999; Wu and Ci 2002; Wu et al. 1997; Zhu and Wang 1990).

A large increase in the area of shifting sandy land (Fig. 2) was observed in "Mu Us Sandy Land" between the end of 1970s and 1990s (Fig. 4), whereas the area of semi-fixed sandy land (Fig. 3) decreased apparently during this period; the area of shifting sandy land decreased dramatically from the end of 1990s to 2010 (Fig. 4) (Yan and Wu 2013).

In addition, the speed of desertification in this region was apparently slower from the late 1970s and the early 1990s than between the late 1950s and the late 1970s (Wu and Ci 1999). A more detailed study showed a negative desertification trend called, called desertification reversal, in "Mu Us Sandy Land" from 1987 to 1993 (Wu et al. 1997).

These studies are useful for the periodical monitoring of regions which are prone to suffer from desertification. Land use dynamics are also analyzed in many studies (Gilruth et al. 1990; Gilruth et al. 1995; Imagawa et al. 1997; Lambin and Ehrlich 1997; Reenberg 1994), which are helpful to indicate the mechanisms of desertification on a regional scale. Based on a long term monitoring, these studies are also valuable to predict the trend of desertification development in those regions which are sensitive to desertification. Using satellite images (Fig. 4) is favorable due to the convenience to store and retrieve images at any time. Studies based on satellite images have therefore great advantages. However, this method has also some shortcomings. For examples, the satellite images for a specific region and time are not always available. In addition, satellite images provide the information such as how land categories and vegetation indices like NDVI (Normalized Difference Vegetation Index) (Holm et al. 2003; Wessels et al. 2004) and NPP (Net Primary Production) (Xu et al. 2010; Xu et al. 2014) change in the studied period. To identify what happened exactly to the soil, vegetation, and other ecological factors, a field survey is still needed.

1.2.3 Changes in soil and plant properties in the process of desertification

Some studies already focus on changes in soil properties and vegetation characteristics in the process of grassland desertification (Huang et al. 2007; Li X. et al. 2006; Zuo et al. 2009a). These studies consist of two classes. One class investigates on soil and vegetation dynamics with time (temporal dynamics) during grassland desertification. This class of studies monitors the same study site over a long term, during which the desertification is generally getting more and more severe. The other class studies spatial variability of soil and vegetation characteristics at the same time in different sites with different stages of desertification. All these sites are located in an area with a desertification. The former trails the whole process of grassland desertification, but it lasts for many years and during this period the study may be accomplished by different people, which may cause deviations. The latter carried out vegetation survey, soil sampling, and laboratory analyses for all stages of desertification in a short time by the same people, which may get a more accurate result.

No matter which class those studies belong to, the results are often similar. Sand fraction in the topsoil increased dramatically from cropland with potential desertification (Fig. 5) to that with extreme desertification (Fig. 6) (Su et al. 2004a); whereas clay and silt fraction in the soil decreased clearly with desertification development (Xu et al. 2012). Soil bulk density increased, but soil organic matter and total N content reduced significantly, and soil total P and K diminished slenderly in the process of desertification (Huang et al. 2007). Soil available N also decreased apparently with the development of desertification (Xu et al. 2012).

Fig. 5: Photo of potential desertification area

Fig. 6: Photo of extreme desertification area

At the same time, there are also obvious changes in vegetation characteristics in the process of desertification. Plant cover and biomass decreased in desert nearly to the half of those in the meadow (Fu et al. 2009). Plant species richness and diversity decreased dramatically as desertification progressed (Huang et al. 2007). Dominant plant species also changed from steppe species to psammophyte and shrubs in the process of desertification (Xu et al. 2012).

Although there have been many studies on changes in soil properties and vegetation characteristics with the development of land desertification, a specific study of changes in these factors with the reversal of sandy desertification is still essential. As desertification is a very complex process, the reversal of sandy desertification is even more complex. An ecosystem undergoing desertification development is quite different from that undergoing desertification reversal. The process of desertification development is not simply equal to the opposite of desertification reversal, because the vegetation of the former undergoes a retrogressive succession whereas that of the latter may restore along another direction and the related changes in soil properties may be quite different, too (Zhao et al. 2008). The reversal of sandy desertification is associated with a lot of factors such as policy, land management, soil-vegetation interactions, changes in soil and vegetation characteristics, and other human and natural factors. The mechanisms of desertification reversal are therefore complex and need a special study for a better understanding.

Simultaneously, there have been many studies on leaf photosynthesis for desert plants, but most of them measured their plant photosynthesis in desert ecosystems affected by environmental factors, such as temperature (Downton et al. 1984; Lawson et al. 2014; Seemann et al. 1986; Xue et al. 2011), light (Lawson et al. 2014; Lehner et al. 2001; Nilsen et al. 1989), radiation (Hui et al. 2014; Yan et al. 2008), elevated CO_2 (Ellsworth et al. 2004; Hamerlynck et al. 2000; Huxman and Smith 2001), oxygen (Glacoleva et al. 1978), precipitation (Barker et al. 2006; Yan et al. 2000), soil water status (de Soyza et al. 2004; Ogle and Reynolds 2002; Schulze et al. 1980; Szarek and Woodhouse 1978; van Heerden et al. 2007), soil nitrogen content (Lajtha and Whitford 1989; Nyongesah and Wang 2013), leaf position (Wang et al. 2005) and herbivory (Zhu C. G. et al. 2014). Studies rarely have considered the effects of changes in the whole desert ecosystems on leaf chlorophyll (Chl) content and photosynthesis (Kappen et al. 1976; Nobel 1978). These changes may include variations in many environmental factors and may have a comprehensive effect on plant Chl content and photosynthesis.

1.2.4 Mechanisms of desertification

Desertification is a process of great complexity (Li and Xie 2013; Mabbutt 1986; Reynolds et al. 2007; Rubio and Bochet 1998). Many factors contribute to the process and they may play different roles in the same region on different time scales (Wang et al. 2012). These factors are mainly climate change and human activities (UNCCD 1994). The relative contributions of climate change and human activities in the process of land desertification have been the topic of much controversy (Nicholson et al. 1998), i.e. which is the major reason for land desertification, climate change or human activities?

Studies evaluating the relative contributions of climate change and human activities to land desertification applied mainly qualitative, semi-quantitative and quantitative methods, but quantitative methods should be the priority (Wang et al. 2012; Xu et al. 2011; Zhou et al. 2013). These quantitative methods ideally include comparing conditions with and without human disturbances, determining the relative effects of climate change and human activities on land desertification using a common indicator, and models using ordination and regression models (Xu et al. 2011).

1.2.4.1 Climate change

Climate change will add the risk to land desertification (Salinas and Mendieta 2013). It poses a general background for the development of land desertification. Climate change results in drier and warmer conditions, with longer, drier, and hotter summers (Neary 2009) in arid and semi-arid regions. A drier condition is always considered to be one of the most important factors for wind erosion and land desertification. Climate change may lead to a lower precipitation, which will further cause a harder wind erosion (Schlesinger et al. 1990). Many studies have shown close relations between climate change and desertification (Lavee et al. 1998; Pickup 1998). Moreover, climate change often combines its effects together with other factors induced by human activities to promote the development of sandy desertification. Climate change is therefore considered to be one of the most import factors resulting in desertification.

1.2.4.2 Anthropogenic factors

It is not correct to attribute desertification simply to climate change (Li and Xie 2013). Desertification is even regarded as a mainly man-made phenomenon (Helldén 1991) resulting mainly from inappropriate human activities such as overgrazing (Akiyama and Kawamura 2007; Su et al. 2004b; Wu and Ci 2002). Anthropogenic reasons accounted for 90 percent of desertification in some regional studies (Wang et al. 2012; Zhou W. et al. 2013). The expansion of desertificated areas from 2000 to 2010 in the agro-pastoral region in northern China was dominantly driven by human activities (Xu et al. 2014).

Except for overgrazing, several other anthropogenic factors including inappropriate management of agriculture (over-reclaiming), deforestation (over-cutting), and collecting for medicinal materials also contribute to land desertification (Akiyama and Kawamura 2007; Wu and Ci 2002; Zhao et al. 2000).

Overgrazing is taken as one of the most important factors contributing to desertification (Arianoutsou-Faraggitaki 1985). Grassland desertification is significantly influenced by grazing intensity (Bo et al. 2013). Overgrazing leads to severe soil erosion under the effect of livestock hoof, which make a small bare spot on the earth's surface at first; under continuous grazing pressure, bare spots merge to be large spot areas (Zhao et al. 2005), which are cooler than those areas covered by vegetation due to high albedo in bare land under the sunlight (Otterman 1974). Albedo is the ratio of the reflected radiation by a surface to the incident radiation (i.e. Albedo = $\frac{\text{reflected radiation}}{\text{incident radiation}}$). Bare land caused by overgrazing has a high albedo due to a lack of vegetation cover. Moreover, overgrazing also results in a series of changes in vegetation characteristics. Unpalatable plants become dominant species after land degradation due to overgrazing (Arianoutsou-Faraggitaki 1985). The cover of perennial grasses decreases in desert grasslands, which convert into shrub-lands under livestock grazing (Kerley and Whitford 2000). Fortunately, some indicators were proposed for the early warning against long-term risk of desertification resulting from overgrazing (Ibáñez et al. 2007); these indicators are three quantities and comparison criteria, which can serve for preventing from long-term desertification with regard to overgrazing.

Over-reclaiming is commonly regarded as one of the primary reasons for sandy desertification in semiarid regions. Cultivation mainly leads to an apparent reduction in soil organic C, total and available nutrients in the topsoil because of wind erosion on bare soil after cultivation (Su et al. 2004b). Over-cutting causes the destruction of natural vegetation and the consequent results of wind erosion, which promotes the process of desertification. Collecting medical materials often leads to over-excavation due to the root of some plant species being the medical materials. Several anthropogenic factors may combine their effects together to cause severe desertification in some regions.

1.2.4.3 Combined effects of climate change and anthropogenic driving factors

Some other studies showed that climate change and human activities can play different roles in different periods for the same region (Wang et al. 2012; Xu et al. 2014). Climate change and human activities account for the close proportion of the reasons for desertification when the desertification development is in a stable stage (Wang et al. 2012). But on the background of climate change, when the land is at the same time suffered from inappropriate human activities, or is overburdened with stress caused by human activities, climate change and human activities combine together in this circumstance to accelerate land desertification.

1.3 Progress in studies of desertification reversal

Because of the reduction of anthropogenic pressure or the adaption of land use and management techniques, the desertification trend in some regions can be actively or passively stopped or even a reversal can be caused.

1.3.1 Concept of desertification reversal

Desertification was once taken as an irreversible process (Nicholson et al. 1998). However, some studies showed a vegetation recovery over great areas in the Sahel from 1982 to 1999 (Eklundh 2003; Herrmann et al. 2005) and a significant decrease in the area of the Sahara desert in the period between 1884 and 1994 (Tucker and Nicholson 1999). Recent studies demonstrated that desertification can be reversed by long-term removal of livestock and the reduction of grazing intensity (Allington and Valone 2010).

Although there have been some studies on desertification reversal, a scientific definition for desertification reversal is still not documented. Hence, we defined the desertification reversal as a process of desertified land recovering to a less desertified status, following with a series of changes in vegetation condition, soil properties and microclimate, due to natural or anthropogenic factors including climate change and livestock removal.

1.3.2 Mechanisms of desertification reversal

There have been relatively less studies on land desertification reversal, especially on the reversal mechanisms (Allington and Valone 2010; Castellano and Valone 2007). Previous studies attributed the reversal of desertification to any of the following reasons: Climate change (Zhou W. et al. 2013), human activities such as livestock removal (Zhou L. et al. 2013) and ecological projects, e.g. Grain for Green project in China. Grain for Green is a Chinese national project, in which farmers grow trees instead of crops on steep slope croplands, and get in kind by grain or cash from the government as a compensation; this project is aimed to increase forest cover and to prevent soil erosion (Uchida et al. 2005).

Climate change provides a background for the development of desertification. Since it plays a role in the development of desertification, it can also have effects on desertification reversal. Some studies suggested that desertification reversal can be controlled by climate change or human activities or their combined effect in different periods (Xu et al. 2009; Xu et al. 2010; Xu et al. 2014). Desertification reversal was mainly driven by climate change on the Ordos Plateau between 1980 and 1990 (Xu et al. 2010). Climate change accounted for the majority proportion of desertification reversal (Zhou W. et al. 2013), but limited the reversal of desertification in the reversed district, during the stable period of desertification process, in which the area of desertified district was equal to that of reversed district (Wang et al. 2012). Multiple years of humid condition, will typically lead to a succession from desertified shrubland to grassland (Peters et al. 2012). Human activities play an important role in regulating the direction of desertification: development or reversal. The reduction of anthropogenic influence such as live stock removal (grazing ban) can promote the reversal of desertification. Desertification reversal was reported to be dominantly controlled by human activities between 1990 and 2000, and also between 1980 and 2000 on the Ordos Plateau in China (Xu et al. 2010).

It is believed that the speed of desertification reversal keeps the same when the implemented degree of grazing reduction is more than 40 percent of the complete ban (Zhou L. et al. 2013). But a grazing ban is quite necessary for the commencement of desertification reversal. A major assumption for the proposed desertification models was put forward holding the view that an increment in soil nutrient concentrations (Fig. 7) and water infiltration (Tab. 2) are related to desertification reversal, based on long-term removal of grazing (Allington and Valone 2010).

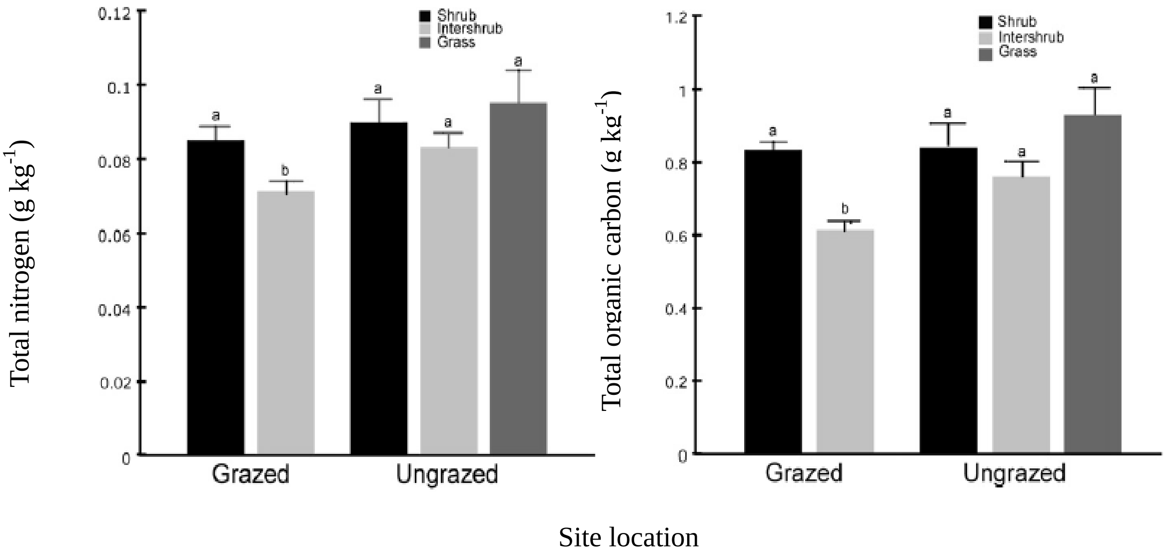

Fig. 7: Comparison of soil nutrient concentrations in different locations under reversal (ungrazed) and without reversal (grazed) from desertification in Chihuahuan Desert. Different letters show differences at P < 0.05 level (from Allington and Valone (2010), changed)

Tab. 2: Comparison of soil water infiltration under reversal (ungrazed) and without reversal (grazed) from desertification in Chihuahuan Desert (from Allington and Valone (2010), changed)

Reversal state	Soil infiltration (mm (10 min)$^{-1}$)	Changes with reversal	t value	P value
Grazed	48.2 ±1.3	24%	4.8	< 0.001
Ungrazed	59.8 ±1.6			

A study based on remote sensing reported an obvious reduction in both the area and degree of the grassland desertification after the implementation of grazing ban policy, although the direction of climate change in this period was not favorable for vegetation recovery in this area (Li et al. 2013). All these studies demonstrated that desertification reversal is effectively promoted by grazing ban (livestock removal). Climate change is sometimes documented to coincidence with land management adaptation for the reversal of desertification. A combined effect of climate change and human activities was concluded to be the dominant driving factor for desertification reversal in the agro-pastoral region in Northern China between 2000 and 2010 (Xu et al. 2014). The combined effect is especially strong when their effects on desertification reversal are in the same direction. Several other studies have observed this combined effect (Xu et al. 2009; Xu et al. 2010; Xu et al. 2014). Human activities should therefore take climate into consideration for a further reversal of desertification.

1.4 Changes of plant physiological properties

Ecological theory proposed that leaf traits should respond to and be in agreement with changes in the environment (Baruch 2011). So we propose the hypothesis that there are a series of responses for leaf traits to the reversal of sandy desertification. However, leaf traits have been mainly concerned on specific leaf area (leaf area per unit dry matter of the leaf), leaf C and N content; less studies have taken into account leaf traits as leaf area, leaf length, leaf width, and leaf perimeter, which are related to the leaf size and are apparent indices for plant species adaptation to changes in the environment (Waite and Sack 2010). Specific leaf area is a leaf trait better for interspecies comparison, but leaf area and other size related leaf traits are appropriate parameters for a study of intraspecific changes responding to the reversal of sandy desertification.

1.4.1 Changes in leaf traits

Leaf traits have been taken as factors having effects on the acquirement and processing of resources in plants (Wei et al. 2011), and are especially important for water keeping, carbon fixation, and energy balance (Ackerly et al. 2002). As one of the leaf traits, leaf area is an important biological indicator in response to the availability of soil water (Ustin et al. 2009) and long-term water use efficiency (Baruch 2011). Numerous studies have proved the relations between leaf area and many other leaf properties such as chlorophyll content, dry matter content, and photosynthetic rate (Alt et al. 2000; Gamon et al. 1993; Ustin et al. 2009).

But few studies have been carried out in terms of changes in leaf area in desertified ecosystems. Wei et al. (2011) reported that leaf areas of seven native species are all larger than a non-native species in an area of karst desertification in southern China. The native species in Wei et al. (2011) are as follows: *Cyclobalanopsis glauca* (Thunb.) Derst, *Syzygium cumini hainanense* Chang et Miau, *Cephalomappa sinensi* (Chun et How) Kosterm, *Sterculia lanceolata* Caw., *Ligustrum lucidum* Ait., *Sapindus mukorossi* Gaertn., and *Cleidiocarpon cavalerei* (Levl.) Airy Shaw; the non-native species is *Cinnamomum camphora* (Linn.) Presl (Fig. 8); the comparison between these eight species was aimed to test whether there were differences in leaf traits between native and non-native species.

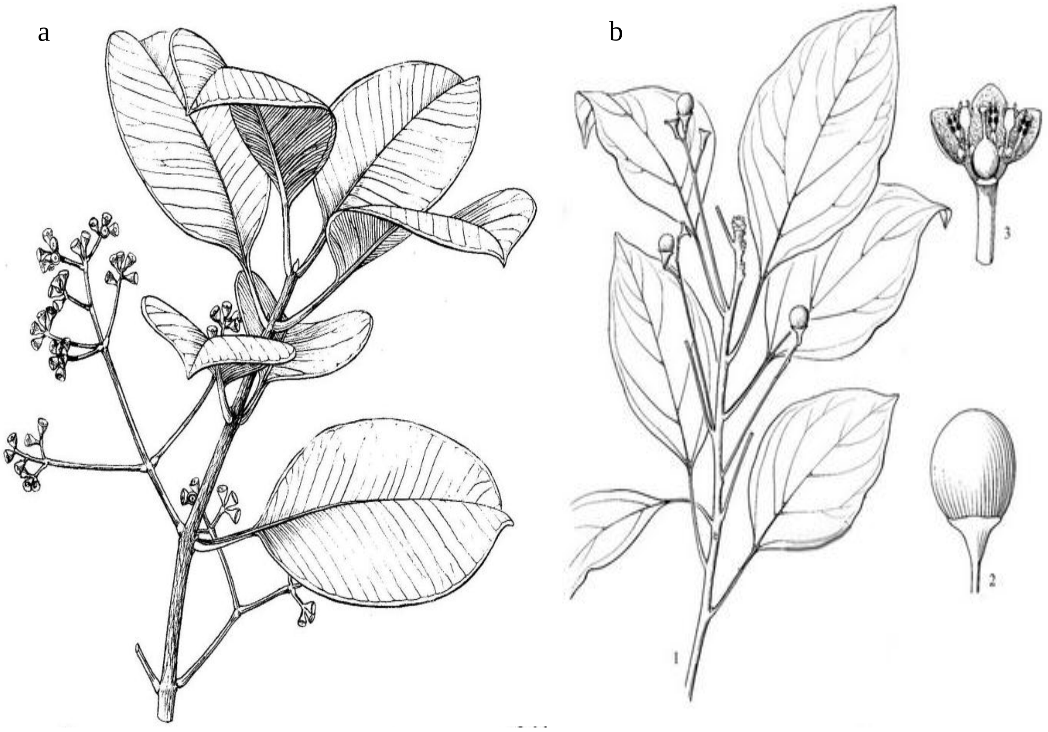

Fig. 8: Illustrations of *Syzygium cumini* (a) and *Cinnamomum camphora* (b) (from Flora of China (2015), changed) In Fig. b: 1 Fruiting branch, 2 Fruit, 3 Flower with three tepals removed

However, how leaf area responds to the reversal of sandy desertification is still not clear. A study of changes in leaf area and other leaf traits in the process of desertification reversal is helpful for understanding the mechanisms of desertification reversal in terms of vegetation and plant morphology changes.

1.4.2 Changes in leaf chlorophyll content and photosynthesis

C_4 plants have higher photosynthetic capacity compared with C_3 plants due to higher CO_2 concentration near the Rubisco in C_4 plants than that in C_3 plants (Yin et al. 2011). This CO_2 concentration mechanism is clear, but whether there is any difference in photosynthesis with regard to leaf chlorophyll content between C_4 and C_3 plants and whether they get any adaptive change with the reversal of sandy desertification, still need further investigations. In this part we focus on the changes of leaf chlorophyll content of *Pennisetum centrasiaticum* (C_4 plant) and *Leymus secalinus* (C_3 plant) and the photosynthetic characteristics of *L. secalinus* with the reversal of sandy desertification.

There have been numerous studies on leaf photosynthesis for desert plants, but these studies are mainly about plant photosynthesis in desert ecosystems affected by environmental factors, such as temperature (Downton et al. 1984; Lawson et al. 2014; Seemann et al. 1986; Xue et al. 2011), light (Lawson et al. 2014; Lehner et al. 2001; Nilsen et al. 1989), radiation (Hui et al. 2014; Yan et al. 2008), elevated CO_2 (Ellsworth et al. 2004; Hamerlynck et al. 2000;

Huxman and Smith 2001), oxygen (Glacoleva et al. 1978), precipitation (Barker et al. 2006; Yan et al. 2000), soil water status (de Soyza et al. 2004; Ogle and Reynolds 2002; Schulze et al. 1980; Szarek and Woodhouse 1978; van Heerden et al. 2007), soil nitrogen content (Lajtha and Whitford 1989; Nyongesah and Wang 2013), leaf position (Wang et al. 2005), and herbivory (Zhu C. G. et al. 2014). Rare studies have considered the effects of changes in the whole desert ecosystem on leaf Chl content and photosynthesis (Kappen et al. 1976; Nobel 1978). These changes may include variations in many environmental factors and may pose a comprehensive effect on plant Chl content and photosynthesis.

Chlorophyll (Chl) is the major photosynthetic pigment and an essential part of the photosystem in the leaves of higher plants. It plays an important role in photosynthetic processes including absorption and exploitation light energy, and therefore directly affects the photosynthesis rate (Zhang K. P. et al. 2009). Moreover, Chl is regarded as an indicator for the overall condition (Wu et al. 2010), growing state, and photosynthetic capacity (Wu et al. 2011) of a plant. Chl content is also an indication for the nutrition status, stress, and mutation of the plant measured (Wu et al. 2008). Numerous studies have reported positive correlations between leaf Chl content and photosynthetic rate (Gratani et al. 1998; Hu et al. 2009; Naidu and Swamy 1995). Leaf Chl content is thus an important parameter of great interest for plant physiological studies (Xie et al. 2007).

Many studies about factors influencing leaf Chl content have been carried out focusing on different issues, such as soil nutrient (Singh et al. 2001; Zhao et al. 2001), salt (Yan et al. 2012; Yasar et al. 2008) or drought (Viljevac et al. 2013; Wang et al. 2008; Zhang et al. 2011) stress, nitrogen fertilization (Zhang X. et al. 2013), heavy metal accumulation (Vajpayee et al. 2000; Vassilev et al. 1998), genetic differences (Song M. et al. 2014; Zhang et al. 2009), temperature changes (Todorov et al. 2003; Vågen et al. 2003), and microorganisms (Suzuki et al. 2014; Vafadar et al. 2014).

Simultaneously, a number of studies have been conducted focusing on the factors affecting plant photosynthetic characteristics, such as soil water (Gorai et al. 2015; Zang et al. 2014; Zhou et al. 2014), nutrient (Bungard et al. 2002; Evans and Terashima 1987; Zhu F. et al. 2014), salinity (Maimaiti et al. 2014; Omoto et al. 2012; Sultana et al. 1999), light density (Graßes et al. 2001; Zhu J. et al. 2014), heat stress (Salvucci and Crafts-Brandner 2004; Zhang J. et al. 2014; Zhao et al. 2014), CO_2 elevating (Yu et al. 2014; Zhu C. W. et al. 2014), and herbivory (Delaney 2012; Tang et al. 2006; Zhu C. G. et al. 2014). Some studies showed that plant photosynthesis is affected by multiple factors (Geissler et al. 2009; Sharkey and Loreto 1993; Yang et al. 2010), such as a combined effect of temperature, N status, and increasing CO_2 (Borjigidai et al. 2006); and the photosynthetic rate of seedlings under drought conditions can be kept in a higher level by increased CO_2 (Zong and Shangguan 2014).

Previous studies showed that stress of soil resources such as water (Basu et al. 1998; Rahbarian et al. 2011; Zhang et al. 2011), nitrogen (Arora et al. 2001; Chapin et al. 1988; Zhang L. et al. 2014) and salt (Moradi and Ismail 2007) can reduce leaf Chl content and/or photosynthesis rate significantly. Water deficiency reduces leaf photosynthesis rate by affecting a series of changes in plant physiological properties and processes, including water potential reduction, stomata closure, changes in the content of photosynthetic pigments, and photosystem efficiency changes (Rahbarian et al. 2011). Nitrogen stress affects leaf photosynthesis by causing an oxidative stress due to a disturbance of water and nutrient accumulation and transportation between different parts of the plant (Zhang L. et al. 2014). Salt stress may reduce plant photosynthetic rate by decreasing the turgor of guard cell and so affect the stomatal resistance directly (Dionisio-Sese and Tobita 2000; Moradi and Ismail 2007).

Several environmental parameters, such as soil water, nutrients, and other physical and chemical properties may change extensively during the process of desertification reversal. Moreover, vegetation may also change largely associated with soil properties. Changes in environmental factors may result in changes in leaf Chl and photosynthetic characteristics, accordingly. A deficiency of soil resources may limit the growth and cause shortage stress on plant physiology. Plants may thus undergo adaptive changes in the reversed areas in terms of physiological properties.

However, few studies have been carried out on leaf Chl content on the background of land desertification. Farghali (1998) found general low contents of leaf Chl for xerophytes. Its total Chl content ranged from 0.10 to 1.83 mg g^{-1} leaf fresh weight. Farghali (1998) also found higher contents of leaf Chl for perennials than for annuals. The total content of perennials and annuals ranged from 0.25 to 1.83 mg g^{-1} leaf fresh weight and from 0.08 to 0.88 mg g^{-1} leaf fresh weight, respectively. While Hernández-González and Villarreal (2007) investigated how cactus leaf Chl was affected by light, Aziz (2007) studied the seasonal changes of plant Chl content in relation to water status.

There is still a lack of knowledge about changes in leaf Chl and photosynthesis rate with regard to common species in areas with different degrees of reversal in the process of desertification reversal. Although it is clear that soil N and P availability influences leaf photosynthesis rate and Chl content for understory species in tropical forest (with rich N) (Zhu F. et al. 2014), its data for common species in temperate and desertified grassland is lacking. This study of the leaf Chl content and photosynthetic characteristics in different reversal stages will provide some information about the mechanisms of desertification reversal at the individual specimen level.

1.5 Changes of vegetation characteristics

As one of the most prominent elements in terrestrial ecosystems, vegetation plays an important role in the process of desertification reversal. We selected the following variables as vegetation characteristics in the present study: plant cover, plant biomass, plant species richness, diversity and evenness.

Plant cover is one of the elementary characteristics of vegetation and is regarded as a practicable indicator for ecological monitoring of grassland desertification in arid and semiarid areas (Qin et al. 2008).

Biodiversity is another very important characteristic of vegetation. Loss of biodiversity was worried to be promoted by desertification (Ricketts et al. 1999). The millennium ecosystem assessment (2005) proposed that desertification contributes significantly to biodiversity loss, which is alleviated by desertification combat.

There are several studies of animal biodiversity in the context of desertification (Bestelmeyer 2005; Whitford 1997), but studies on plant biodiversity in desertified grasslands are relatively scarce. Fang and Peng (1997) investigated the species diversity response to vegetation restoration in a degraded tropical ecosystem in China and found a rapid enlargement of species diversity after the recovery of vegetation. However, there is still a particular lack of knowledge about how plant biodiversity interacts with the reversal of sandy desertification.

Previous studies demonstrated that many ecological factors such as grazing (Belsky 1992), competition (Wardle and Barker 1997), herbivory (Wardle and Barker 1997), disturbance (Belsky 1992), soil properties (Fattahi and Ildoromi 2011) and fire (Belsky 1992) have significant effects on plants at the following levels of resolution: plant population, plant community, and even the whole ecosystem. However, research investigating the effects of desertification reversal on plant species diversity, which plays an important role in the process of desertification reversal by regulating plant community structure and plant species distribution, is scarce so far. The present study considering desertification reversal as an ecological factor is therefore helpful for our understanding on the mechanisms of desertification reversal.

1.6 Relationships between soil and vegetation

The relationship between soil and vegetation is one of the essential issues which need to be considered for desertification reversal by recovering vegetation (Su et al. 2005). Many studies have shown strong relationships between soil and vegetation in various types of ecosystems (Abd el-Ghani and Amer 2003; Chigani et al. 2012; M. et al. 1990; Silva and Batalha 2008; Thwaites and Cowling 1988; Zuo et al. 2009a). Positive correlations were shown between plant species richness and the spatial heterogeneity of soil depth (Lundholm 2009; Lundholm and Larson 2003).

Vegetation establishment was reported to be determined mainly by soil in old arable land(Cañadas et al. 2010). Higher content of soil cations and clay were found to be related to a forest ecosystem than to the Cerrado. (Ruggiero et al. 2002). The Cerrado is a savanna eco-region of Brazil. Soil properties such as salinity, pH, water content, and available nitrogen were shown to be the predominant soil factors in determining the vegetation pattern of coastal regions (Li W. et al. 2008).

These studies focus on relationships between soil and vegetation in different ecosystems, showing that there are close relationships and interactions between soil and vegetation characteristics in specific areas. They provide us with a perspective to highlight on recognizing soil-vegetation relationships, which may strongly regulate the development of an ecosystem. However, there is still a lack of knowledge about soil-vegetation relationships in desert ecosystems. Our understanding on the quantitative relationships between soil and vegetation in arid and semi-arid regions is still very limited. A study of the soil-vegetation relationships in the process of desertification reversal is especially required. This study will investigate the soil-vegetation correlations and the predictive soil factors in regulating vegetation characteristics in the process of desertification reversal. This will be especially useful for understanding the process of desertification reversal and give important information for land management and vegetation restoration.

There are some studies concerning prediction modes for plant species diversity in several ecosystems. Lundholm and Larson (2003) suggested flooding and ramet density as the major factors determining plant species richness and evenness. Chawla et al. (2010) found positive correlations between plant species diversity and concentrations of soil nutrients, including organic C, total N, and available N. Predictive models for plant species diversity provide us with quantitative information about relationships between vegetation characteristics and soil properties. Studies on such kind of models show apparently which soil properties are the predominant factors for plant species diversity and how they each predict it quantitatively. Soil-vegetation relationships showed in these studies are meaningful for the understanding of the development of an ecosystem.

However, plant species diversity is only one of the aspects of vegetation characteristics. Vegetation is a comprehensive element for an ecosystem and investigations should include some other important characteristics, such as plant cover and plant biomass. Simultaneously, the number of soil properties that are used in the prediction analyses should also be enough, including soil physical properties, soil nutrients, and soil biological activities. Otherwise, some important factors may be omitted, which will lead to a severe deficiency of the built model. Hence, to better understand the development of an ecosystem, comprehensive multiple regression analyses for vegetation characteristics including plant cover, plant biomass, species richness, species diversity, and species evenness are necessary. On this purpose, we analyzed many of the common tested physical and soil chemical properties, and soil biological activities and conducted a series of multiple regression analyses for all the vegetation characteristics mentioned above in this study, based on the correlation analyses.

For this part, we posed the following questions. (1) How can each characteristic of vegetation (i.e. plant cover, plant biomass, plant species richness, plant species diversity, and plant species evenness) be predicted by soil properties? (2) Are all vegetation characteristics predicted by the same, or similar, or very different soil properties? (3) What are the implications of predictive factors for the reversal of sandy desertification? Simultaneously, we propose the following hypotheses. (1) Each characteristic of vegetation (i.e. plant cover, plant biomass, plant species richness, plant species diversity, and plant species evenness) can be predictive by different soil properties. (2) The predictive factors for all vegetation characteristics are similar and often overlap. (3) The predictive factors can interpret the mechanisms of the reversal of sandy desertification from the aspect of vegetation restoration.

2 Study site description

2.1 Overview of the study area

The study was conducted in Yanchi County in Ningxia Hui Autonomous Region in northern China. Yanchi County is located in the east of Ningxia (106°30′ E - 107°47′ E, 37°04′ N - 38°10′ N) (Fig. 9). It is adjacent to Inner Mongolia in the north, to Shaanxi province in the east, to Gansu Province in the south, and to Tongxin County in the west (Li and Zhang 1995). Yanchi County extends 110 km from north to south and 66 km from west to east. The area of the whole county is 8661.3 km^2 (Compilation committee of the Ecological Construction Annals of Yanchi County 2004).

Yanchi County is located in the southwestern part of "Mu Us Sandy Land". The environmental conditions in this area are relatively unfavorable for agriculture with strong winds, sandy soils and low precipitation. Yanchi County underwent both severe land desertification and reversal in the last 50 years (Chen and Duan 2009; Zhou and Zhao 2005) due to a combined effect of environmental change and human activities. Land desertification in this area developed rapidly from 1961 to 1989 and showed a decreased tendency after 1989, but the desertification was still very severe until 2000 (Zhou and Zhao 2005). Human activities including over grazing, over cropping, deforestation and over excavation of medicinal plants played an important role in the development of desertification in Yanchi County (Zhou et al. 2010). The desertification in this area showed a substantial reduction in 2003 (Tab. 3) (Zhou and Zhao 2005). Land desertification in Yanchi County has partially become reversed in the recent ten years. The grazing ban policy has played an important role in the recent desertification reversal (Zhou et al. 2010).

Tab. 3: Changes in the area (km^2) of desertification in Yanchi County (from Zhou and Zhao (2005), changed)

Year	Shifting sandy land	Semi-fixed sandy land	Fixed sandy land	Total area of desertification
1961	204.13	214.96	587.02	1006.11
1983	394.90	158.99	78.52	1225.80
1986	440.20	422.70	274.40	1090.42
1989	1032.70	997.00	337.90	2366.67
1995	547.20	700.80	268.00	1515.96
2000	424.10	743.30	145.60	1313.02
2003	63.18	166.55	207.96	455.75

Fig. 9: Location of Ningxia in China, and Yanchi County in Ningxia (from Hui Family in Ningxia (2015), changed)

2.2 Geographic and topographic features

Yanchi County is composed of two parts with different topographical features. The southern part is the region of Loess Hills and accounts for 20% of the whole area of the county; the northern part is the relative flat region with many mounds and accounts for 80% of the whole county area (Compilation committee of the Ecological Construction Annals of Yanchi County 2004). The altitude above sea level of Yanchi County ranges from 1295 to 1951 m, with ground surface higher in the south than that in the north (Li and Zhang 1995). The altitude above sea level of the southern part is higher than 1600 m, whereas that of the northern part is almost between 1400 m and 1600 m. The northern part lies in the southwestern corner of Ordos Plateau (Fig. 10). Yanchi County is a transitional region in topography from the Loess Plateau (Fig. 11) in the south to the Ordos Plateau in the north. Gullies are distributed all over in the south. In contrast, the land is open and flat in the north (Compilation committee of the Ecological Construction Annals of Yanchi County 2004).

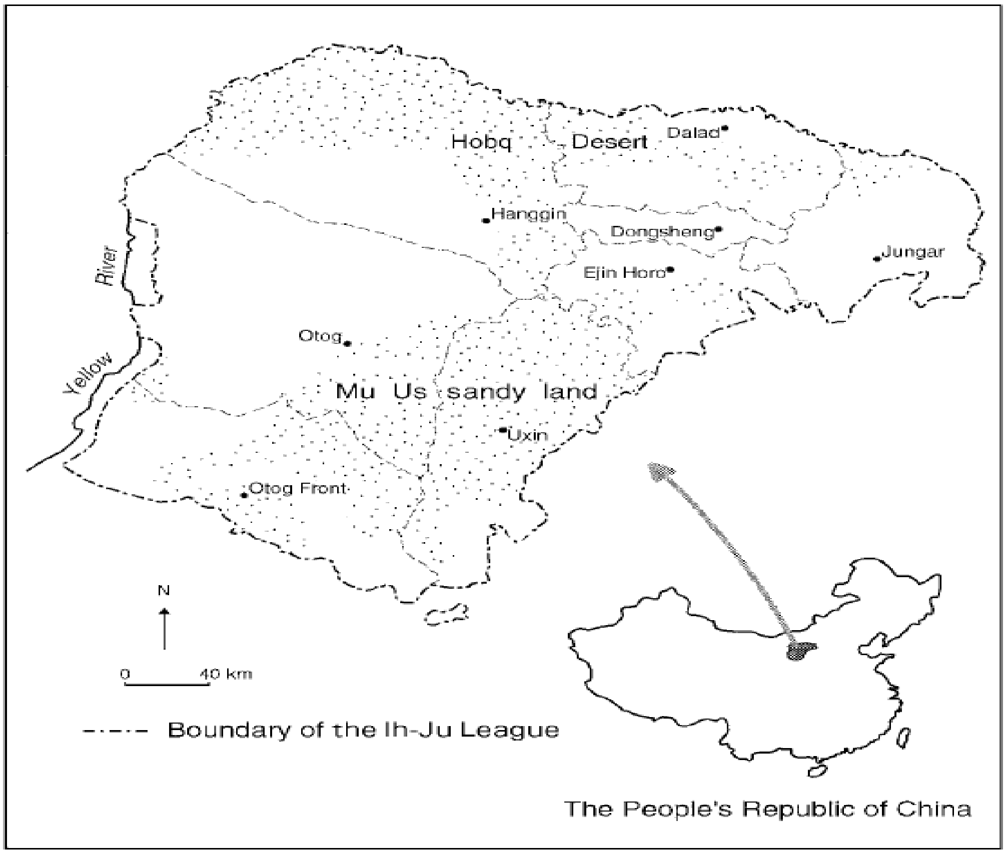

Fig. 10: Map of Ordos Plateau and its location in China (from Jiang (1999), changed)

Dots display sand cover

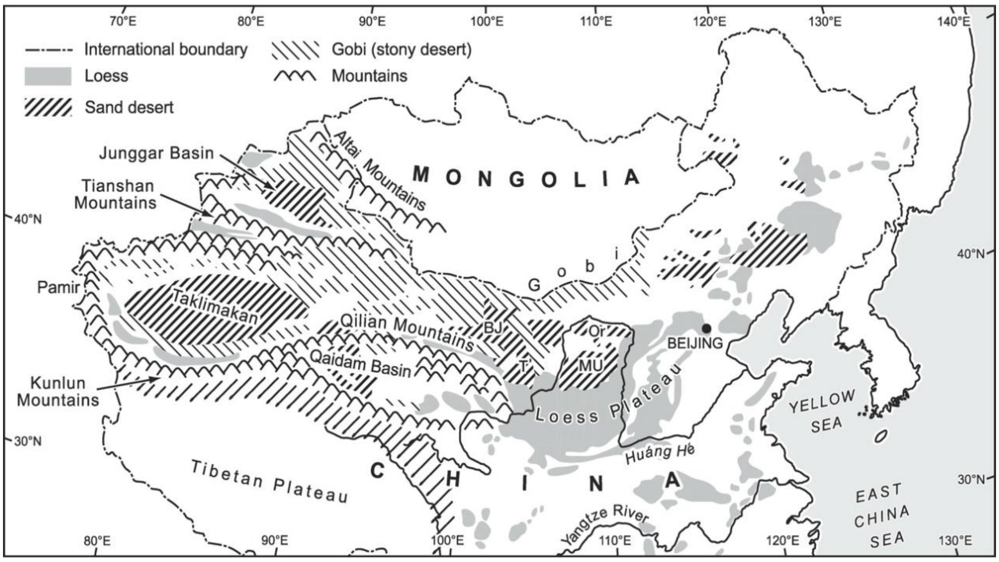

Fig. 11: Map showing the location and extent of Loess Plateau in China and surrounding deserts and sandy land (from Maher et al. (2009), changed)

Or: Ordos Plateau; BJ: Badain Juran Desert; T: Tengger Desert; Mu: "Mu Us Sandy Land"

In addition, Yanchi County is also a transitional region in climate from the semi-arid area to arid area, in vegetation from dry steppe (Fig. 12) to desert steppe (Fig. 13), and in land utilization from agricultural area to pastoral area. This transitional feature in geography results in a diverse, harsh, and vulnerable characteristic of the environmental conditions in Yanchi County, typical of ecotone boundaries (Li and Zhang 1995).

Fig. 12: Photo of vegetation in the southern part of Yanchi County, China

Fig. 13: Photo of vegetation in the northern part of Yanchi County, China

2.3 Climate

We describe here the climate conditions only for the northern part of Yanchi County because our study sites are all located in the northern part. The climate in this area belongs to a mid-temperate continental climate and is deeply influenced by dry and cold air from Mongolia and Siberia in winter time. This results in long winters and short summers with large daily and annual temperature differences. The annual precipitation amount is low. In addition to the long sunshine duration, evaporation and erosion are affected by strong wind (Li and Zhang 1995). The climate diagram of Yanchi County is shown in Fig. 14.

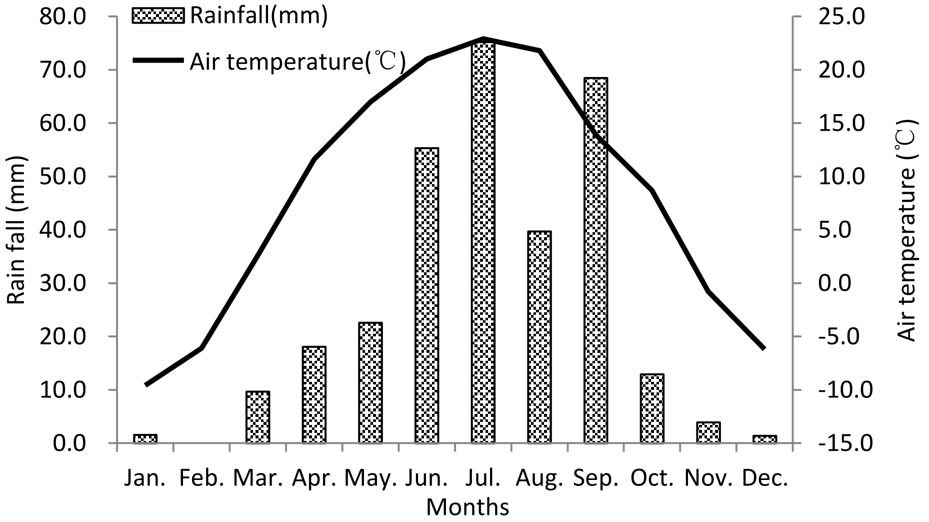

Fig. 14: A climatic diagram for Yanchi County in 2012

The annual total solar radiation is 5924.1 MJ m^{-2}. The total solar radiation during the growth period (from May to August) is 2641.4 MJ m^{-2}, which takes up 44.6% of the annual total solar radiation. The annual total sunshine duration is 2867.9 h and the sunshine percentage is 63% (Li and Zhang 1995). The annual mean temperature is 8.1 ℃ (Chen and Duan 2009). The mean temperature of the hottest month (July) is 22.3 ℃ and that of the coldest month (January) is -8.9 ℃. The highest temperature measured is 38.1 ℃ and the lowest is -29.6 ℃. The diurnal temperature variation is 14.1 ℃. The period with daily average temperature above 0 ℃ is 243 days and the cumulative temperature for this period is 3526 ℃. The period with daily average temperature above 10 ℃ is 158 days and the cumulative temperature for this period is 2944.9 ℃. The period of daily mean temperature for many years which is stably higher than 0 ℃ is 243 days and the cumulative temperature for this period is 3526 ℃. The period of daily mean temperature for many years which is steadily more than 10 ℃ is 158 days and the cumulative temperature during this period is 2944.9 ℃ (Li and Zhang 1995).

The average frostless period is 165 days (Chen and Duan 2009) and ranging from May 16th to September 22nd

(Li and Zhang 1995).The annual precipitation is 296.4 mm, whereas in some northern areas like Gaoshawo, where some of our study sites are located, the value is even less than 250 mm. The precipitation falls mainly between July and October. The annual evaporation is 2179.8 mm and the aridity index is 3.1 (Li and Zhang 1995). The annual average wind speed (only for 2010 and 2011) is about 2 m s^{-1} and the maximum wind speed is 15.8 m s^{-1} (only for 2010) (Statistical Bureau of Wuzhong 2012). Strong wind weather (wind speed > 8 m s^{-1}) occurs in average more than 23.4 times in a year (Chen Y. et al. 2014).

2.4 Vegetation

There is a total area of 5.57×10^5 hm^2 of steppe in Yanchi County, taking up 65.1% of the total area of the county (Zhou and Chen 2014). The vegetation in Yanchi County belongs to the middle Asia grassland subzone of Eurasian grassland zone and is a transitional vegetation type ranging from Loess Plateau to Ordos Plateau (Li and Zhang 1995). The vegetation feature can be summarized as follows: the number of plant species and genera is relatively few; the structure of plant communities is relatively simple; the plants have a high content of dry matter and protein, and a high capability of drought and cold resistance (Jiang 1983). The vegetation types in Yanchi County include shrub land, grassland, meadow, sandy land (dune) vegetation and desert vegetation (Qiao et al. 2006). The main types are typical steppe and desert steppe (Li et al. 2013). There are no natural forests in this county and only a small amount of artificial forest, but shrubs (such as *Salix psammophila* and *Caragana microphylla*) cover a large area (Qiao et al. 2006). Vegetation in the typical steppe is composed mainly of xerophytic and mid-xerophytic plant species, such as *Agropyron cristatum*, *Stipa grandis*, *Stipa bungeana*, and *Thymus serpyllum* var. *mongolicus* (Qiao et al. 2006). Desert steppe includes species like *Oxytropis aciphylla*, *Agriophyllum squarrosum*, and *Salsola beticolor*. The plant community of field investigation in Yanchi County is shown in Tab. 4.

Tab. 4: Sandy land vegetation in Yanchi County

1. *Artemisia ordosica* - *Leymus secalinus* - community

1.1 Unit of *Salsola beticolor*

1.2 Unit of poor differential plants

1.1.1 Typical variant

1.1.2 Variant of *Glycyrrhiza uralensis*

1.1.3 Variant of *Chenopodium album*

Continuous number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29			
Plot number	23	24	25	26	21	28	20	27	2	19	22	17	14	15	16	18	10	11	1	4	5	6	9	29	7	8	12	3	13			
Area of the plot (m ^{2})	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10			
Plant cover (%)	40	10	55	36	14	19	25	37	16	49	59	8	27	24	28	66	47	34	41	53	34	29	55	3	19	3	15	5	5			
Number of species	8	10	11	6	12	10	15	7	16	16	16	14	19	15	17	12	10	15	17	16	13	14	20	5	6	5	10	5	7	Absolute continuity	% Continuity	Class of continuity
Characteristic species																																
Artemisia ordosica	+	+	+	2	+	+	+	1	2	2	+	+	2	+	+	+	1	2	2	2	2	2	+	+	+	1	+	1	+	29	100	V
Leymus secalinus	+	1	2		1	1	1		1	1	3		2		2		2	+	1	3	+		2	r			+	+	r	21	72	IV
Ixeris chinensis	3	r	1	1	+	r	r	r	1	2	1	+	1	1	1	+	r	+	+	1	1	1	+		r					24	83	IV
Differential species																																
Salsola beticolor	1	r	r	1	2	+	2	r	r	+	+	1	1	1	1	+				2		r								18	62	IV
Artemisia scoparia	r	r	3					1		2	2	r	1	2	r	4	3		3				+							14	48	III
Setaria viridis	2	r	+	1	1	r	2			+	1	1	r	+	+				1	r			r							16	55	III
Glycyrrhiza uralensis										r	r	+	r	+	+	+														7	24	II
Peganum nigellastrum													1		r	+														3	10	I
Tribulus terrestris							+				r	r			r															4	14	I
Chenopodium album																	1	1	1	1	1	1	+							7	24	II
Heteropappus altaicus																	r	+		2	1	r	+							6	21	II
Thermopsis lanceolata																		+	r		2	2	r							5	17	I
Companions																																
Pennisetum centrasiaticum			r			r		3	r							+	r	+	1	3	2	r	2		1	+	r	+	r	17	59	III
Cleistogenes squarrosa			1				r		1	1	r				+	1	r	2	2	+	+	2	3				r		r	16	55	III
Euphorbia humifusa					+		1	r	1	+	r	r		r	r			r	1	+	+		1			r				15	52	III
Bassia dasyphylla	+			r		1	r	r		+	1	r	r	+		1			+					+						13	45	III
Agriophyllum squarrosum	1	1			1	2	+		r															1	1	r	r		+	11	38	II
Agropyron mongolicum		r	+			r			r	r	2		+				1	+					+							10	34	II
Lespedeza potaninii									r		r	r	2	+	1							r					r		r	9	31	II
Echinops gmelini		r	+						r			r	+	r		r					r									8	28	II
Gueldenstaedtia stenophylla													r	r	r			+				r					r	+		7	24	II
Cuscuta chinensis					r		+			+		r	r	1		r														7	24	II
Euphorbia esula					r				+		r		r	+	r				r											7	24	II
Kochia scoparia									1			+		r								r			r			+	r	7	24	II
Chenopodium acuminatum					r		+			2	r		r			1			+											7	24	II
Sophora alopecuroides									r								1	+	r				+				2			6	21	II
Astragalus melilotoides				+									r							r	+	+					2			6	21	II
Oxytropis racemosa							r					+	+					r							2					5	17	I
Cynanchum komarovii					r				r	r										r										4	14	I
Panzeria alaschanica					+		r			r																				3	10	I
Hedysarum mongolicum																								r		r	r			3	10	I

Setaria arenaria																		+			r		1								3	10	I
Stipa bungeana			1																	r		r									3	10	I
Cynanchum thesioides						r				r																					2	7	I
Stipa breviflora																		2					1								2	7	I
Plantago asiatica																				+		r									2	7	I
Incarvillea sinensis													r						r												2	7	I
Typha minima																				r	r										2	7	I
Salix psammophila		r																													1	3	I
Oxytropis aciphylla															+																1	3	I
Inula salsoloides									r																						1	3	I
Olgaea leucophylla															r																1	3	I
Polygala tenuifolia															r																1	3	I
Equisetum ramosissimum																			+												1	3	I
Polygonum aviculare																			1												1	3	I
Artemisia dubia var. subdigitata																							+								1	3	I
Artemisia mongolica																							r								1	3	I
Silene conoidea																				r											1	3	I
Chenopodium glaucum											1																				1	3	I
Thalictrum aquilegifolium var. sibiricum																							+								1	3	I
Rubia cordifolia																							+								1	3	I
Allium mongolicum																							+								1	3	I
Plantago depressa														r																	1	3	I
Xanthium sibiricum							r																								1	3	I

2.5 Soil

There are nine soil types in Yanchi County, including sierozem, sandy soil, dark loessial soil, saline soil, new accumulative soil, meadow soil, planosol, heaping soil, and bare rock. The main types are sierozem and sandy soil (Chen and Duan 2009; ISSCAS 2001), the distribution area of which accounts for 39.7% and 38.0%, respectively, of the total soil area of the county. These two types of soils are distributed mainly in the northern part of Yanchi County, whereas dark loessial soil is distributed mainly in the southern part and occurs 18.9% of the total soil area of the county. The area of the other five types of soils accounts for only a small proportion (Li and Zhang 1995).

2.6 Study sites

The study sites were located in the desertified areas of Yanchi County. There were five large shifting sand dunes in Yanchi County. For example, the shifting sand dune in the middle of Yanchi County was about 9 km wide and 59 kilometers long. These shifting sand dunes were the main sandy desertification areas in Yanchi county (Compilation committee of the Ecological Construction Annals of Yanchi County 2004; Zhang K. B. 2003). However, with the implementation of the grazing ban policy in the recent ten years, the sandy desertification is getting reversed (Zhou et al. 2010). Some shifting sand lands were fixed by vegetation in the past years. The study sites were located in the former shifting sand dune and their adjacent areas. The study site of Nanhaizi, Haba, and Habahu were located in the former shifting sand dune of Habahu; the study site of Yuzhuangzi and Lijihaizi was located in the former shifting sand dune of Yuzhuangzi - Huangshawo; the study sites of Weizhuangzi and Machang were located in the former shifting sand dune of Weizhuangzi - Machang.

3 Methods and materials

3.1 Vegetation survey and soil sampling

The fieldwork was conducted in 2012 and 2013 during July/August, which typically includes the optimal phase of the vegetation period. Based on a detailed survey of the whole Yanchi County, we selected seven study sites of 25-100 ha in size. They distributed in the middle and northern part of Yanchi County. All the study sites were located in the previous typical desertification areas in Yanchi County. We selected sub-sites with different reversal stages of desertification at each site according to the proportion of the bare sand area and plant cover to the total area (Li et al. 2003; Li et al. 2013; Li et al. 2004; Verón et al. 2006; Zhu 1998). The proportion of the bare sand area was the main criterion, and that of plant cover was the secondary; when the bare sand area in a grassland satisfied the criterion of a reversal stage while the plant cover did not, this grassland was still classified to this reversal stage (Zhao et al. 2008). In most cases, however, the bare sand area and plant cover criterion both satisfied the attribution of a grassland to the same reversal stage.

Based on previous studies (Li et al. 2003; Li X. et al. 2006; Li Y. et al. 2006; Zhu et al. 2010) and the natural conditions of our study sites, the criteria of the reversal stages of desertification were set as follows: when the bare sand area accounts for more than 50% of the total land area, and plant cover is less than 10%, then this area is classified as "Very Severe Desertification" (VSD) (Fig. 15).

Fig. 15: Photo showing very severe desertification

When the proportions are 30-50% and 10-30%, respectively, then this area is sorted to "Severe Desertification" (SD) (Fig. 16).

Fig. 16: Photo showing severe desertification

When they take up 10-30% and 30-40%, respectively, of the whole land area, then this area is classified as "Moderate Desertification" (MD) (Fig. 17).

Fig. 17: Photo showing moderate desertification

When their proportions are less than 10% and 40-50% respectively, then this area is assigned to "Light

Desertification" (LD) (Fig. 18).


2013/07/31

Fig. 18: Photo showing light desertification

In addition, we also found four "Potential Desertification" (PD) (Fig. 19) sub-sites without bare sand and the plant cover adding up to more than 50%.


2012/08/11

Fig. 19: Photo showing potential desertification

These sub-sites were undergoing different stages of desertification reversal due to differences in factors such as grazing prohibiting time, micro-topography, and geographic location.

Three 1m × 1m quadrats were randomly established in each sub-site for herbaceous plants and 10 m × 10 m quadrats for shrubs and sub-shrubs. For each quadrat, the abundance, height, cover and frequency of every plant species were recorded. The abundance was counted one by one. The height was measured with the highest plant of each species in the quadrat. The cover was measured with needling method (Song 2001): Set 100 points homogeneously distributed in the quadrat with scaled wires and put a slender stick at each point with the stick vertically stretching into the quadrat (Fig. 20). The number of points where the stick encountered a given species in the quadrat was recorded as the cover of this species. The total plant cover of this quadrat is the sum of the covers of all plant species in it. But when the stick encounters more than one species at one point, the number of overlapped species at this point should be deducted from the total cover.

Fig. 20: Photo of investigating the plant cover in a quadrat

The above ground parts of all plants in the quadrat were then cut, collected, and weighed immediately. Parallel, an iron circle with a diameter of 0.5 m was used to survey the plant frequency (Wang et al. 1997). It was thrown randomly in the area around the quadrat for ten times and all the plant species enclosed within the circle were recorded every time (Fig. 21). The total times one species enclosed in the circle was taken as its frequency.

Fig. 21: Photo of investigating the plant species frequency

After vegetation survey, soil was sampled in a depth of 0-20 cm with an auger of 4 cm diameter. Soil samples were taken for five times and the sampling points homogeneously distributed in each quadrat. All samples taken from the same quadrat were then mixed together as one sample. Additional samples were taken for the analyses of soil water content and soil bulk density.

Soil bulk density was analyzed with the cutting ring method (Fig. 22). The sampling process is showed as follows: Put the cutting ring on the ground surface and press it into the soil vertically to the ground surface from the top side of the cutting ring, until the whole cutting ring is filled with soil. Then cut the soil around the cutting ring and take out the whole cutting ring with soil in it. Cut off all surplus soil beyond the cutting ring on the bottom side and close both sides to avoid water evaporation. Lastly, weigh the cutting ring with soil in it immediately. The cutting ring was weighed before the sampling. Soil samples were then taken to the laboratory for water content measurement. Soil water content was measured with drying method.

Fig. 22: Photo of taking soil samples for the analysis of soil bulk density with cutting ring method

3.2 Plant leaf sampling

Two common species in different stages of desertification reversal, *Leymus secalinus* and *Pennisetum centrasiaticum*, were studied. All the sampled leaves for both species were "climax leaves" in the center of the plants. Each plant was sampled only for one time. 8-12 individual plants were randomly selected and sampled in each reversal stage of desertification. The selected plants for sampling were all mature individuals and were in the same stage in their lives. All sampled leaves were cut at the base of the leaf blade and thoroughly unfolded to scan immediately with Leaf Area Meter AM 300 (ADC BioScientific Ltd.) (Fig. 23). Leaf area, length, width, and perimeter were calculated by the meter after scanning.

Fig. 23: Photo of the Leaf Area Meter AM 300

3.3 Field monitoring

In the field, micrometeorology, soil respiration, plant photosynthesis, and plant leaf Chl content were monitored and measured.

The micrometeorological indices were monitored on sunny day. Geothermometers were set at the study site before the day of monitoring. Each sub-site of reversal stage had a set of meteorology meter for monitoring and all meteorological parameters were measured at each full hour from 8.00 to 19.00. All sub-sites were monitored at the same time. Soil temperature was measured at the depth of 5 cm, 10 cm, 15 cm, and 20 cm, with a bend tube geothermometer. Solar illumination was measured with CEM/ DT1301 Light Meter. Wind speed was measured with 16025 Cup-type Anemometer.

Soil respiration was measured with an EGM-4 Portable Environmental Gas Monitor (PP Systems) (Fig. 24) for CO_2. The measurement was conducted once for every two hours from 8.00 to 12.00.

Fig. 24: The measurement of soil respiration with EGM-4 Portable Environmental Gas Monitor

Plant photosynthesis was measured with a LCI Photosynthesis System. The measured plant was *L. secalinus*, which was the most common species in different stages of desertification reversal at the study site of Lijihaizi. The data of the photosynthetic rate, transpiration rate, stomatal conductance, and Intercellular CO_2 concentration were obtained from the LCI photosynthesis system after measurement. The leaf Chl content of two common species, i.e. *L. secalinus* and *P. centrasiaticum*, was measured with a FieldScout CM1000 Chlorophyll Meter (Spectrum Technologies, Inc.) (Fig. 25). Plants were randomly selected for photosynthesis and chlorophyll content measurement in each stages of desertification reversal; but all selected plants were mature and in the same development stage in their lives.

Fig. 25: Photo of the FieldScout CM1000 Chlorophyll Meter

3.4 Laboratory analyses

In the laboratory, the above ground parts of plants were dried in an oven at 105 ℃ for 30 minutes and then at 80 ℃ for 24 hours until the weight of the plant material did not change any longer. After cooling to room temperature, the material was weighed again.

Soil samples for water content measurement were dried in an oven at 105 ℃ for 8 hours until the weight of the soil did not change any longer. All dried soil samples were then weighed again. Soil water content (SW) and soil bulk density were calculated from these results. Other soil samples were dried naturally in the air in a dark and ventilated room. Following, each soil sample was mixed adequately and then sieved through a sieve of 2 mm mesh size. Plant roots, litter, and gravel in the soil were picked out carefully. The remaining soil sample was divided into two parts. One part was used for physical analyses and the other part was for chemical analyses. The part for chemical analyses of the soil sample was first sieved through a sieve of 1 mm mesh size. It was further divided into two parts: One part as used for available nutrient and enzyme activity analyses; the other part was sieved with 0.149 mm mesh size and used for total nutrient analyses.

Soil particle size distribution was measured with Microtrac S3500 Particle Size Analyzer (Microtrac Inc.) (Fig. 26) and the wet analysis method was applied in this study. Soil particle size distribution was classified into the following groups: coarse sand (0.25 mm < soil particle size < 2.0 mm); fine sand (0.1 mm ≤ soil particle size ≤ 0.25 mm); very fine sand (0.05 mm < soil particle size < 0.1 mm); clay + silt (soil particle size ≤ 0.05 mm) (Sumner 2000).

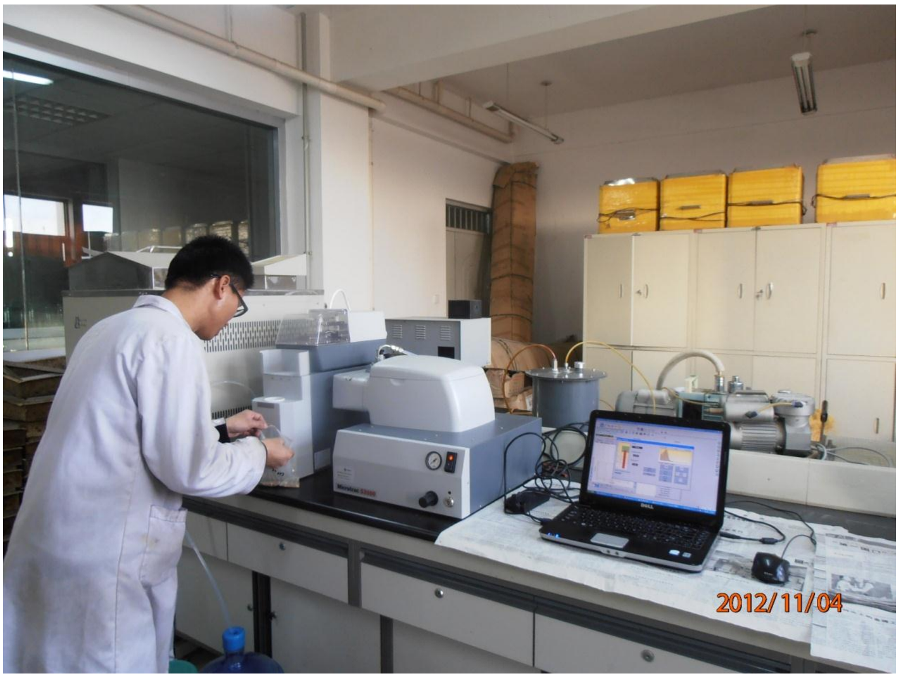

Fig. 26: Photo of measuring the soil particle size distribution with Microtrac S3500 Particle Size Analyzer

Soil organic carbon was determined with the method of potassium dichromate oxidation by heating at 180 ℃ for 5 minutes after boiling (ISSCAS 1978). Soil total nitrogen was measured with a UDK 159 Automatic Kjeldahl Analyzer (Velp Scientifica Corp.) (Fig. 27).

Fig. 27: Photo of the UDK 159 Automatic Kjeldahl Analyzer

Soil total phosphorus was analyzed with the NaOH melting - colorimetry method (ISSCAS 1978); soil total potassium was determined with the method of NaOH melting and flame photometry; soil available nitrogen was measured with the alkali hydrolyzing and standard acid titration method (ISSCAS 1978); soil available phosphorus was analyzed with the method of extraction with the solution of Na_2CO_3 which concentration is 0.5 mol L^{-1}; soil available potassium was determined by extraction with an ammonium acetate solution and flame photometry (ISSCAS 1978). Soil pH and electrical conductivity were measured by soil solution with a ratio of water and soil of 5:1. Soil pH was measured with a PHB-4 portable pH meter. Soil electrical conductivity was analyzed using a DDS-307A electrical conductivity meter (INESA Instrument) (Fig. 28).

Fig. 28: Photo of the DDS-307A electrical conductivity meter

Soil catalase activity was measured with the method of titration using a 0.1N $KMnO_4$ solution (Guan 1986). The activity of soil catalase was expressed as the volume of the $KMnO_4$ solution used in the titration per gram soil per hour (ml 0.1mol/L $KMnO_4$ g^{-1} soil h^{-1}). The volume represents the volume of $KMnO_4$ solution used in the titration of the soil samples subtracted from that of the blank control (without soil).

Soil phosphatase activity was analyzed by the disodium phenyl phosphate colorimetry method (Guan 1986). Soil samples were incubated in a disodium phenyl phosphate solution at 37 ℃ for 24 hours; the activity of soil phosphatase was calculated as the content of hydroxybenzene produced in the enzymatic process per gram soil per hour (μg hydroxybenzene g^{-1} soil h^{-1}).

Soil urease activity was determined by the indophenol colorimetry method (Guan 1986). Soil samples were incubated in the solution, with urea as substrate at 37 ℃ for 24 hours; the activity of soil urease was calculated as the content of NH_4^+-N produced in the enzymatic process per gram soil per hour (μg NH_4^+-N g^{-1} soil h^{-1}).

Soil invertase activity was measured with the 3,5-Dinitrosalicylic acid colorimetry method (Guan 1986). Soil samples were incubated in the solution with sucrose as the substrate at 37 ℃ for 24 hours. The activity of soil invertase was calculated as the content of glucose produced by soil invertase per gram soil per hour (mg Glucose g^{-1} soil h^{-1}).

Soil protease activity was analyzed with the casein colorimetry method (Li Z. et al. 2008). Soil samples were incubated in the solution with casein as the substrate at 30 ℃ for 48 hours. The activity of soil protease was calculated as the content of tyrosine produced in the enzymatic process per gram soil per hour (µg tyrosine g^{-1} soil h^{-1}). One soil sample was incubated in the solution without substrate as a blank control, for soil enzyme activities including phosphatase, urease, invertase, and protease.

3.5 Statistical analyses

The data was processed with Excel and SPSS. The importance value (IV) of a given plant species was calculated with the following formula (Yang et al. 2014): (Equation (1))

$$\mathrm{IV} = \frac{(\mathrm{RA+RH+RC+RF})}{4} \times 100 \qquad (1)$$

where RA represents the relative abundance of this species; RH represents the relative height; RC represents the relative cover and RF represents the relative frequency. RA is the proportion of the number of individuals of this species to the sum of the individuals of all species in the same quadrat. RH, RC, and RF were calculated in the same way (Myers and Bazely 2003). The formula was developed from the following formula (Zhang et al. 2005): (Equation (2))

$$\mathrm{DV} = \frac{(\mathrm{RA+RH+RC})}{3} \times 100 \qquad (2)$$

where DV is the dominance value; RA, RH, and RC represent the same meaning as above.

The number of plant species in a quadrat was taken as the species richness. Species diversity was calculated with the Shannon - Wiener index (Belsky 1992; Chawla et al. 2010; Magurran 1998; Shannon 1948): (Equation (3))

$$H' = -\sum_{i=1}^{S} P_i \ln P_i \qquad (3)$$

whereH' is the Shannon - Wiener index; S is the number of plant species; P_i is the proportion of the number of individuals for species i to the whole number of individuals for all plant species: (Equation (4))

$$P_i = \frac{n_i}{N} \qquad (4)$$

where n_i is the the number of individuals for species i; N is the whole number of individuals for all plant species.

Species evenness was calculated with Pielou index, i.e. the ratio of the measured species diversity (H') to the maximum value of species diversity (H'_{max}) (Pielou 1969).

Pielou index is calculated with the folloing formula: (Equation (5))

$$J' = H'/H'_{max} \tag{5}$$

where J' is the measured Pielou index; H'_{max} is the maximum value of Shannon-Wiener index. (Equation (6))

$$H'_{max} = \ln S \tag{6}$$

where S is the number of plant species.

Hence, $J' = \left(-\sum_{i=1}^{S} P_i \ln P_i\right) / \ln S$ (Ma and Liu 1994) (7)

Soil water content was calculated with the following equation: (Equation (8))

$$SW = \frac{W-G}{G} \times 100\% \tag{8}$$

where W is the wet weight of the soil sample; G is the dry weight (after 8 hours dried in oven with 105 ℃) of the soil sample.

Soil bulk density was calculated with the following equation: (Equation (9))

$$BD = \frac{W}{(1+SW)\times V} \times 100\% \tag{9}$$

where BD is soil bulk density; W is the wet weight of the soil sample in the whole cutting ring; SW is soil water content; V is the volume of the cutting ring.

The Kolmogorov - Smirnov test (K-S test) for normality was implemented for each group of data. For those data whose distributions are not normal, a logarithmic transformation of the data was done and then tested again by the K-S test. Following, variance analyses between different desertification reversal stages was conducted with SPSS (Lu 2003).

All figures of vegetation and environment properties responding to desertification reversal were generated in Excel 2007. Correlation analyses and stepwise multiple regression analyses between vegetation characteristics and soil properties were implemented with SPSS. Predictive models and relevant parameters were produced in SPSS in the process of regression analyses. Correlation analyses and stepwise multiple regression analyses represent related parts in this study. We implemented the analyses step by step. The analysis process is described as follows:

Firstly, we conducted correlation analyses using all vegetation characteristics and soil properties. The results showed soil properties which were significantly correlated with a specific vegetation characteristic. We conducted then the stepwise multiple regression analysis. Data with a residual, which is more than 3 times of the standard deviation of all residuals, were taken as outliers and removed from the data set. Results showed the predictive models and the relevant statistics for every characteristic of vegetation.

The process of stepwise regression analysis is described as follows: Firstly, enter variables with the largest effects on the dependent variable into the model; then, select the variable inside the model with the smallest partial regression sum of squares and perform the F test; if the test is significant, then all variables will be kept in the model; if the test is not significant, this variable will be removed from the model; then perform the F test for other variables in the same way until the F tests of all the variables in the model are significant; finally, select the variable not including in the model with the largest partial regression sum of squares and perform the F test; if the test is significant, then this variable will entered into the model; after entering the new variable into the model, the variables inside the model will undergo another round of F test to keep all of their effects on the dependent variable are significant; the variables outside of the model will be selected again until all of their F test are not significant; the variables are entered into or removed from the model in this way until no variable in the model can be removed from it and no variable outside the model can be entered into it.

Residuals of a given predictive model produced in the regression analyses were tested for the autocorrelation, by calculating the Durbin-Watson value (DW) and comparing with the lower limit d_L and the upper limit d_U of the DW statistics. The lower limit and the upper limit can be determined from the Durbin-Watson Table with specified n and k; n and k are the number of samples and the number of independent variables in the model, respectively. There is positive first-order autocorrelation between residuals, if $0 \leq DW \leq d_L$; there is negative first-order autocorrelation between residuals, if $4\text{-}d_L \leq DW \leq 4$; there is none first-order autocorrelation between residuals, if $d_U \leq DW \leq 4\text{-}d_U$; it cannot be determined whether there is first-order autocorrelation between residuals or not, if $d_L \leq DW \leq d_U$, or $4\text{-}d_U \leq DW \leq 4\text{-}d_L$, in which case another testing method is needed (Sun 2005).

High-order autocorrelation diagnostics were conducted in the EViews software with the methods of Correlogram-Q-Statistics and Breusch-Godfrey Serial Correlation TM Tests (Sun 2005). If there was no first or high-order autocorrelation between residuals, the model kept unchanged and the normality and homoscedasticity of random errors (residuals are their estimated values) for the model were tested with SPSS. If there was autocorrelation between residuals, the model was modified using the generalized difference method in EViews to eliminate the autocorrelation. In this case, random errors of the new model met all the hypotheses for multiple linear regression models, including the normality, homoscedasticity, autocorrelation, and independence, because the generalized difference method is designed to eliminate the autocorrelation based on the assumption that random errors meet all the hypotheses, and so random errors in the modified model do not need to be tested again.

4 Results

4.1 Changes in vegetation and quantitative plant characteristics with the reversal of sandy desertification

Plant species importance values (IVs) changed dramatically with the reversal of sandy desertification (Tab. 5). In the very severe desertification areas (VSD) (Fig. 15) and severe desertification areas (SD) (Fig. 16), *Artemisia ordosica* and *Agriophyllum squarrosum* were the dominant species of the plant communities. The total IV of these two species accounted for 62.2% and 28.6% in VSD and SD, respectively. The IV of *A. ordosica* decreased gradually from VSD, via the middle desertification areas (MD) (Fig. 17), to potential desertification areas (PD) (Fig. 19). *A. squarrosum* disappeared in MD and PD, and almost also in light desertification areas (LD) (Fig. 18). *A. ordosica* and *A. squarrosum* are pioneer plants for sand fixation in sandy desertification areas. The changes in IVs of *A. ordosica* and *A. squarrosum* indicate a reversal of sandy desertification from VSD, via MD, to PD.

The IVs of perennial grass species, including *Leymus secalinus*, *Pennisetum centrasiaticum*, *Cleistogenes squarrosa*, *Agropyron mongolicum* and *Stipa bungeana*, increased in general with the reversal of desertification (Tab. 5). The IV of *Artemisia scoparia* increased substantially from 0.41% in VSD to 15.80% in PD. However, the IVs of some other annual species, such as *Salsola beticolor* and *Setaria viridis*, decreased in general with the desertification reversal. Illustrations of plants are shown in Fig. 29.

Tab. 5: Changes of plant species importance values (IVs) with the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

		Desertification reversal stage				
Species	Life form	VSD	SD	MD	LD	PD
Artemisia ordosica Krasch.	PS	32.89	12.25	14.72	10.54	4.31
Agriophyllum squarrosum (L.) Moq.	AF	29.27	16.35		0.47	
Leymus secalinus (Georgi) Tzvel.	PG	9.52	21.30	4.96	11.85	26.46
Salsola beticolor Iljin	AF	9.42	5.99	1.46	4.30	2.26
Setaria viridis (L.) Beauv.	AG	8.46	5.38	1.26	5.88	2.85
Pennisetum centrasiaticum Tzvel.	PG	3.74	0.69	12.58	4.34	9.26
Kochia scoparia (L.) Schrad.	AF	2.85	3.43	0.81	2.29	
Ixeris chinensis (Thunb.) Nakai var. *graminifolia* (Ledeb.) H.C.Fu	PF	2.18	3.68	6.62	9.94	4.11
Panzeria alaschanica Kupr.	PF	0.53	0.09	0.09		
Artemisia scoparia Waldst. et Kit.	AF	0.41	1.01	19.42	18.98	15.80
Euphorbia humifusa Willd.	AF	0.30	1.32	0.75	0.18	0.82
Chenopodium acuminatum Willd.	AF	0.16		5.21	1.84	0.34
Tribulus terrestris L.	AF	0.11	0.60			
Lespedeza potaninii Vass.	PS	0.09	1.81	1.37	2.32	0.10
Bassia dasyphylla (Fisch. et Mey.) O. Kuntze	AF	0.07	2.06	0.48	0.46	0.88
Oxytropis racemosa Turcz.	PL		8.06	0.25	0.31	
Sophora alopecuroides L.	PS		6.77	1.65	1.19	1.04
Cleistogenes squarrosa (Trin.) Keng	PG		1.89	5.20	2.13	7.09
Astragalus melilotoides Pall.	PL		1.85	0.98	2.82	0.58
Salix psammophila C.Wang et Ch.Y. Yang.	SH		0.96			
Hedysarum mongolicum Turcz.	PS		0.74			
Agropyron mongolicum Keng	PG		1.03	0.66	2.91	8.44
Oxytropis aciphylla Ledeb.	PS		0.69			

Cynanchum thesioides (Freyn) K. Schum	PF	0.54	0.13		
Gueldenstaedtia stenophylla Bge.	PL	0.53	0.72	0.19	
Inula salsoloides (Turcz.) Ostenf.	PF	0.32			
Cynanchum komarovii Al. Iljin.	PF	0.24	0.27		0.34
Olgaea leucophylla (Turcz.) Iljin	PF	0.13			
Euphorbia esula L.	PF	0.13	0.81	0.09	
Polygala tenuifolia Willd.	PF	0.09			
Echinops gmelini Turcz.	AF	0.06	0.32	0.29	0.59
Chenopodium album L.	AF		4.13	1.14	0.94
Stipa breviflora Griseb.	PG		3.62	4.46	0.98
Thermopsis lanceolata R. Br.	PL		3.57	1.79	0.20
Heteropappus altaicus (Willd.) Novopokr.	PF		2.25	1.88	4.66
Setaria arenaria Kitag.	AG		1.46	0.08	1.13
Cuscuta chinensis Lam.	AF		1.36		
Glycyrrhiza uralensis Fisch.	PL		1.14	1.74	1.93
Equisetum ramosissimum Desf.	PF		0.94		
Polygonum aviculare L.	AF		0.40		
Stipa bungeana Trin.	PG		0.16		1.71
Plantago asiatica L.	PF		0.12		0.11
Incarvillea sinensis Lam.	AF		0.11	0.19	
Kalidium foliatum (Pall.) Moq.	SH			1.27	
Artemisia sacrorum Ledeb.	PF			1.24	
Limonium aureum (L.) Hill. ex Kuntze	PF			1.00	
Peganum nigellastrum Bge.	PF			0.91	
Typha minima Funk.–Hoppe	PF			0.54	0.88
Sonchus arvensis L.	PF			0.34	
Mulgedium tataricum (L.) DC.	PF			0.09	
Artemisia dubia Wall. ex Bess. var. *subdigitata* (Mattf.) Y. R. Ling	PF				1.37
Artemisia mongolica Fisch. ex Bess.	PF				0.32

Silene conoidea L.	AF	0.27
Chenopodium glaucum L.	AF	0.23

Desertification Reversal Stages:

VSD: Very Severe Desertification; SD: Severe Desertification; MD: Moderate Desertification; LD: Light Desertification; PD: Potential Desertification (Figs. 15- 19).

Life forms:

AF: Annual Forb (A forb is a herbaceous plant which is not a grass species); AG: Annual Grass; PF: Perennial Forb; PG: Perennial Grass; PL: Perennial Legume; PS: Perennial Sub-shrub; SH: Shrub.

The abbreviations are the same below.

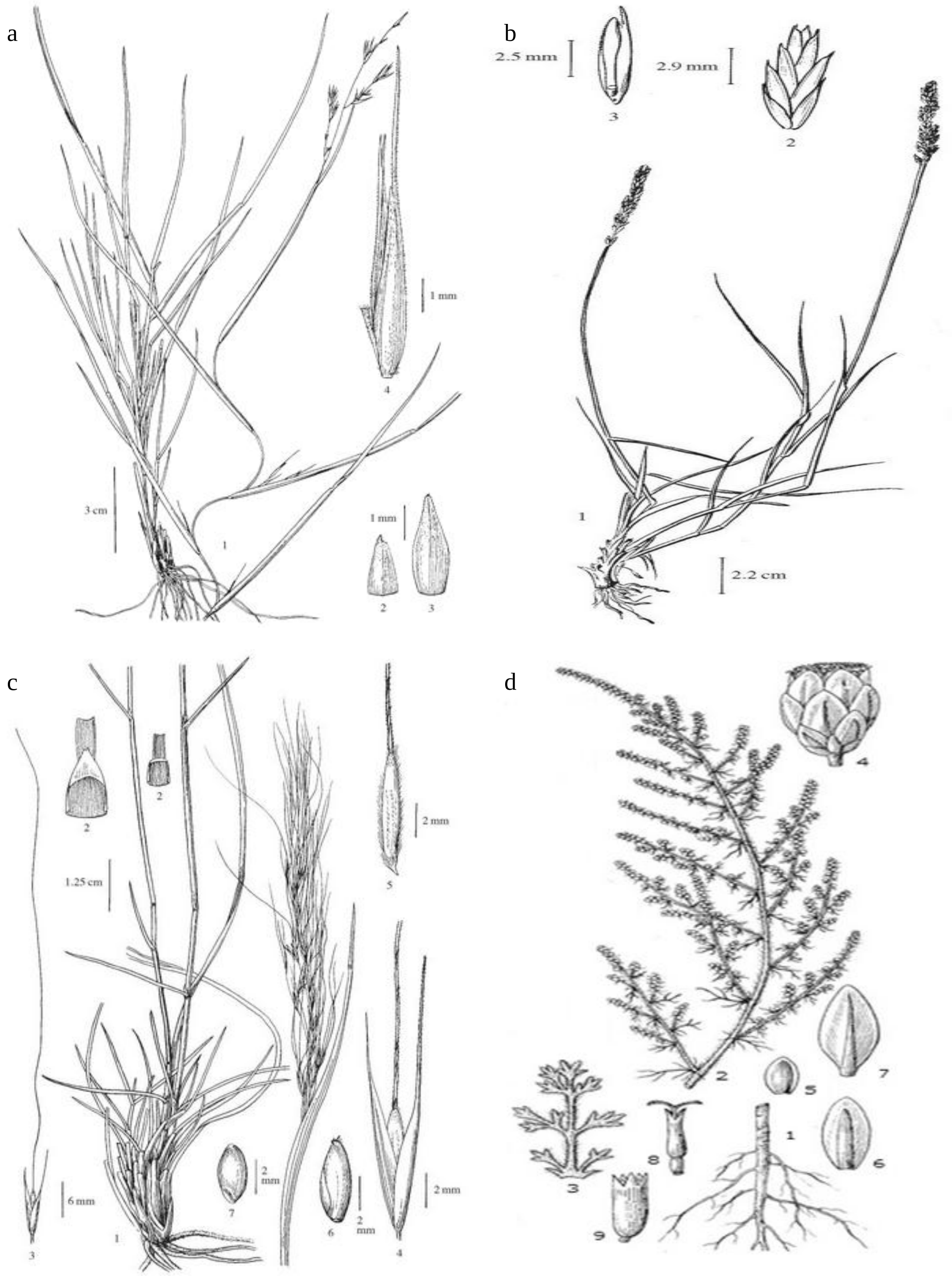

Fig. 29: Illustrations of plant species found in this study: a. *Cleistogenes squarrosa*; b. *Agropyron mongolicum*; c. *Stipa bungeana*; d. *Artemisia scoparia* (from Flora of China (2015) , changed)

In fig. a: 1. Habit, 2. Lower glume, 3. Upper glume, 4. Floret;

in fig. b: 1. Habit, 2. Spikelet, 3. Floret, 4. the small flower;

in fig. c: 1. Habit, 2. Ligules of culm leaves and basal leaves, 3. Spikelet, 4. Spikelet without portion of awn, 5. Floret,

6. Cleistogamous spikelet, 7. Caryopsis produced in cleistogamous spikelet;

in fig. d: 1. lower part of the plant, 2. upper part of the plant, 3. Basal leaf, 4. Capitulum, 5-7. Phyllaris, 8. Female floret, 9. Bisexual floret.

The number of plant species and IVs summarized for life forms are shown in Tab. 6. The number of annual forb and perennial grass taxa increased from SD to MD, and that of perennial forbs and perennial legume increased abruptly from VSD to SD and then maintained the relative stability. IVs of life form groups changed noticeably with the reversal of sandy desertification. The IVs of annual forbs and perennial sub-shrubs decreased dramatically from 42.59% and 32.98% in VSD to 22.13% and 5.54% in PD, respectively (Tab. 6). Those of perennial grass and forbs increased prominently from 15.97% in VSD to 65.83% in PD. Perennial grasses became the main life form in PD, with the IV value of 53.94%. Changes in annual forbs and perennial sub-shrubs showed that an increase in plant species does not guarantee an increase in IV.

Tab. 6: Changes in the number of plant species and importance values (IVs) for different life forms with the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

		Desertification reversal stage				
Life form		VSD	SD	MD	LD	PD
AF	S	8	8	11	10	9
	IV	42.59	30.82	34.45	30.14	22.13
AG	S	1	1	2	2	2
	IV	8.46	5.38	2.72	5.96	3.98
PF	S	2	8	8	9	7
	IV	2.71	5.22	11.23	16.03	11.79
PG	S	2	4	6	5	6
	IV	13.26	24.91	27.18	25.69	53.94
PL	S	0	3	5	5	3
	IV	0.00	10.44	6.66	6.85	2.71
PS	S	2	5	3	3	3
	IV	32.98	22.26	17.74	14.05	5.54
SH	S	0	1	0	1	0

	IV	0.00	0.96	0.00	1.27	0.00

S: The number of plant species. Other abbreviations are the same as Tab. 5.

4.2 Responses of vegetation characteristics to the reversal of sandy desertification

Changes of vegetation characteristics, including species richness, diversity, and evenness for each study site are shown in Tab. 7. Species richness varied between 1.0 and 11.3 (1.0 is the mean value of the numbers of plant species for the three quadrats of VSD investigated at the study site of Weizhuangzi; 11.3 is the mean value of the numbers of plant species for the three quadrats of PD investigated at the study site of Habanong. Tab. 7); species diversity changed between 0.0 and 2.01 (0.0 and 2.01 are the values of the Shannon-Wiener index calculated with equation (3)); species evenness varied between 0.1 and 0.95 (0.1 and 0.95 are the values of Pielou index calculated with equation (5)). For each study site, species richness and diversity generally increased with the reversal of sandy desertification, whereas species evenness changed irregularly in the reversal process. There were significant differences ($P < 0.05$) of any of the variables: species richness, diversity and evenness between different desertification reversal stages.

For all study sites, the trends in summary statistics of vegetation characteristics are clearer than those for single study sites. Mean species richness and diversity increased from 3.0 and 0.57 in VSD to 9.0 and 1.22 in PD, respectively for the data of all study sites, while species evenness changed irregularly with the reversal of sandy desertification.

Tab. 7: Changes of vegetation characteristics with the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Study Site	Reversal Stage	Species Richness	Species Diversity	Species Evenness
Nanhaizi	1	2.3±0.6 ^{a}	0.67±0.04 ^{a}	0.84±0.17 ^{ad}
	2	7.0±2.0 ^{b}	1.08±0.51 ^{ab}	0.54±0.19 ^{bc}
	3	9.3±0.6 ^{b}	1.05±0.16 ^{ab}	0.47±0.08 ^{b}
	4	8.0±2.6 ^{b}	1.51±0.13 ^{b}	0.75±0.13 ^{cd}
Haba	1	2.3±0.6 ^{a}	0.56±0.26 ^{a}	0.66±0.12 ^{a}
	2	4.0±1.0 ^{b}	1.02±0.19 ^{ab}	0.75±0.03 ^{ab}
	3	7.7±1.2 ^{c}	1.02±0.59 ^{ab}	0.52±0.32 ^{ab}
	4	7.7±1.5 ^{c}	1.19±0.21 ^{b}	0.60±0.17 ^{b}

	5	8.7 ± 2.9^{c}	1.01 ± 0.31^{ab}	0.47 ± 0.12^{ab}
Habanong	1	2.7 ± 0.6^{a}	0.92 ± 0.25^{ab}	0.95 ± 0.04^{a}
	2	4.3 ± 2.5^{ac}	0.82 ± 0.81^{a}	0.51 ± 0.34^{ab}
	3	9.7 ± 1.5^{bd}	2.01 ± 0.10^{b}	0.89 ± 0.04^{ab}
	4	5.7 ± 1.5^{c}	1.13 ± 0.28^{ab}	0.66 ± 0.08^{b}
	5	11.3 ± 1.2^{d}	1.62 ± 0.66^{ab}	0.66 ± 0.25^{ab}
Yuzhuangzi	1	6.3 ± 1.2^{a}	0.88 ± 0.25^{a}	0.49 ± 0.17^{a}
	2	8.0 ± 1.0^{a}	0.50 ± 0.10^{a}	0.24 ± 0.04^{b}
	3	7.7 ± 1.5^{a}	0.65 ± 0.33^{a}	0.31 ± 0.13^{ab}
	4	10.3 ± 1.2^{b}	1.66 ± 0.13^{b}	0.71 ± 0.04^{c}
Machang	1	4.3 ± 1.5^{a}	0.90 ± 0.23^{a}	0.66 ± 0.21^{a}
	2	6.0 ± 1.0^{ac}	1.13 ± 0.29^{a}	0.63 ± 0.12^{a}
	3	10.3 ± 1.2^{b}	1.28 ± 0.06^{a}	0.55 ± 0.01^{a}
	4	7.3 ± 1.5^{c}	0.90 ± 0.33^{a}	0.45 ± 0.12^{a}
Weizhuangzi	1	1.0 ± 0.0^{a}	0.00 ± 0.00^{a}	–
	2	5.7 ± 2.1^{b}	0.89 ± 0.37^{b}	0.52 ± 0.12^{ab}
	4	5.7 ± 2.1^{b}	0.71 ± 0.13^{b}	0.42 ± 0.04^{a}
	5	9.0 ± 1.0^{c}	1.47 ± 0.30^{c}	0.67 ± 0.11^{b}
Lijihaizi	1	2.3 ± 1.2^{a}	0.07 ± 0.07^{a}	0.10 ± 0.02^{ad}
	2	5.0 ± 1.0^{bc}	0.68 ± 0.24^{b}	0.45 ± 0.21^{b}
	3	3.7 ± 1.5^{ab}	0.22 ± 0.26^{ac}	0.16 ± 0.19^{ab}
	4	5.3 ± 0.6^{bc}	1.42 ± 0.14^{bd}	0.85 ± 0.04^{c}
	5	7.0 ± 1.7^{c}	0.80 ± 0.52^{bd}	0.40 ± 0.21^{bd}
All Study Sites	1	3.0 ± 1.8^{a}	0.57 ± 0.40^{a}	0.65 ± 0.29^{a}
	2	5.7 ± 1.9^{b}	0.87 ± 0.41^{b}	0.52 ± 0.21^{ab}
	3	8.1 ± 2.5^{cd}	1.04 ± 0.62^{bc}	0.48 ± 0.27^{b}
	4	7.1 ± 2.2^{c}	1.22 ± 0.37^{c}	0.63 ± 0.17^{a}
	5	9.0 ± 2.3^{d}	1.22 ± 0.53^{c}	0.55 ± 0.20^{ab}

Desertification Reversal Stages: 1. Very Severe Desertification (VSD); 2. Severe Desertification (SD); 3. Moderate

Desertification (MD); 4. Light Desertification (LD); 5. Potential desertification (PD) (Figs. 15-19).

Values are shown as: Mean ± Standard Deviation (in 1-m^2 plot).

Different letters within the same study site and variable indicate significant differences between the different desertification reversal stages at $P < 0.05$ level.

In middle Yanchi (Nanhaizi, Haba, and Habanong), plant cover changed regularly with the reversal of sandy desertification. It increased gradually from very severe desertification area to potential desertification area (Fig. 30). Differences in plant cover between different reversal stages were significant ($P < 0.05$) for study sites in Nanhaizi and Habanong, but not for that in Haba.

Plant cover in Northern Yanchi (Yuzhuangzi, Machang, Weizhuangzi, and Lijihaizi) also changed regularly. It raised in the main from very severe desertification areas to potential desertification areas in each study site (Fig. 30). But there was an exception at the study site of Yuzhuangzi and the plant cover in severe desertification area in this site was larger than that in both moderate and light desertification areas. This is due to the reason that the topography of the severe desertification area was much higher than those of moderate and light desertification areas, and this made the area of severe desertification easier to be eroded and more difficult to reverse although with larger plant cover. Plant cover is only a minor important standard for the determination of desertification reversal stages (The most important standard is the area percentage of bare sand in the whole area.). There were significant differences ($P < 0.05$) of plant cover between different reversal stages.

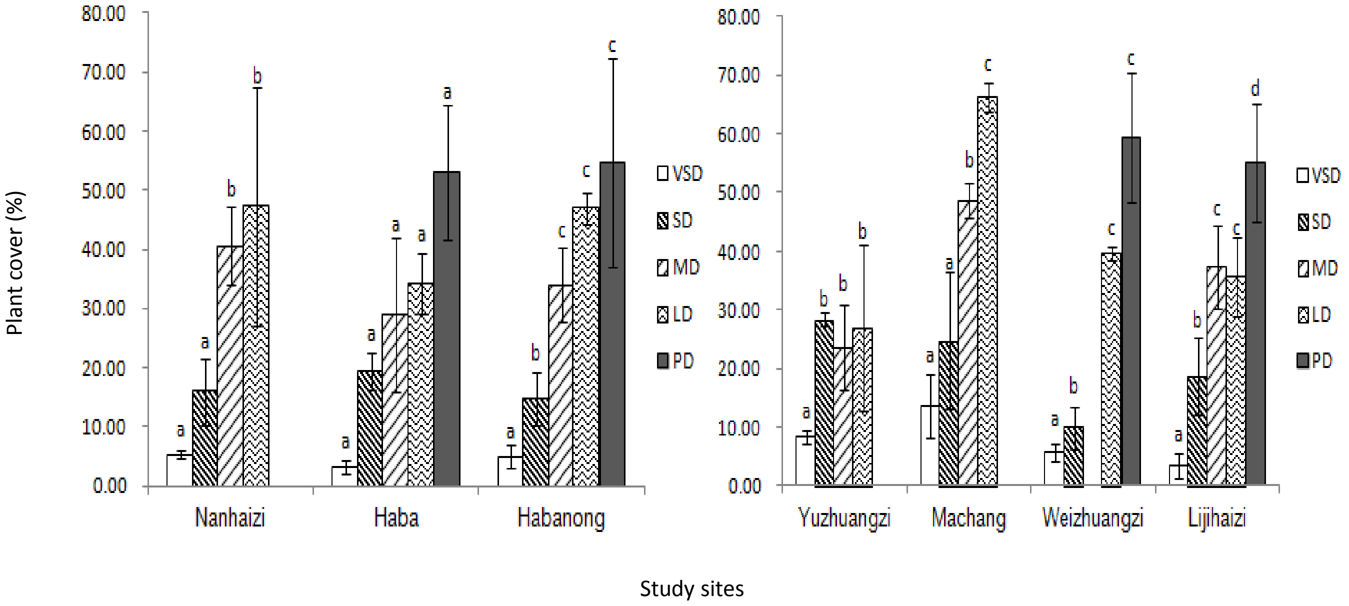

Fig. 30: Responses of vegetation cover to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China[*]

*Different letters within the same study site indicate significant differences between the different desertification reversal stages at P<0.05 level. The length of the column is the mean value of plant cover; the length of the bar on each column is the value of the standard deviation. The meanings of the letters, of the column lengths and bar lengths are the same for all figures below.

The value of plant aboveground biomass was very low in very severe desertification areas and increased gradually with the reversal of desertification at every study site (Fig. 31). There were significant differences between different reversal stages. Simultaneously, there were also some exceptions. At the study site of Habanong, the plant aboveground biomass in light desertification area was higher than that in potential desertification area; at the study site of Yuzhuangzi and Lijihaizi, the plant aboveground biomass in moderate desertification area was higher than that in light desertification area. This result is due to the existence of more sub-shrubs in those study areas. Sub-shrubs with ligneous parts are relatively heavier than herbaceous species.

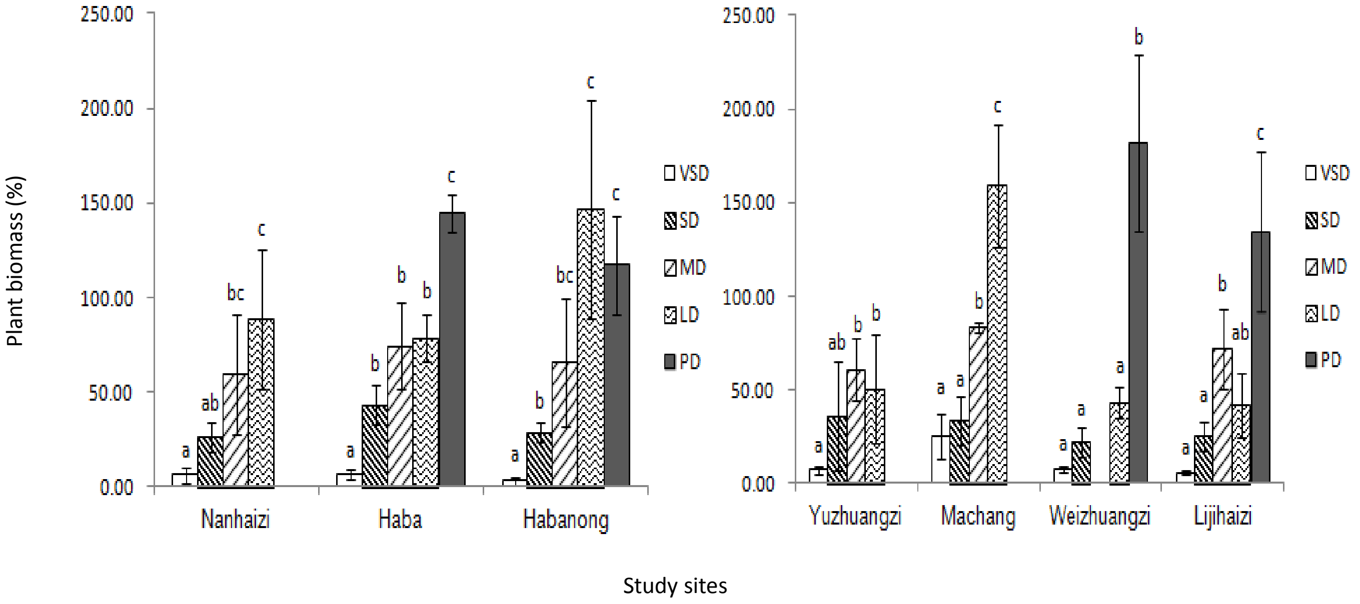

Fig. 31: Responses of plant aboveground biomass to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

4.3 Responses of plant physiological properties to the reversal of sandy desertification

In this section, plant physiological properties including leaf traits, leaf chlorophyll content and photosynthetic characteristics, were investigated to detect the adaptive changes in common plant species with the reversal of sandy desertification, and the relationships between plant physiological properties and soil properties.

4.3.1 Leaf traits of common plant species

The leaf areas of both *Leymus secalinus* and *Pennisetum centrasiaticum* showed an increasing tendency in the process of desertification reversal (Fig. 32), although there was a small slide in the severe desertification area for both species. For *L. secalinus*, leaf area differences between different desertification reversal stages were significant ($P < 0.05$). However, for *P. centrasiaticum*, only a minor increase was recorded, with significant differences between LD and any of VSD, SD, and MD, and between SD and PD.

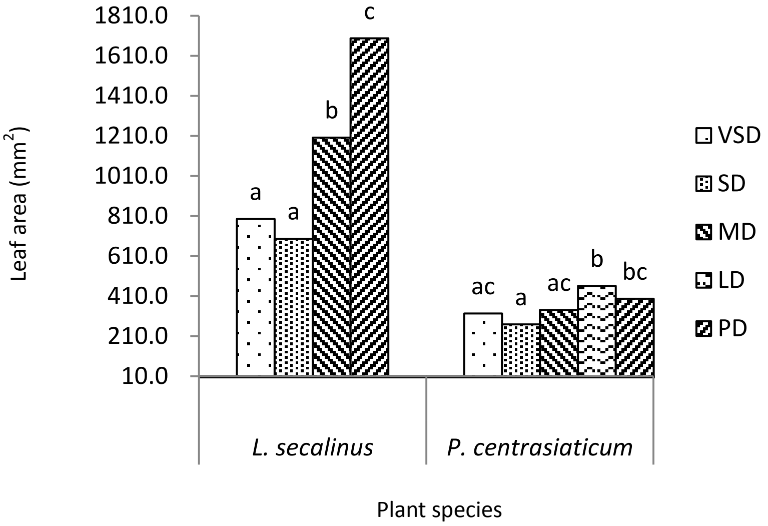

Fig. 32: Responses of leaf area of common plant species to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

The leaf width of *L. secalinus* increased obviously from VSD to PD (Fig. 33) but there were only significant differences between PD and any of VSD and SD. In contrast, the leaf width of *P. centrasiaticum* kept almost the same with desertification reversal and differences between different reversal stages were not significant.

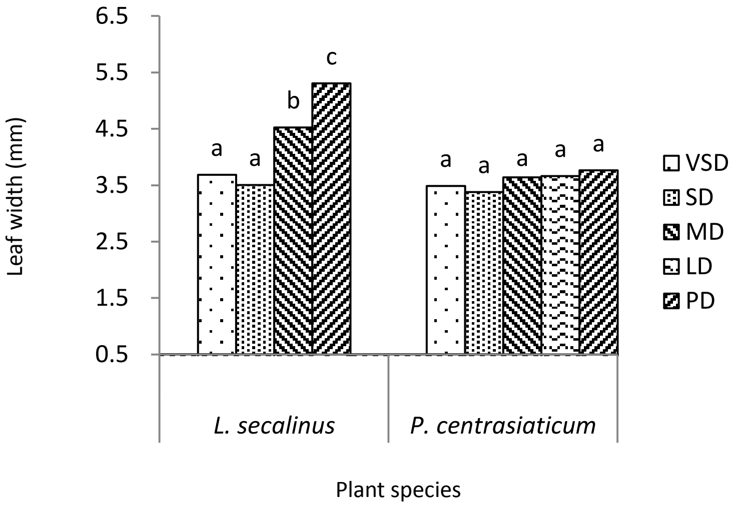

Fig. 33: Responses of leaf width of common plant species to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

The leaf length of *L. secalinus* increased significantly ($P < 0.05$) from SD to PD (Fig. 34). However, the leaf length of *P. centrasiaticum* fluctuated with the desertification reversal and the changes were relatively small, although there were significant differences between VSD, SD, MD and LD, and also between SD and PD.

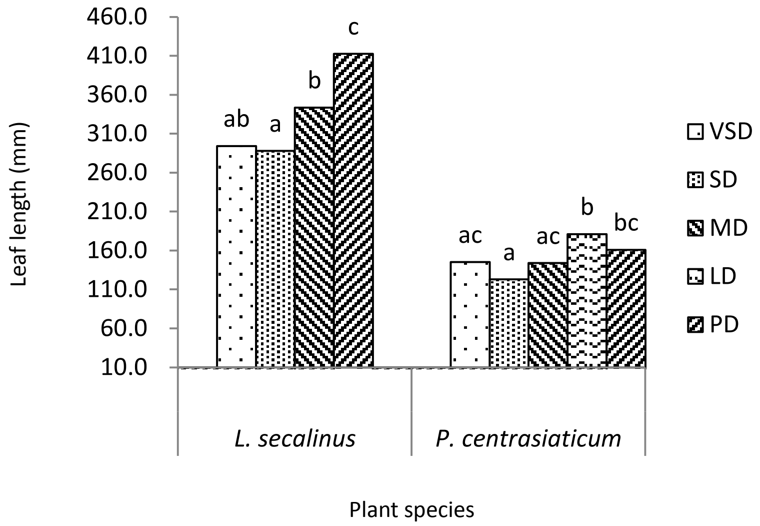

Fig. 34: Responses of leaf length of common plant species to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

The perimeter of *L. secalinus* also increased significantly ($P < 0.05$) in the process of desertification reversal (Fig. 35). The perimeter of *P. centrasiaticum* changed similarly to the leaf length of *P. centrasiaticum* but significant differences existed only between LD and any of SD and MD, and also between SD and PD.

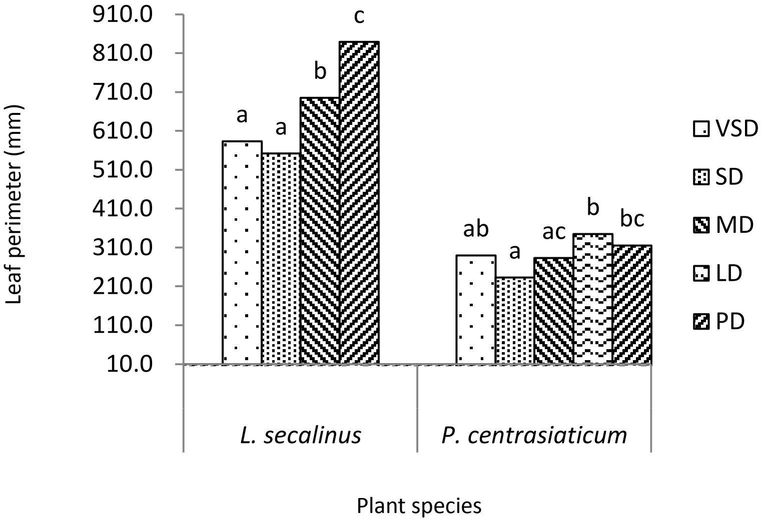

Fig. 35: Responses of leaf perimeter of common plant species to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

4.3.2 Leaf chlorophyll content of common plant species

The leaf chlorophyll content of *L. secalinus* increased significantly ($P < 0.05$) from VSD to PD. That of *P.*

centrasiaticum also increased but relatively slightly and significant differences existed only between one of VSD, SD and one of LD and PD; we detected no significant differences of leaf chlorophyll content between VSD, SD and MD, and also between LD and PD (Fig. 36).

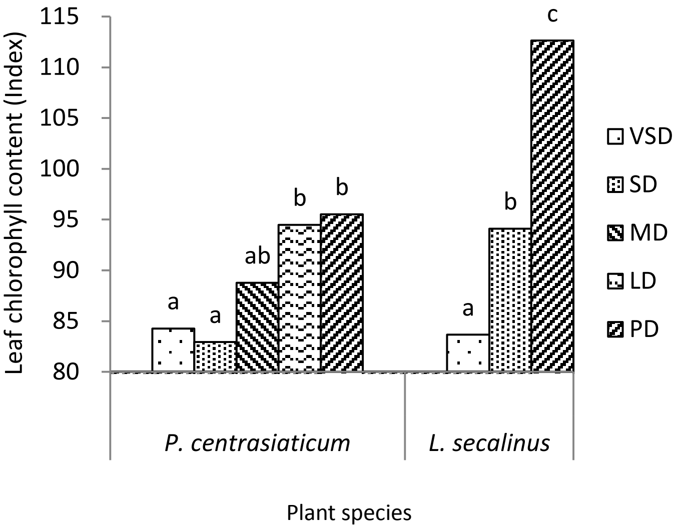

Fig. 36: Responses of leaf chlorophyll content of common plant species to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

4.3.3 Photosynthetic characteristics of *L. secalinus*

The photosynthetic rate (P_n) of *L. secalinus* increased significantly from VSD to PD ($P < 0.05$) (Fig. 37), although the differences between VSD and SD, and between MD and PD were not significant ($P > 0.05$). The transpiration rate (Tr) of *L. secalinus* first increased from VSD to SD, and then decreased from SD to PD (Fig. 37); there were only significant differences between VSD and PD.

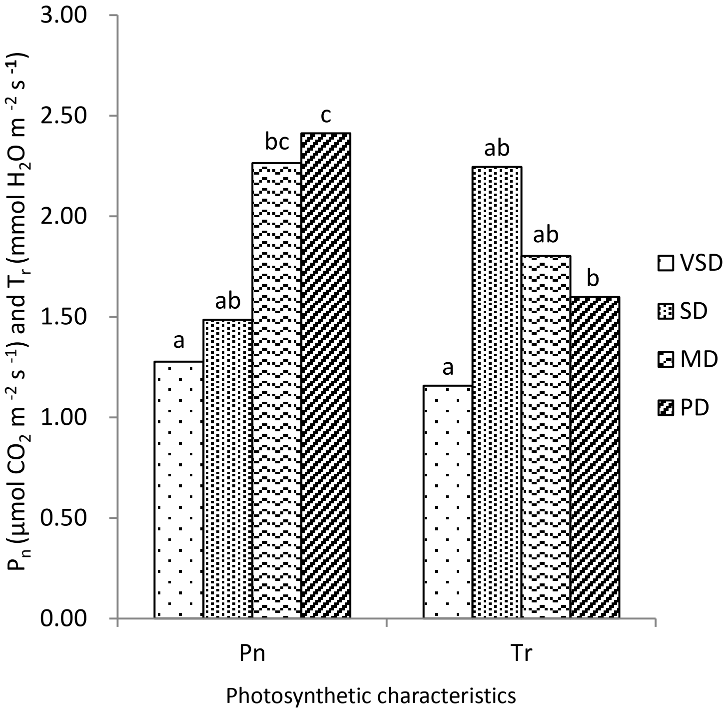

Fig. 37: Responses of photosynthetic rate and transpiration rate of *L. secalinus* to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

Pn: Photosynthetic rate; Tr: Transpiration rate

The stomatal conductance (G_s) of *L. secalinus* showed a similar tendency with the transpiration rate (Fig. 38); there were significant differences ($P < 0.05$) between different reversal stages. The Intercellular CO_2 concentration (C_i) of *L. secalinus* increased slightly from VSD to SD and then decreased significantly ($P < 0.05$) from SD to PD.

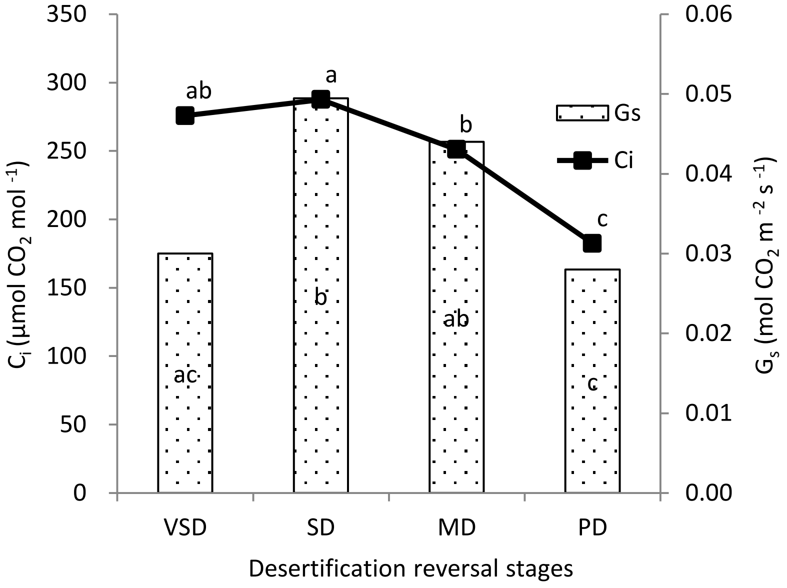

Fig. 38: Responses of stomatal conductance and intercellular CO_2 concentration of *L. secalinus* to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

C_i: Intercellular CO_2 concentration; G_s: Stomatal conductance

4.3.4 Relationships between plant physiological properties and soil nutrients, soil water content

Univariate regression analyses showed that both photosynthetic rate (P_n) (Fig. 39) and leaf chlorophyll (Chl) content (Fig. 40) were positively and significantly ($P < 0.05$) correlated with soil available nitrogen (AN) and with soil available phosphorus (AP). Both the P_n of *L. secalinus* and the Chl content of *P. centrasiaticum* could be predicted by AN and AP with the regression models. However, there were no significant ($P > 0.05$) correlations between P_n and soil water content (SW), and also between Chl content and SW. Both P_n and Chl content were not well predicted by SW.

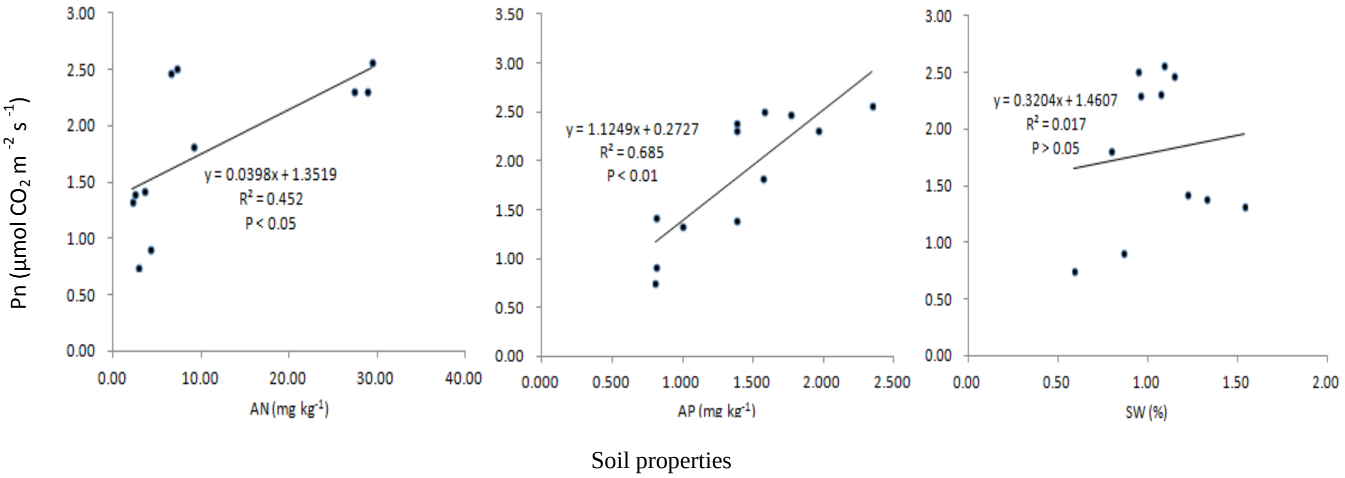

Fig. 39: Univariate regression analyses between photosynthetic rate (P_n) of *L. secalinus* and soil available N (AN), soil available P (AP) and soil water content (SW)

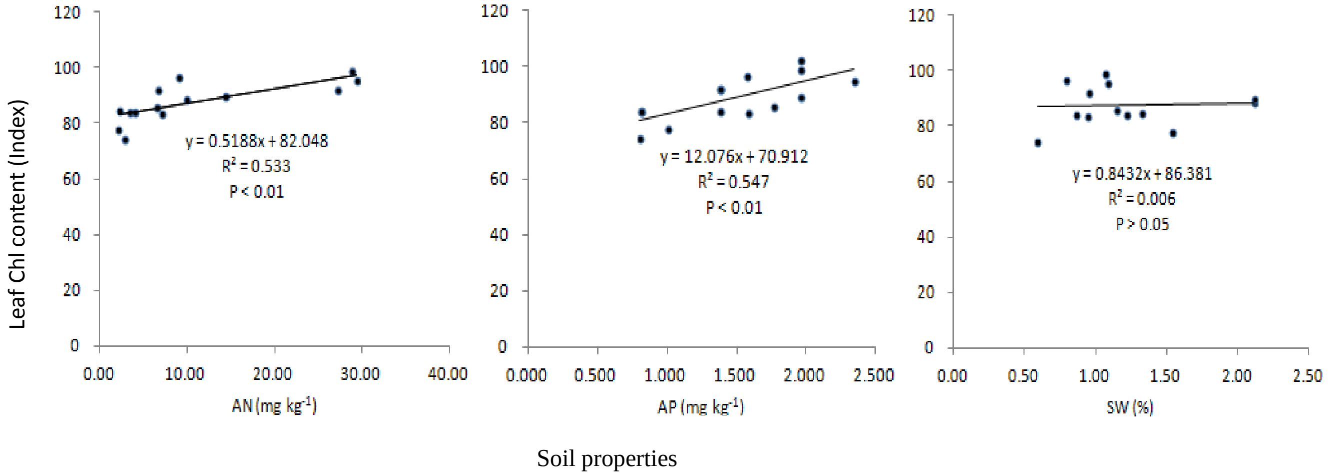

Fig. 40: Univariate regression analyses between leaf chlorophyll (Chl) content of *P. centrasiaticum* and soil available N (AN), soil available P (AP) and soil water content (SW)

4.4 Responses of soil physical properties on the local scale to the reversal of sandy desertification

Soil physical properties analyzed in this study included soil particle size distribution, soil bulk density and soil water content. For every parameter, the results will be described for every study site.

4.4.1 Soil particle size distribution

At the study site of Nanhaizi, soil particle comprised mainly fine sand and coarse sand in VSD. The proportion of clay plus silt increased obviously from VSD to LD (Fig. 41). The proportion of very fine sand showed a slight increase, too. Simultaneously, the proportion of fine sand and coarse sand decreased with the reversal of sandy desertification. As a result, the total of clay, silt and very fine sand accounted for a larger proportion of the particle composition in the reversed areas.

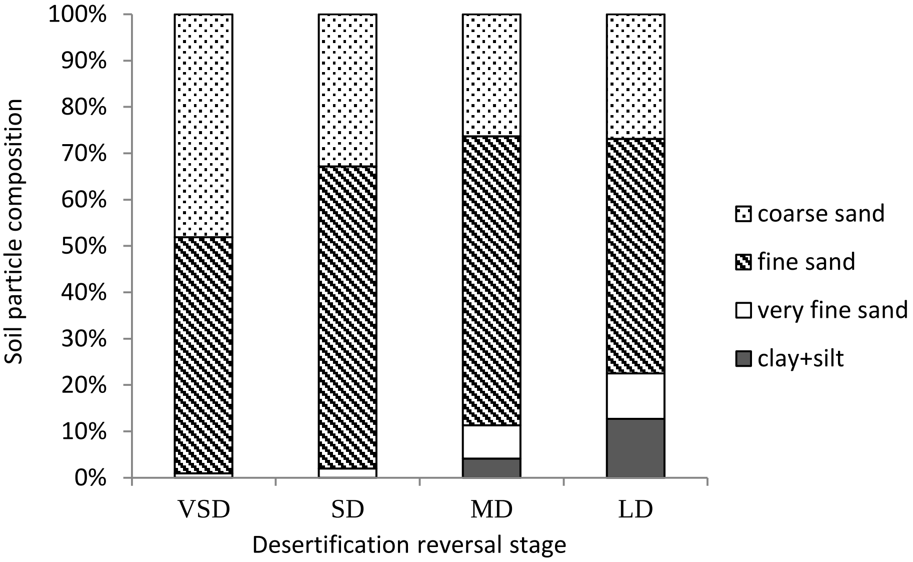

Fig. 41: Responses of soil particle size distribution to the reversal of sandy desertification at Nanhaizi in southern "Mu Us Sandy Land", China

At the study site of Haba, the proportion of clay, silt and very fine sand in soil increased suddenly from SD to MD (Fig. 42), amounts of fine sand and coarse sand decreased correspondingly. This is due to the fact that the soil type in this study site differs from that of the others. The soil type in this study site was camborthid, and that of other study sites were light sierozem accompanied with aeolian sandy soil. Difference in soil types may lead to the difference in soil particle size distribution. Clay, silt and very fine sand accounted for a substantial proportion in LD and PD, too.

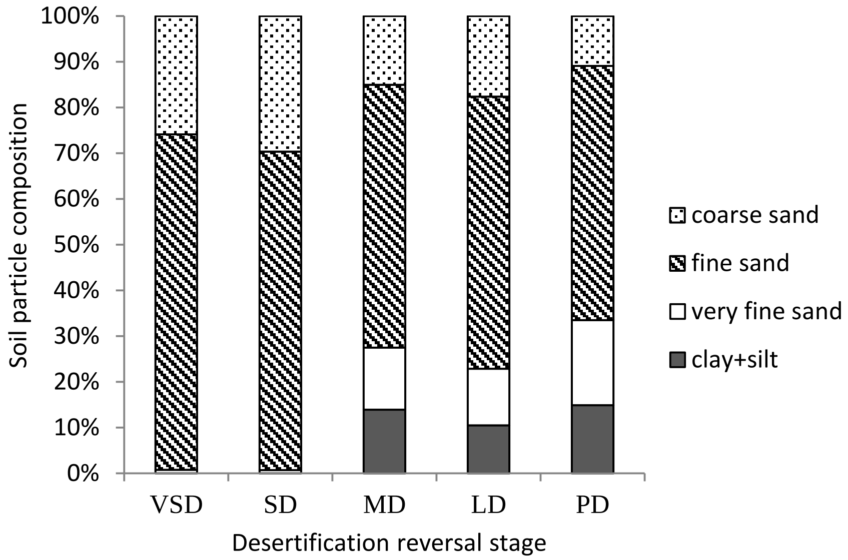

Fig. 42: Responses of soil particle size distribution to the reversal of sandy desertification at Haba in southern "Mu Us Sandy Land", China

At the study site of Habanong, the changes of soil particle size distribution showed more uniform tendency. The content of clay, silt and very fine sand in soils increased steadily from VSD to PD (Fig. 43). Simultaneously, the proportions of fine sand and coarse sand decreased gradually from VSD to PD. Coarse sand fraction was lowest in LD and PD with a value of 20%.

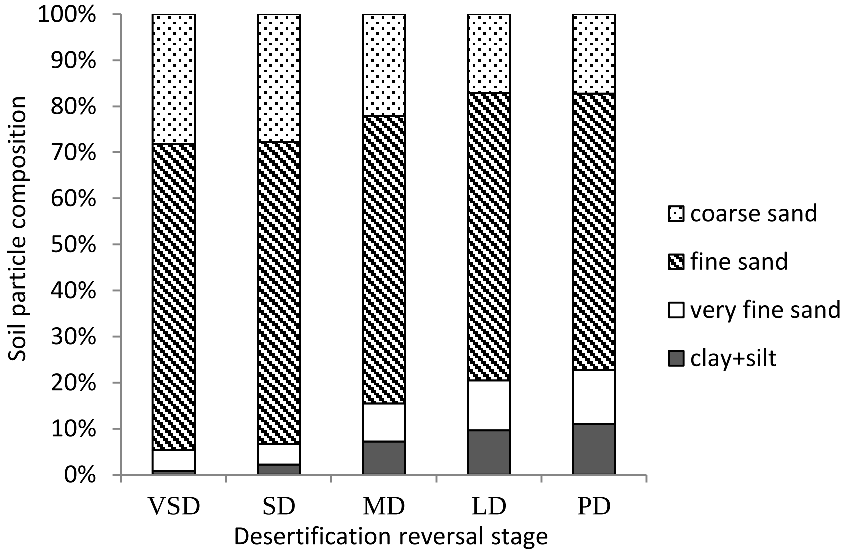

Fig. 43: Responses of soil particle size distribution to the reversal of sandy desertification at Habanong in southern "Mu Us Sandy Land", China

At the study site of Yuzhuangzi, the content of clay and silt in soil increased obviously with the reversal of sandy desertification (Fig. 44), while very fine sand in soil changed quite slightly. The proportion of fine sand and coarse sand decreased in general from VSD to LD.

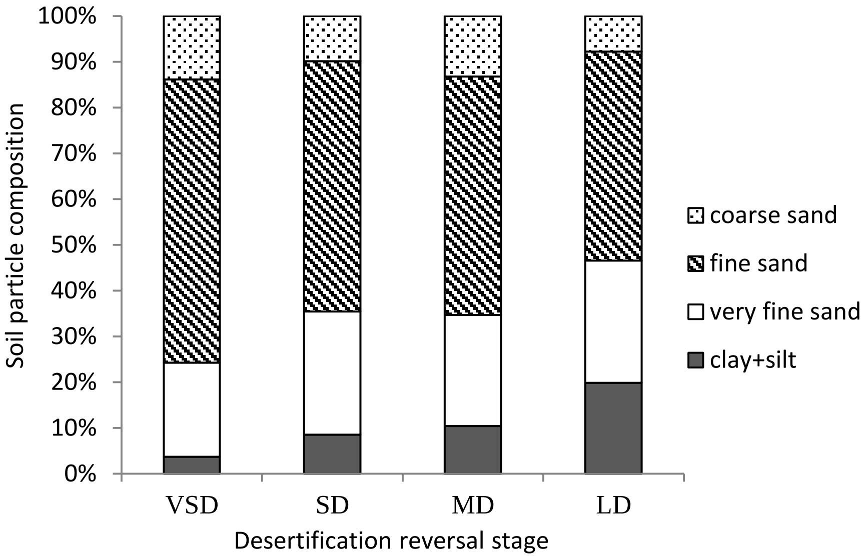

Fig. 44: Responses of soil particle size distribution to the reversal of sandy desertification at Yuzhuangzi in southern "Mu Us Sandy Land", China

At the study site of Machang, the content of clay and silt increased little from VSD to LD (Fig. 45), while the content of very fine sand increased relatively largely in this process. At the same time, the proportion of fine sand and coarse sand declined gradually with the sandy desertification reversal.

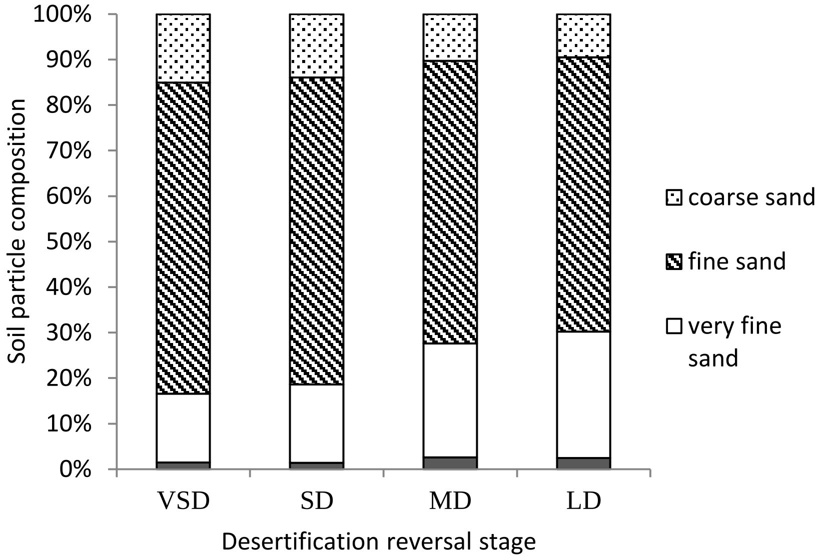

Fig. 45: Responses of soil particle size distribution to the reversal of sandy desertification at Machang in southern "Mu Us Sandy Land", China

At the study site of Weizhuangzi, there were almost no clay and silt in VSD, SD, and MD soils, and their fraction increased only slightly in LD and MD (Fig. 46). The content of very fine sand increased little in SD and MD but dramatically in LD and PD. Coarse sand content kept unchanged from VSD to MD but decreased noticeably in LD. However, the proportion of fine sand decreased very little with the reversal of sandy desertification.

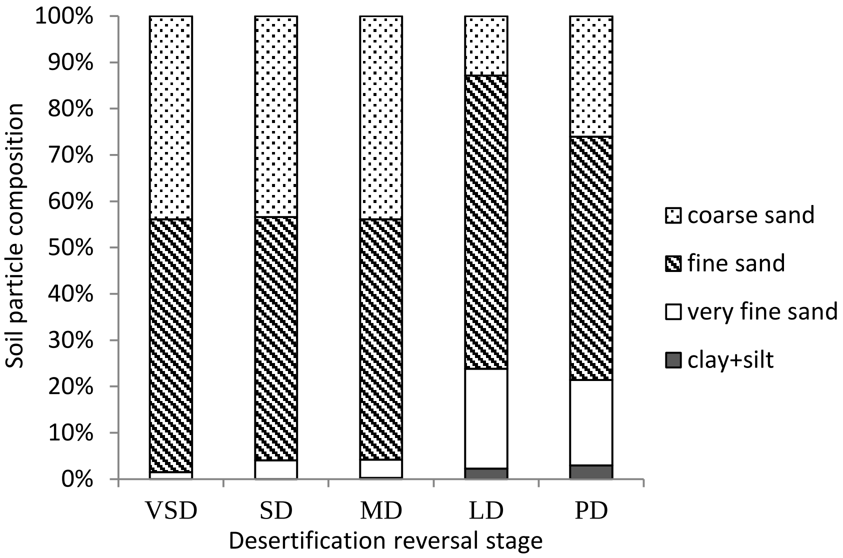

Fig. 46: Responses of soil particle size distribution to the reversal of sandy desertification at Weizhuangzi in southern "Mu Us Sandy Land", China

At the study site of Lijihaizi, the proportion of clay, silt and very fine sand in soil increased regularly with the process of desertification reversal (Fig. 47). At the same time, the content of fine sand and coarse sand in soil decreased dramatically along the reversal sequence. As a result, the total of clay, silt and very fine sand took up 40% of the whole soil particle composition in potential desertification area.

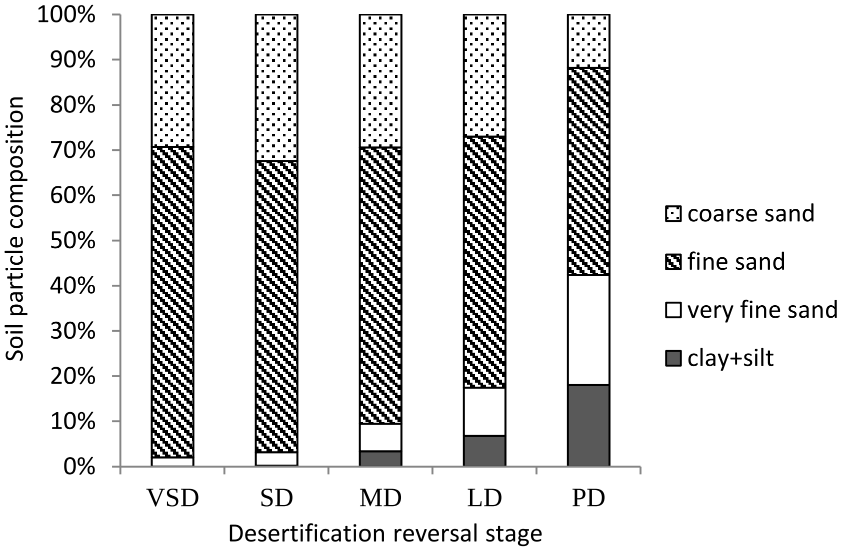

Fig. 47: Responses of soil particle size distribution to the reversal of sandy desertification at Lijihaizi in southern "Mu Us Sandy Land", China

Generally, a clear increasing trend of fine particle (clay, silt and very fine sand) fraction in soils could be observed with the reversal of sandy desertification at every study site. Especially, the amount of coarse sand showed a corresponding decrease.

4.4.2 Soil bulk density

Soil bulk density decreased in general with the reversal of sandy desertification in each study site (Fig. 48). The differences between different reversal stages were significant ($P < 0.05$) in every study site except for Yuzhuangzi and Machang.

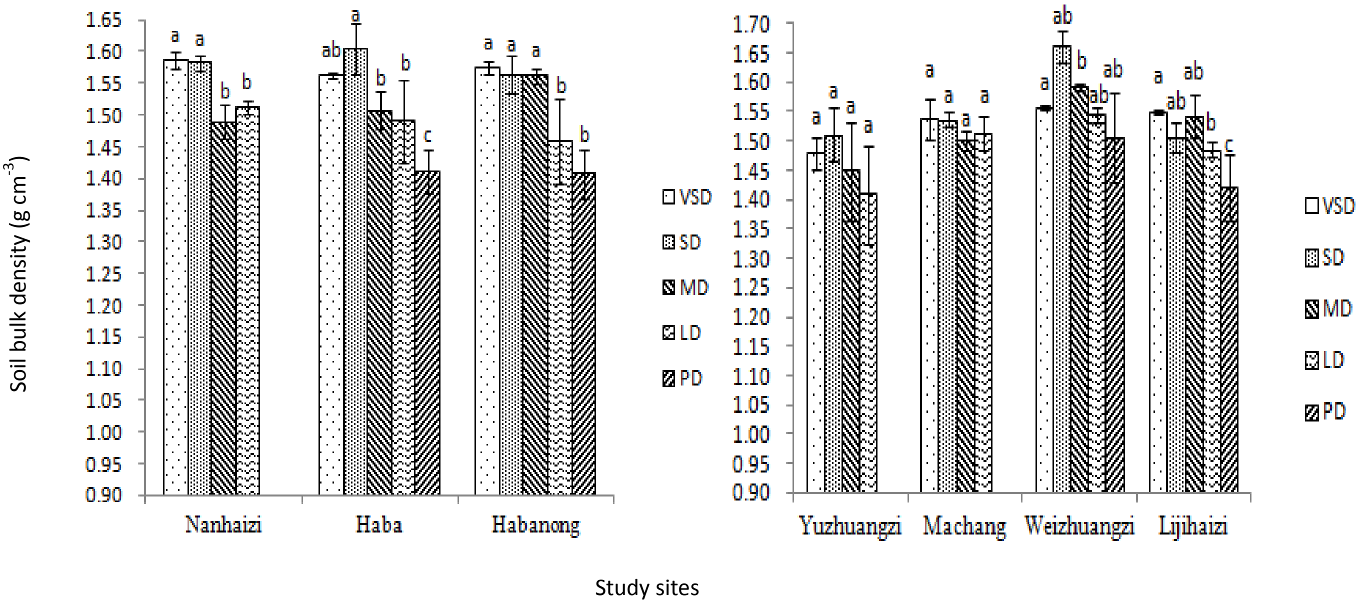

Fig. 48: Responses of soil bulk density to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

4.4.3 Soil water content

The regularity of soil water content showed no clear trends with the reversal of sandy desertification. There were many fluctuations of soil water content along the reversal stages (Fig. 49). At the study site of Nanhaizi and Yuzhuangzi, soil water content showed an increased tendency, whereas at the study site of Machang, soil water content decreased with the reversal process.

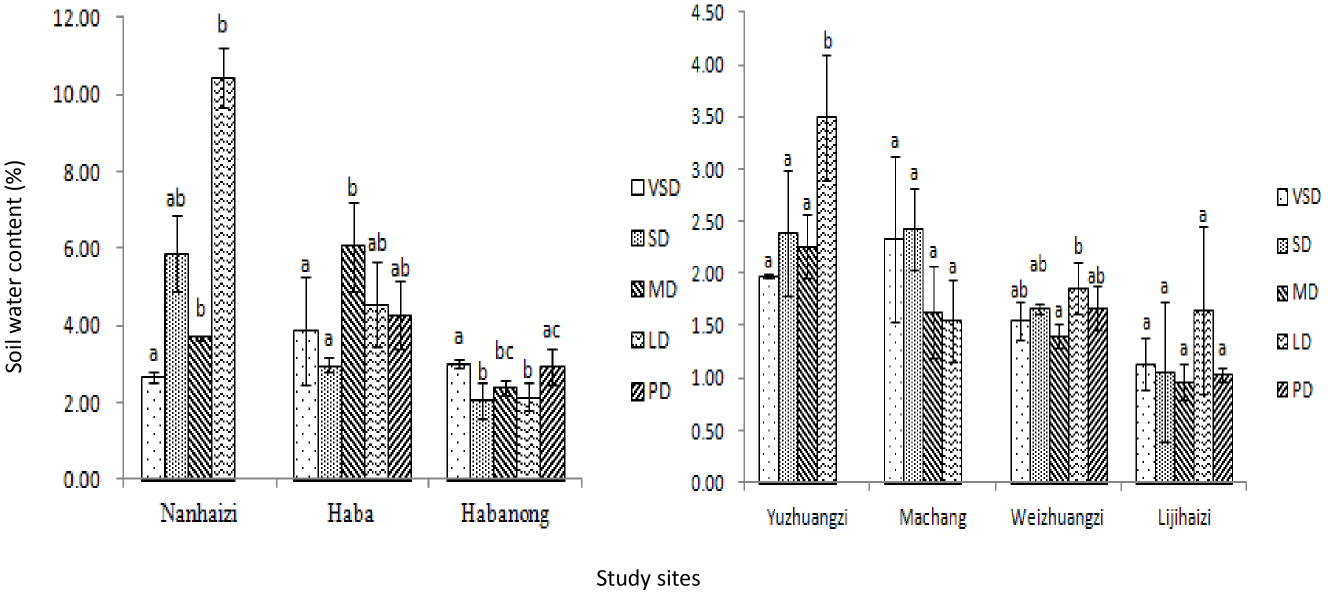

Fig. 49: Responses of soil water content to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

4.5 Responses of soil chemical properties on the local scale to the reversal of sandy desertification

This section will show the results of changes in soil nutrients, pH value, and electrical conductivity with the reversal of sandy desertification. As one of the most important soil properties, changes in soil chemical properties will provide us some implications for the desertification reversal.

4.5.1 Soil nutrients

Soil organic carbon content (SOC) increased dramatically with the reversal of sandy desertification in all study sites (Fig. 50). Changes of SOC along the reversal sequence at the study sites of Habanong, Weizhuangzi and Lijihaizi were highly significant.

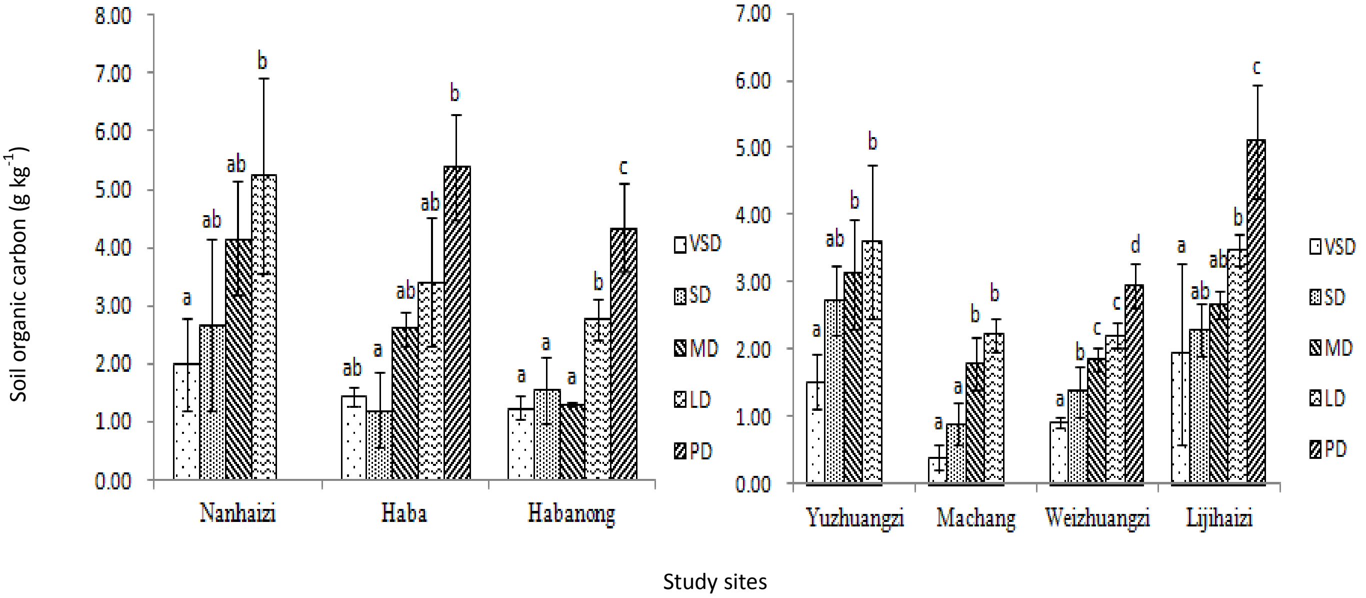

Fig. 50: Responses of soil organic carbon content to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil total nitrogen content (TN) increased dramatically from VSD to PD in all study sites (Fig. 51), although there were some fluctuations between reversal stages at the study site of Haba and Weizhuangzi. At the study site of Haba, TN is slightly (not significantly) higher in MD than that in LD; at the study site of Weizhuangzi, TN kept almost unchanged from VSD to MD. Significant differences ($P < 0.05$) of TN between different reversal stages existed in all study sites. The strongest changes along the reversal sequence occurred at the study sites of Nanhaizi, Habanong, Yuzhuangzi and Lijihaizi.

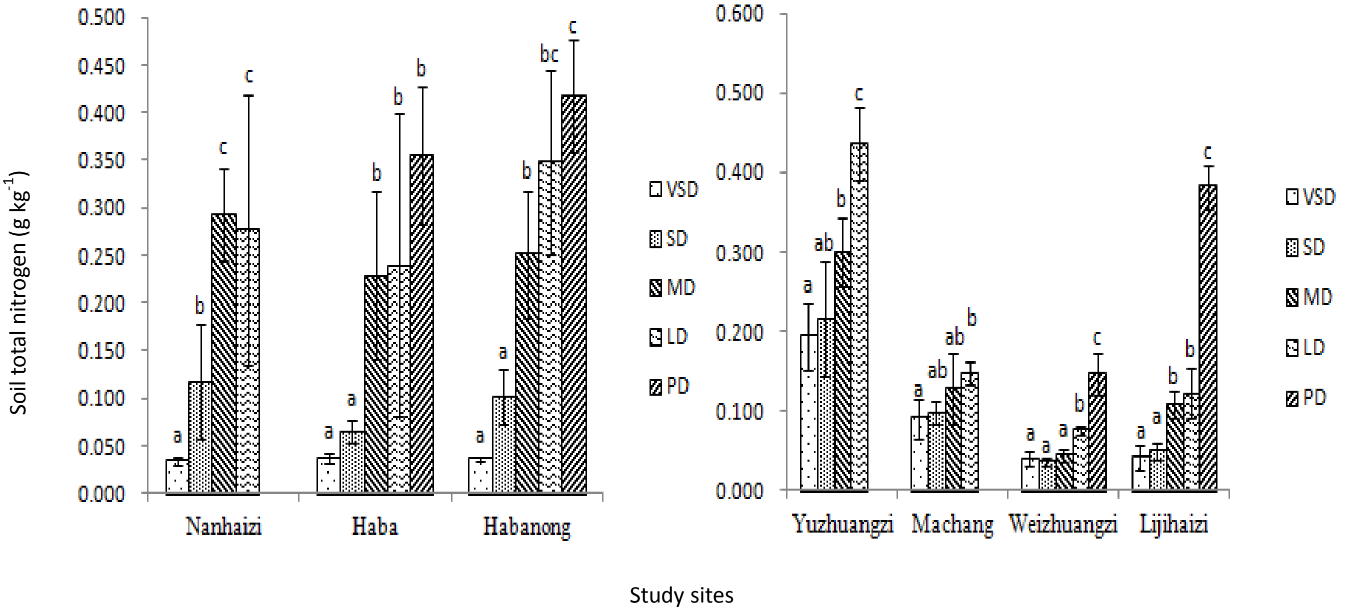

Fig. 51: Responses of soil total nitrogen content to the reversal of sandy desertification in typical desertification areas

in southern "Mu Us Sandy Land", China

Soil total phosphorus content (TP) increased in general with the reversal of sandy desertification in all study site (Fig. 52). Significant differences ($P < 0.05$) between different reversal stages occurred in every study site. The clearest changes along the reversal sequence existed at the study sites of Haba, Habanong, Yuzhuangzi and Lijihaizi. The fluctuations of in content of TP in soils generally were higher than that of TN. At the study site of Nanhaizi, TP was higher in VSD than that in SD; at the study site of Habanong, TP was higher in LD than that in PD; at the study site of Machang, TP was higher in VSD than that in SD; at the study site of Weizhuangzi, TP kept constant from VSD to SD; at the study site of Lijihaizi, TP was higher in VSD than that in SD. Although there were relatively many fluctuations, the changing tendency of TP with the desertification reversal was clear and all the untypical decreases described above were not significant.

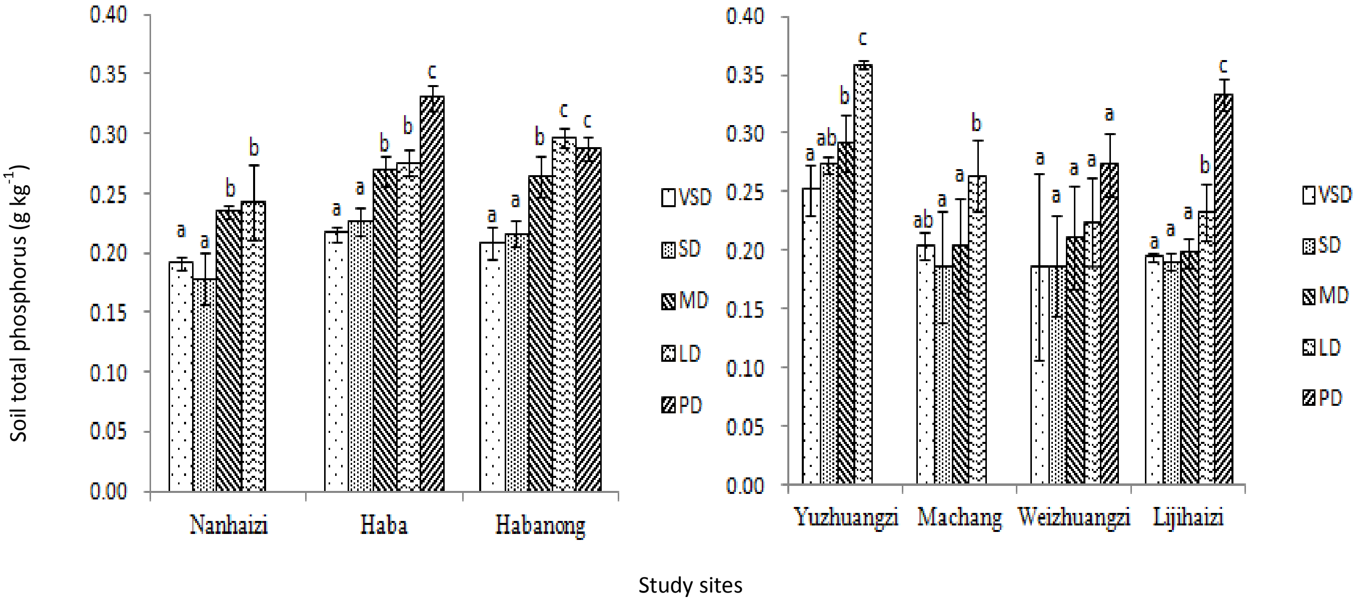

Fig. 52: Responses of soil total phosphorus content to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil total potassium content (TK) changed irregularly along the reversal stages and there were few similar trends in the different study sites (Fig. 53). At the study site of Nanhaizi, TK increased significantly ($P < 0.05$) from VSD to MD and then decreased in LD; at the study site of Haba, TK decreased significantly ($P < 0.05$) from VSD to SD, increased in MD and then kept steady in LD and PD; at the study site of Habanong, TK decreased from VSD to SD, kept almost unchanged from SD to LD and then increased in PD, but all changes were not significant.

At the study site of Yuzhuangzi, TK decreased significantly from VSD to SD, then increased in MD and kept unchanged in LD; at the study site of Machang, TK decreased at first and then increased steadily from SD to LD but all the changes were not significant; at the study site of Weizhuangzi, TK kept at the same level from VSD to SD, then decreased very slightly in LD and kept unchanged in PD, and all changes were not significant; at the study site of Lijihaizi, TK stayed at the similar level from VSD to SD and then increased significantly ($P < 0.05$) from SD to PD.

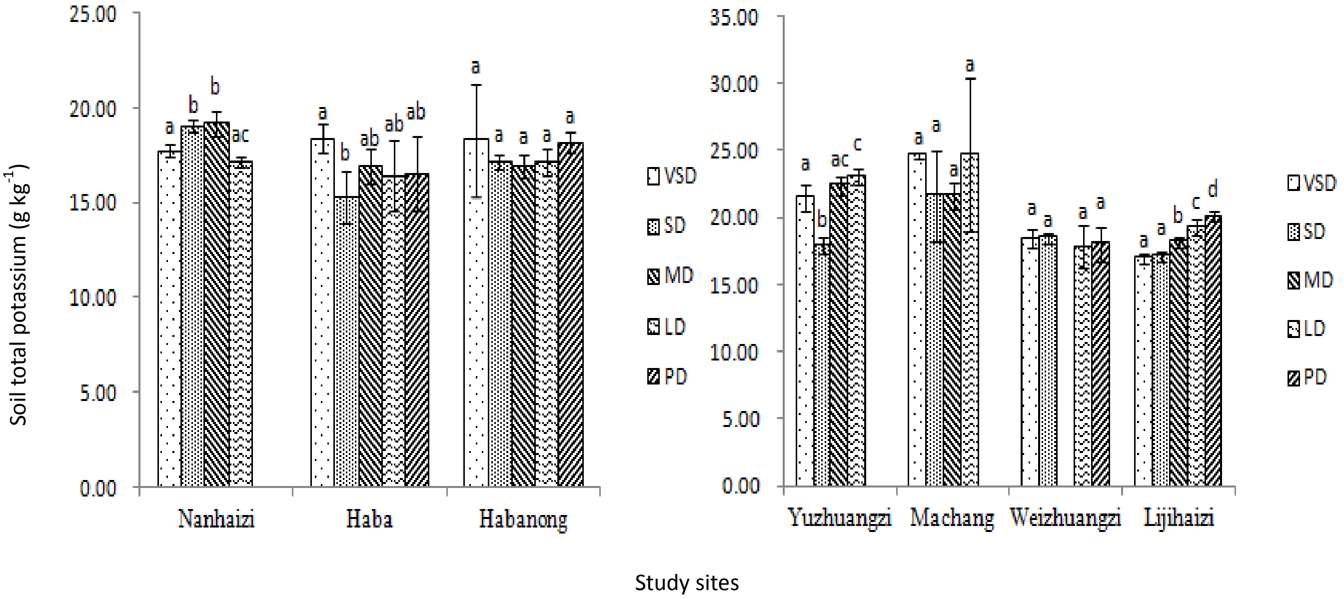

Fig. 53: Responses of soil total potassium content to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil available nitrogen content (AN) increased regularly from VSD to PD in most study site (Fig. 54). Differences of AN between different reversal stages were significant ($P < 0.05$) in all study sites. The most significant changes along the reversal sequence were at the study sites of Weizhuangzi and Lijihaizi. Although the general regularity of AN responding to the desertification reversal was clear, there were some small fluctuations along the reversal sequence. At the study site of Nanhaizi, AN decreased from MD to LD (not significantly); at the study site of Haba, AN decreased slightly from VSD to SD and increased from MD to LD very slightly; at the study site of Yuzhuangzi, AN decreased from VSD to SD (not significantly); at the study site of Machang, AN decreased very slightly from VSD to SD. In spite of the minor fluctuations, an increasing trend in AN showed its clear response to the reversal of sandy desertification.

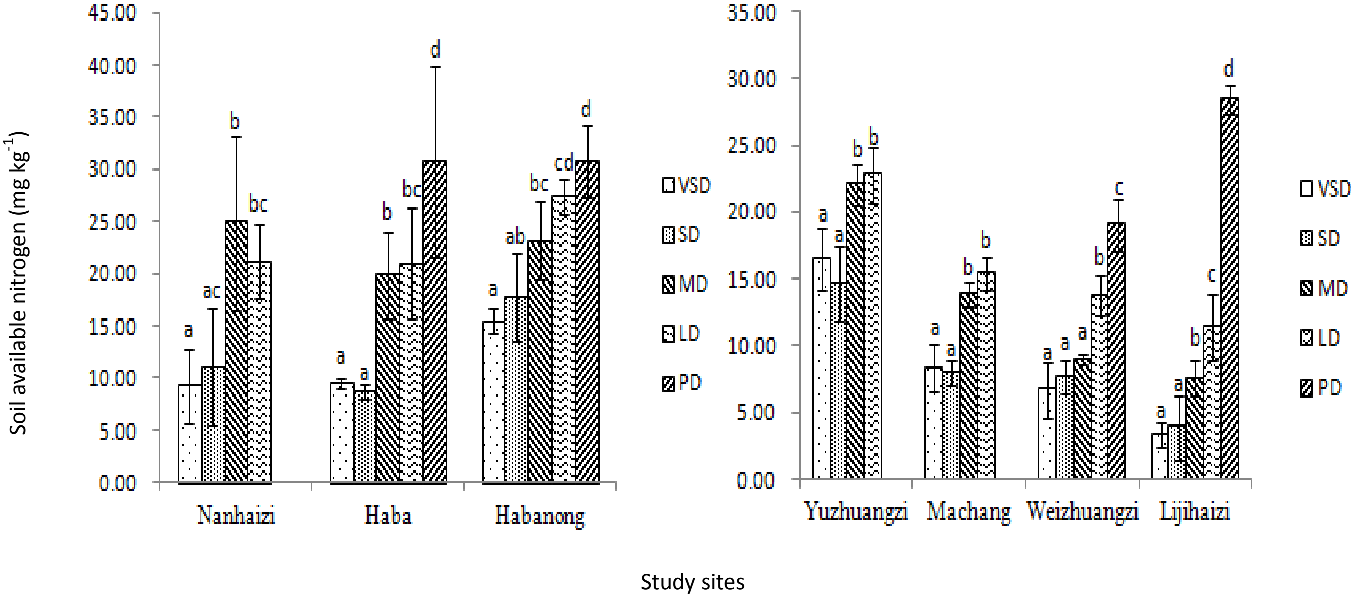

Fig. 54: Responses of soil available nitrogen content to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil available phosphorus content (AP) increased in general with the reversal of sandy desertification in some study sites including Haba, Habanong, Machang, and Lijihaizi, although there were some small fluctuations (Fig. 55). However, in other study sites, AP fluctuated strongly along the reversal sequence and no clear trend along the reversal of desertification was recognizable.

At the study site of Haba and Machang, there was an unexpected decrease of AP from MD to LD areas; at the study site of Habanong and Lijihaizi, there was an unexpected decrease of AP from LD to PD sites. Despite the decreases, a clear trend of increasing AP with the reversal of sandy desertification existed at these sites. Differences of AP between different reversal stages were significant ($P < 0.05$) only between LD and PD in Haba, between VSD, SD and LD in Habanong, between VSD and MD in Machang, and between VSD, MD, LD and PD in Lijihaizi.

At the study site of Weizhuangzi and Yuzhuangzi, AP still showed an increasing tendency along the reversal sequence and the changes were significant ($P < 0.05$) (Fig. 55). At the study site of Weizhuangzi, AP decreased to very low in SD and then increased significantly from SD to PD; at the study site of Yuzhuangzi, AP decreased slightly from VSD to SD, increased significantly from SD to MD and then decreased in LD. At the study site of Nanhaizi, AP decreased steadily from VSD to MD, then increased dramatically in LD and the changes were significant.

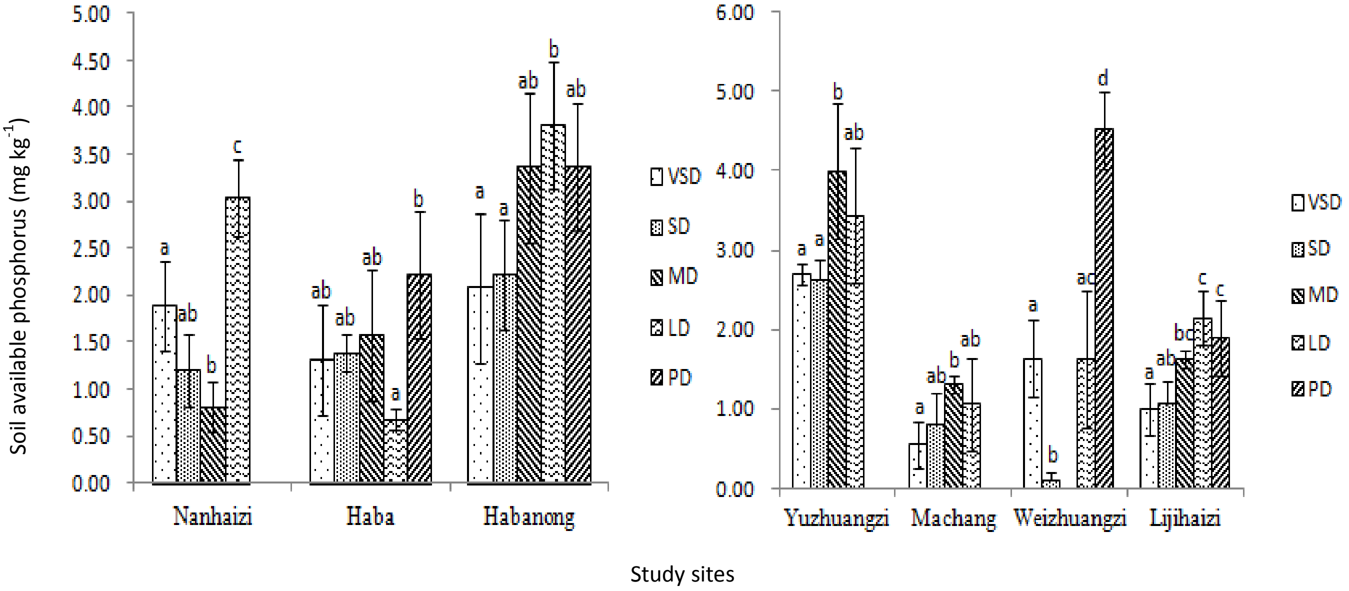

Fig. 55: Responses of soil available phosphorus content to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil available potassium content (AK) increased along the reversal sequence in all study sites (Fig. 56). Significant differences ($P < 0.05$) of AK between different desertification reversal stages in each study site existed, and the strongest differences were recorded at the study site of Nanhaizi. In spite of the general increasing trend of AK content, two exceptions existed. AK decreased from VSD to SD at the study site of Yuzhuangzi and kept unchanged from MD to LD at the study site of Lijihaizi. The TK, AN, AP and AK content of the soil were all higher in the VSD area than those in the SD area at the study site of Yuzhuangzi, probably because of the local topography. The relative low position of the VSD area probably facilitated the availability of soil available nutrients in this plot.

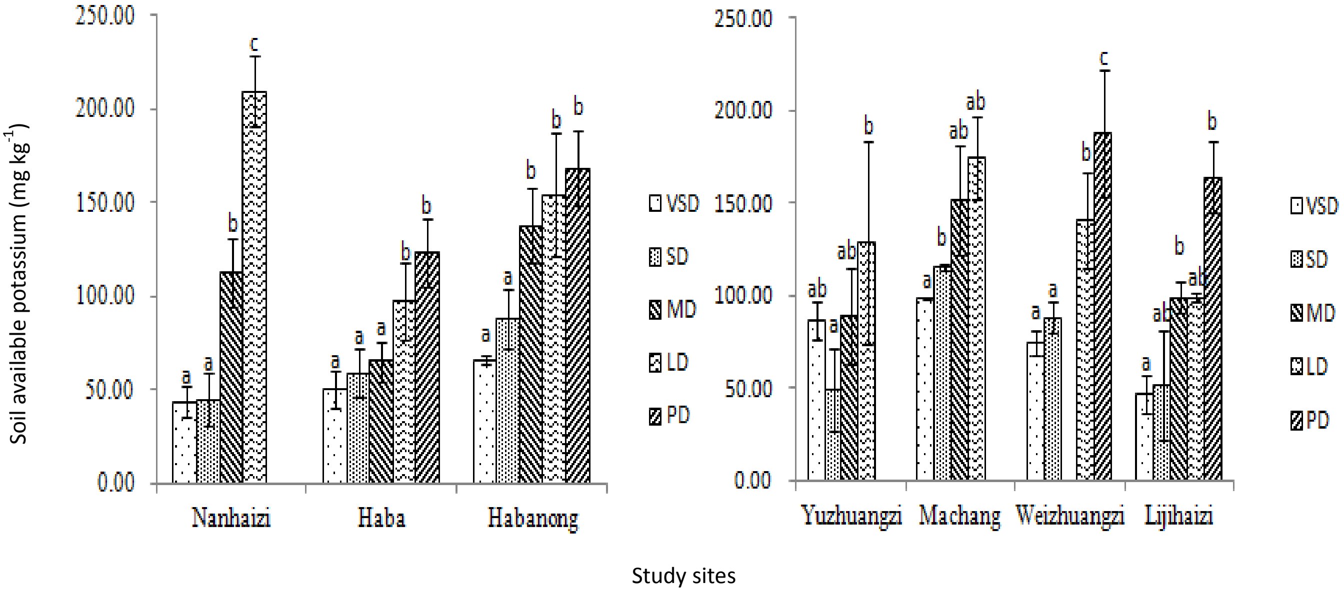

Fig. 56: Responses of soil available potassium content to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

4.5.2 Soil pH and electrical conductivity

At some sites, soil pH showed a decreasing tendency with the reversal of sandy desertification, but generally many fluctuations recorded (Fig. 57). Significant differences ($P < 0.05$) of soil pH between different reversal stages were only observed at the study sites of Nanhaizi, Habanong, Yuzhuangzi, Weizhuangzi, and Lijihaizi.

A clear response of soil pH to the reversal of sandy desertification is shown at the study sites of Nanhaizi and Habanong. Soil pH decreased along the reversal sequence almost without fluctuations in these two study sites. At the study sites of Haba, soil pH decreased dramatically from MD to LD. At the study site of Weizhuangzi and Lijihaizi, and from VSD to PD, respectively, but the two or three "earlier" reversal stages always had similar values in soil pH (VSD and SD at the study site of Haba; MD and LD at the study sites of Weizhuangzi and Lijihaizi).

At the study site of Yuzhuangzi and Machang, soil pH fluctuated along the reversal sequence without any regularity, although there was significant difference of pH between different reversal stages at the study site of Yuzhuangzi.

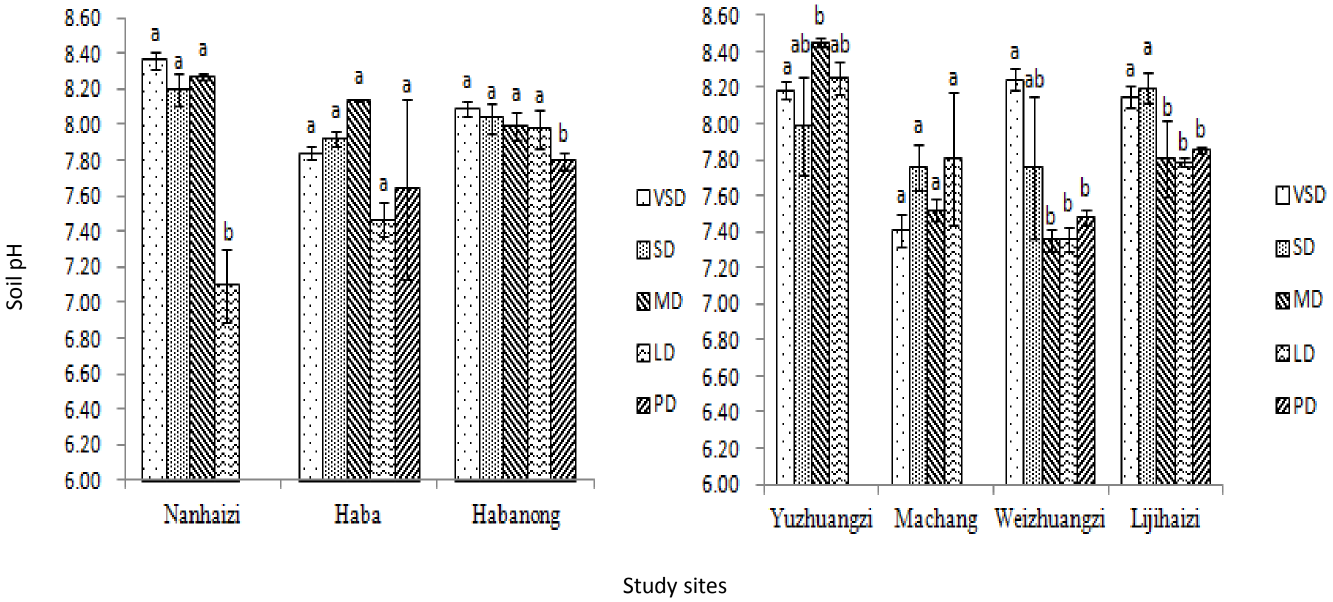

Fig. 57: Responses of soil pH value to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil electrical conductivity (EC) increased with the sandy desertification reversal in most study site except for Haba and Machang (Fig. 58). Differences of EC between different reversal stages were significant ($P < 0.05$), however, not large in most study sites, and the largest differences occurred at the study site of Habanong. In addition, at some sites fluctuations against the main trend existed. At the study site of Machang, EC decreased from MD to LD; at the study site of Weizhuangzi, EC decreased from SD to MD; at the study site of Haba, EC decreased significantly from MD to PD.

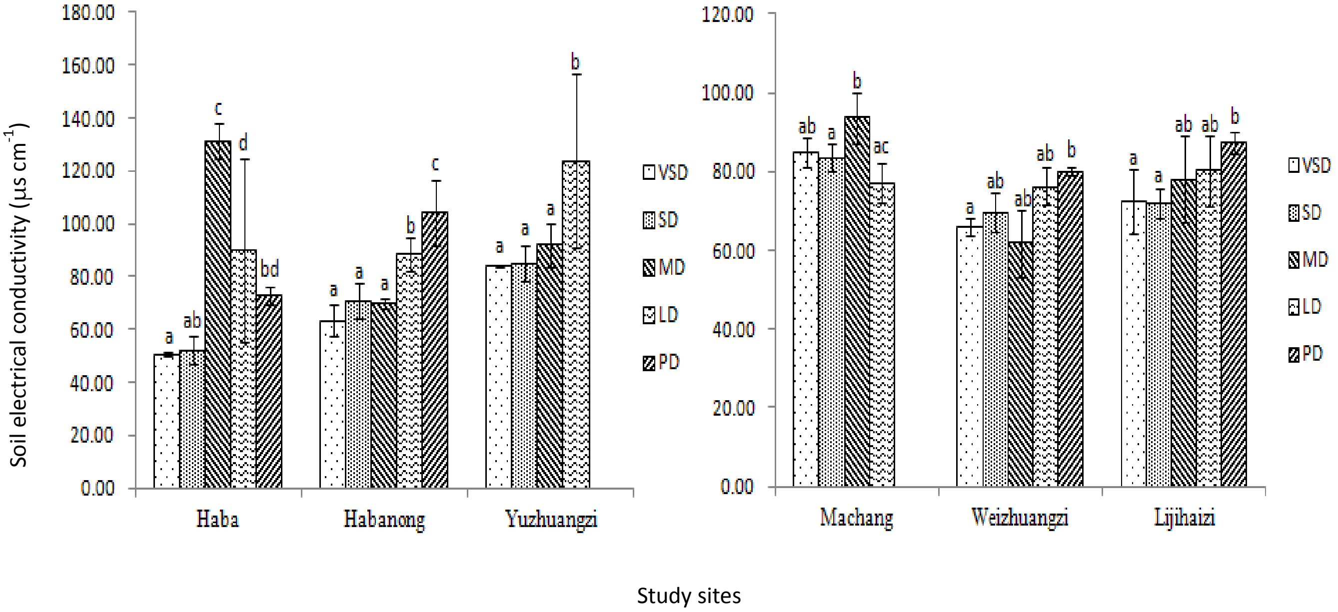

Fig. 58: Responses of soil electrical conductivity to the reversal of sandy desertification in typical desertification

areas in southern "Mu Us Sandy Land", China

4.6 Responses of soil biological activities on the local scale to the reversal of sandy desertification

Soil biological activities analyzed in this study include soil enzyme activities and soil respiration rate. Both of them are sensitive to environmental changes. Results of soil biological activities are therefore especially significant for indicating the reversal of sandy desertification.

4.6.1 Soil enzyme activities

Soil catalase activity (CAT) increased in general with the reversal of sandy desertification in each study site (Fig. 59). There were significant differences ($P < 0.05$) of CAT between different reversal stages in every study site, especially in Haba, Habanong, Weizhuangzi, and Lijihaizi. Against the general trend, a minor decrease (not significant) of CAT from LD to PD existed in both the study sites of Habannong and Lijihaizi. At the study site of Nanhaizi, there was a significant decrease ($P < 0.05$) from MD to LD.

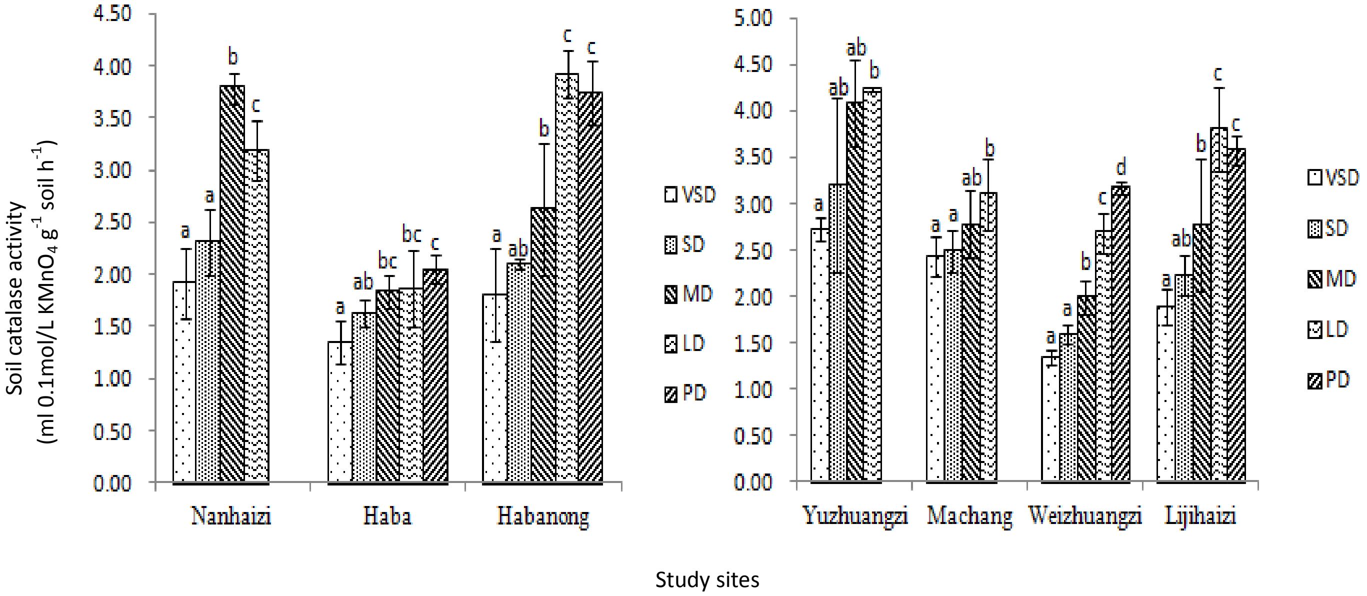

Fig. 59: Responses of soil catalase activity to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil alkaline phosphatase activity (PHO) generally increased along the sequence of desertification reversal in all study sites (Fig. 60). Differences in PHO between different reversal stages were significant ($P < 0.05$) in each study site except for Nanhaizi. The most pronounced differences between different reversal stages occurred at the study sites of Haba and Yuzhuangzi. Against the general trend, at the study site of Nanhaizi, PHO decreased slightly from MD to LD; at the study site of Habanong, PHO decreased (not significantly) from SD to MD; at the study site of Machang, PHO decreased significantly ($P < 0.05$) from MD to LD.

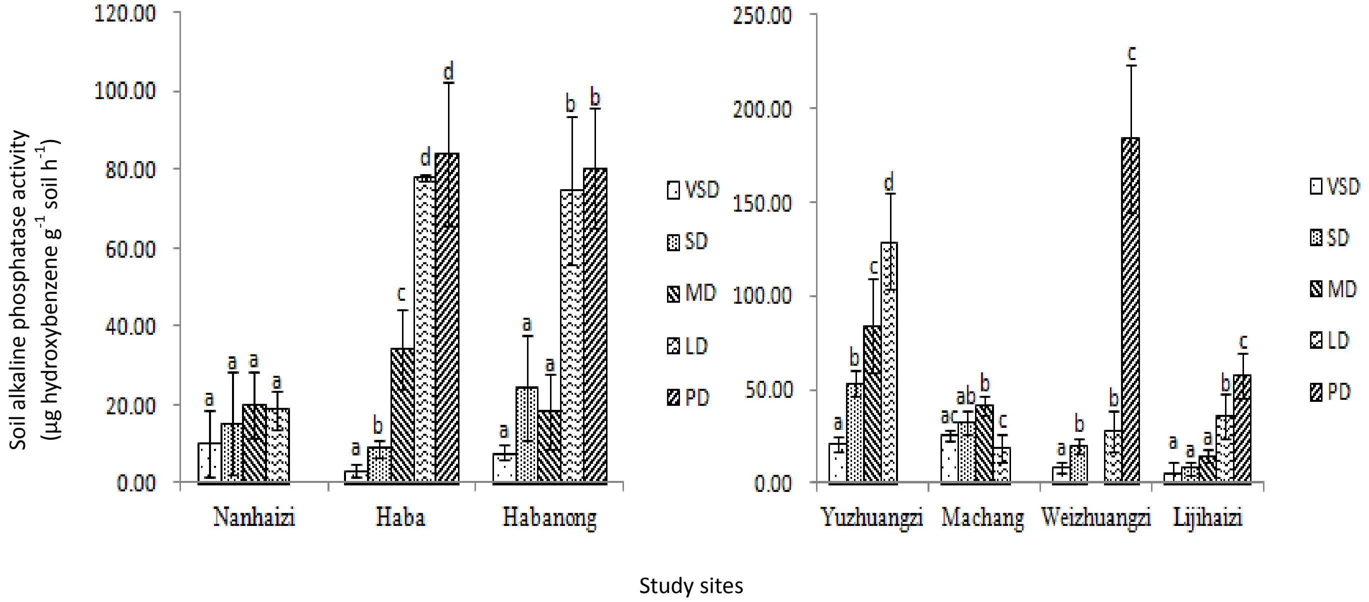

Fig. 60: Responses of soil alkaline phosphatase activity to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil urease activity (URE) mainly increased with sandy desertification reversal in all study sites except for Nanhaizi (Fig. 61). There were significant differences ($P < 0.05$) of URE between different reversal stages in every study site, and the most pronounced differences existed at the study site of Weizhuangzi and Lijihaizi. The fluctuations of URE occurred at the study site of Nanhaizi and Haba, where URE decreased significantly from MD to LD, and decreased insignificantly from VSD to SD, respectively.

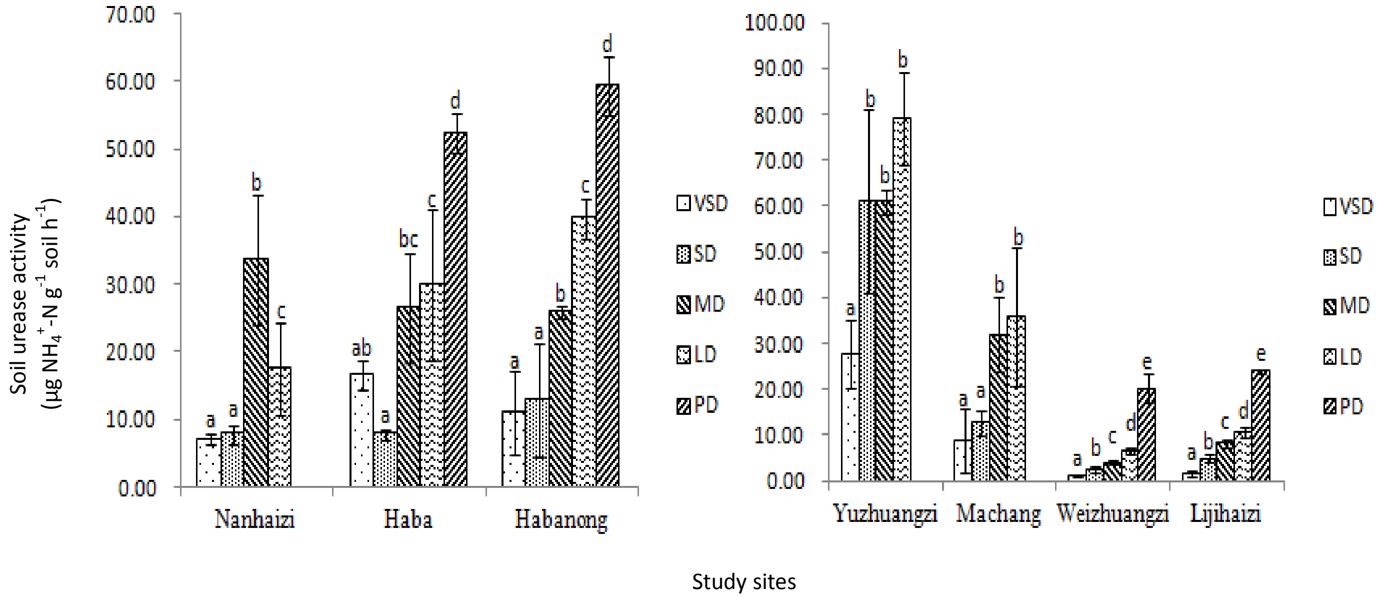

Fig. 61: Responses of soil urease activity to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil invertase activity (INV) showed a tendency of increase along the reversal sequence in all study sites (Fig. 62), however, fluctuations were recorded in some study sites, including Nanhaizi, Yuzhuangzi, and Lijihaizi. Differences of INV between different reversal stages were significant ($P < 0.05$) in every study site, especially at the study sites of Haba, Machang, and Weizhuangzi. Against the trend, at the study site of Nanhaizi a significant decrease from MD to LD occurred; at the study site of Yuzhuangzi, there was a slight decrease from VSD to SD; at the study site of Weizhuangzi, INV decreased insignificantly from VSD to MD.

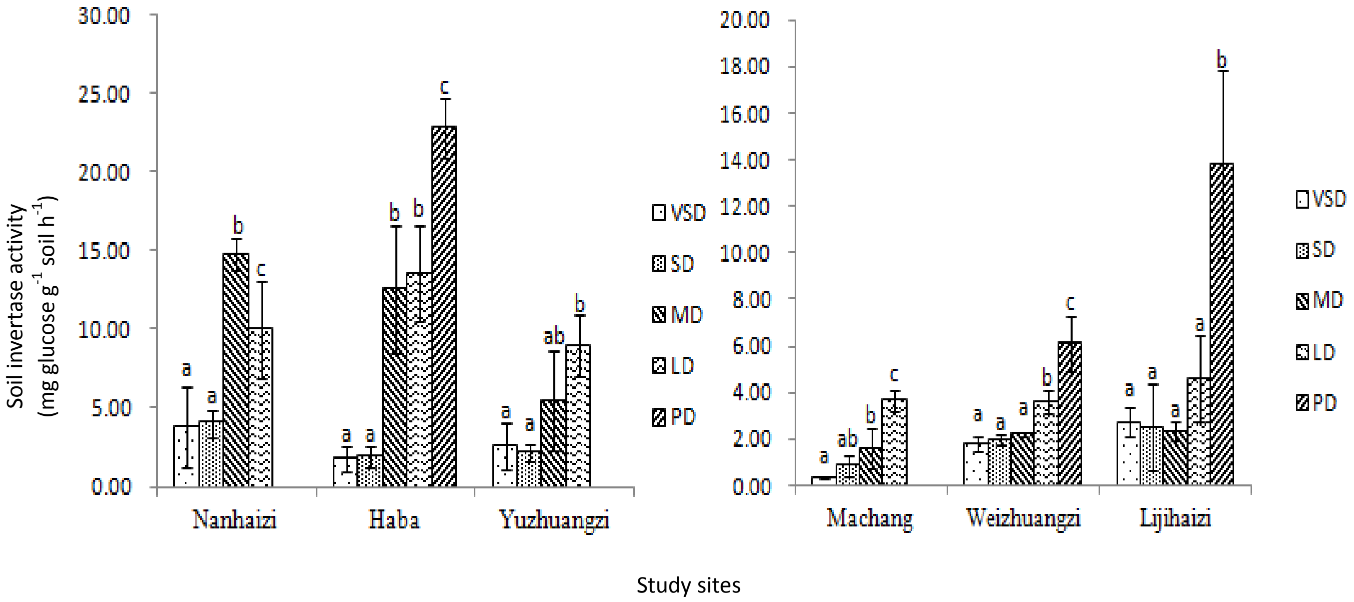

Fig. 62: Responses of soil invertase activity to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

Soil protease activity (PRO) generally increased with the reversal of sandy desertification at all study sites (Fig. 63). There were significant differences ($P < 0.05$) of PRO between different reversal stages. The most pronounced changes were measured at the study sites of Nanhaizi and Haba. Although the general increasing trend of PRO along the reversal sequence was clear, a decrease from VSD to SD (significant at the study site of Yuzhuangzi, and insignificant at the study site of Nanhaizi and Lijihaizi) was recorded.

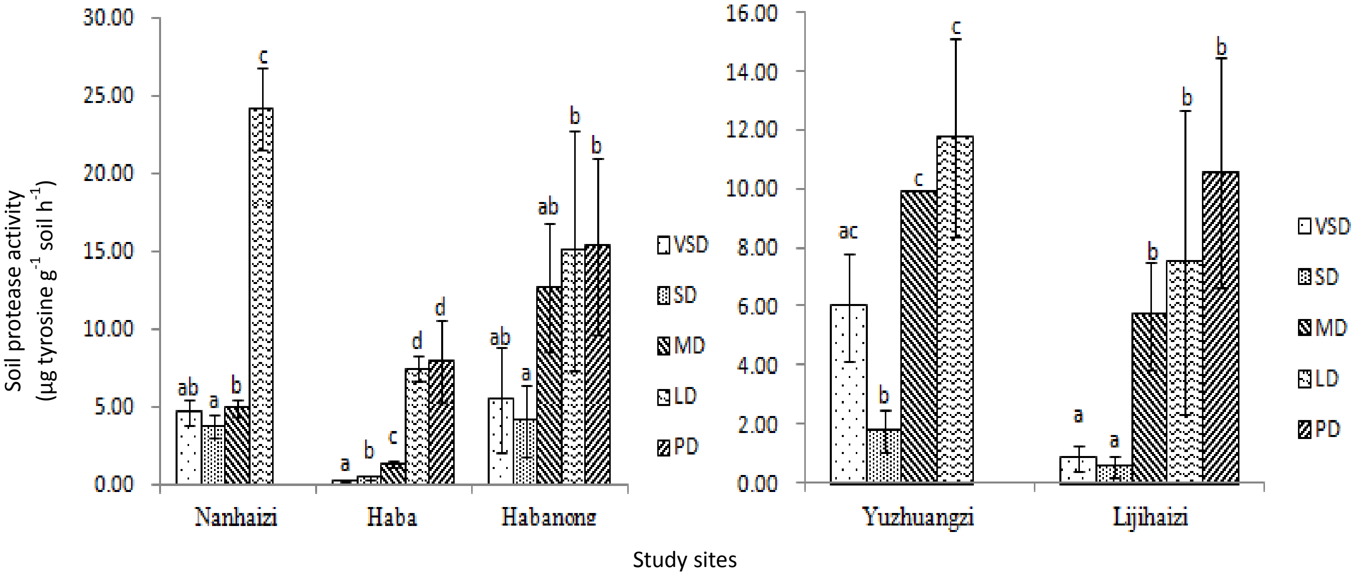

Fig. 63: Responses of soil protease activity to the reversal of sandy desertification in typical desertification areas in southern "Mu Us Sandy Land", China

4.6.2 Soil respiration rate

Soil respiration rate (RES) increased steadily with the reversal of sandy desertification at each studied daytime (Fig. 64). Significant differences ($P < 0.05$) between different reversal stages were measured at each studied daytime, especially at 12:00 noon. Despite the general trend, two exceptions including an insignificant decrease of RES from MD to LD at 8:00 a.m. and from LD to PD at 10:00 a.m. were recorded.

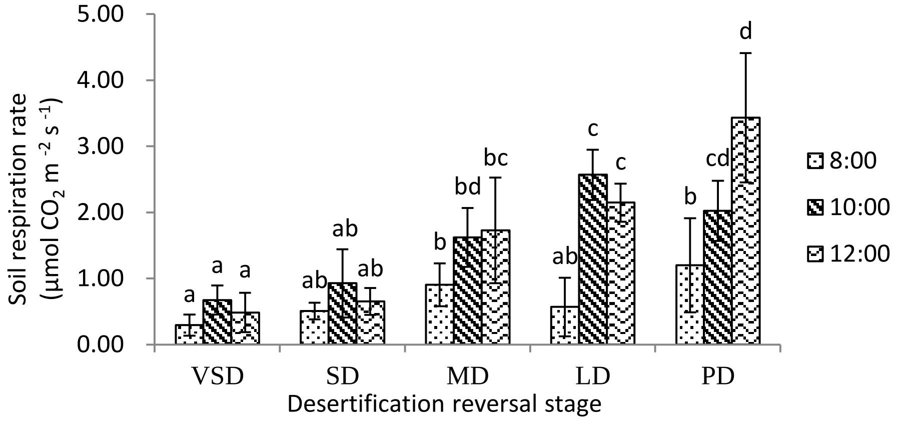

Fig. 64: Responses of soil respiration rate to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China*

*Different letters within the same measured time (columns with the same legend) showed significant differences between the different desertification reversal stages at $P < 0.05$ level.

4.7 Responses of vegetation and soil properties on the regional scale to the reversal of sandy desertification

Both plant cover and aboveground biomass increased significantly ($P < 0.05$) from VSD to PD on the regional scale (Fig. 65). Differences of cover and aboveground biomass between every two reversal stages were both significant, except for differences between MD and LD, as well as between LD and PD for both parameters.

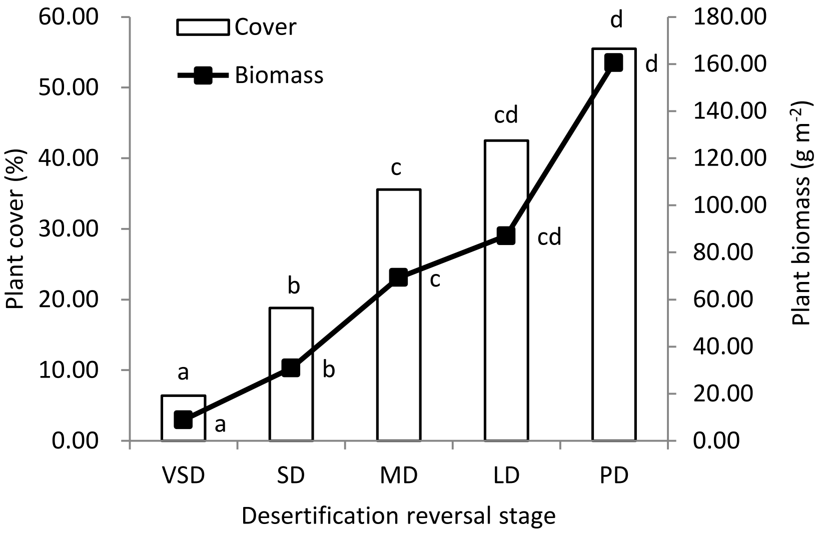

Fig. 65: Responses of plant cover and aboveground biomass to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

The proportion of clay and silt, and that of very fine sand in soil both increased steadily from VSD to PD on the regional scale (Fig. 66). There were significant differences ($P < 0.05$) between different reversal stages for both clay and silt, and very fine sand.

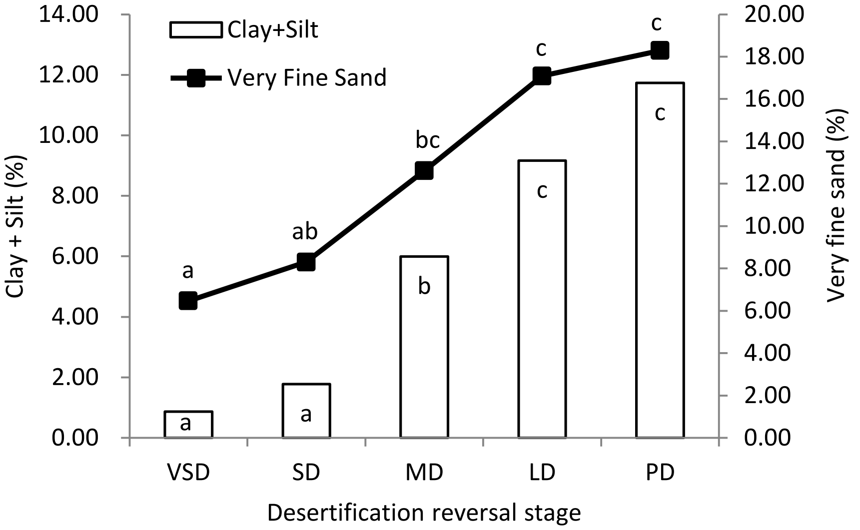

Fig. 66: Responses of clay, silt and very fine sand proportion in the soil to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

The proportion of fine sand in the soil on the regional scale decreased gradually from VSD to PD and that of coarse sand decreased also from VSD to LD but then kept almost unchanged in PD (Fig. 67). Differences of fine and coarse sand between different reversal stages were both significant ($P < 0.05$).

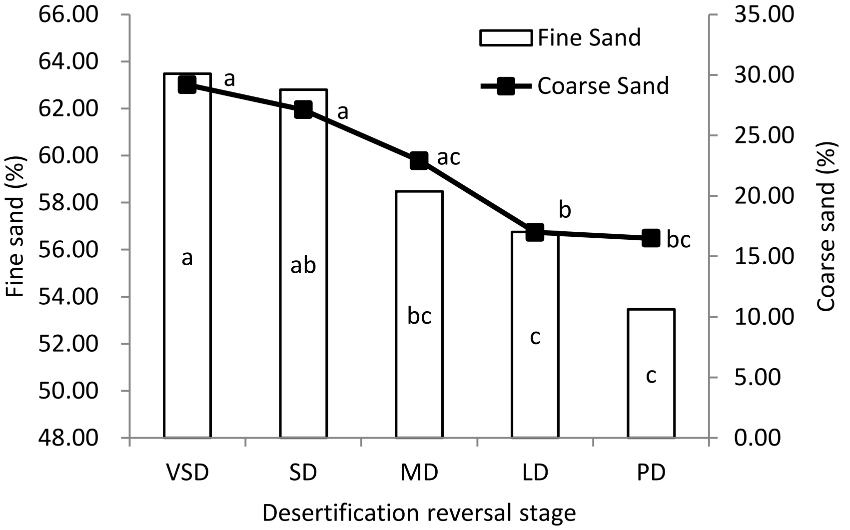

Fig. 67: Responses of fine sand and coarse sand proportion in the soil to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

Soil bulk density increased slightly from VSD to SD on the regional scale and then decreased significantly ($P < 0.05$) from SD to PD (Fig. 68). Soil water content on the regional scale increased at first from VSD to SD and then decreased gradually from SD to PD, but all these changes were not significant ($p > 0.05$).

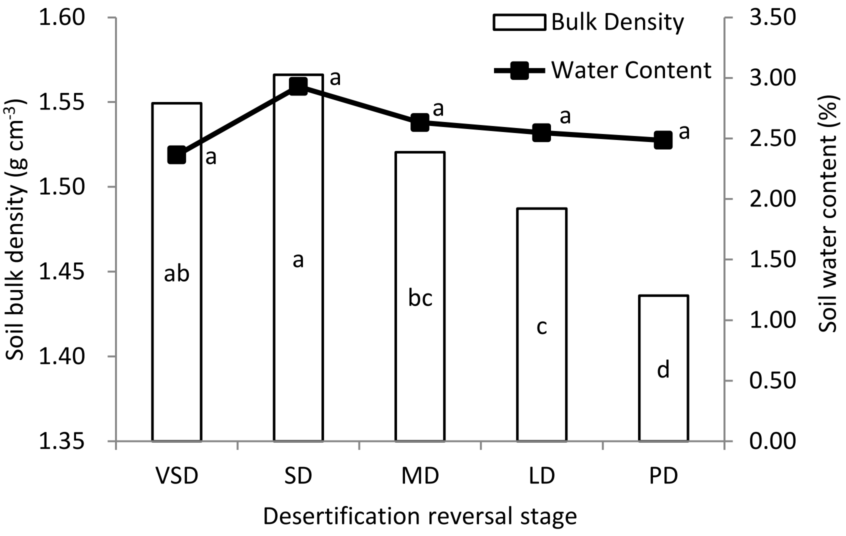

Fig. 68: Responses of soil bulk density and water content to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

Both soil organic carbon (SOC) and soil total nitrogen (TN) on the regional scale increased steadily along the desertification reversal sequence (Fig. 69). There were significant differences ($P < 0.05$) between different reversal stages for both soil parameters, especially for TN.

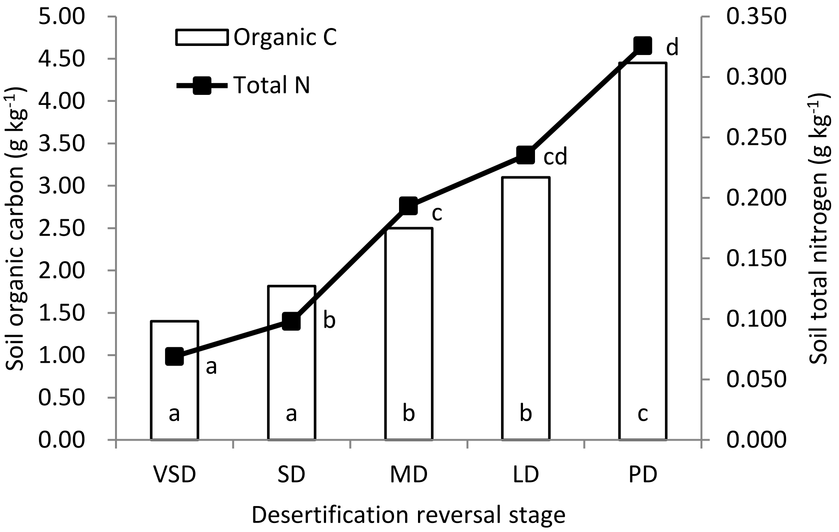

Fig. 69: Responses of soil organic carbon and total nitrogen to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

Soil total potassium (TK) on the regional scale showed the following changing tendency along the reversal sequence: LD > MD > VSD > PD > SD (Fig. 70). There was no significant difference of TK between any two reversal stages. Soil total phosphorus (TP) on the regional scale showed a tendency of increase with the reversal of sandy desertification, although it kept almost unchanged at the very beginning from VSD to SD. There were significant differences of TP between different reversal stages (P < 0.05).

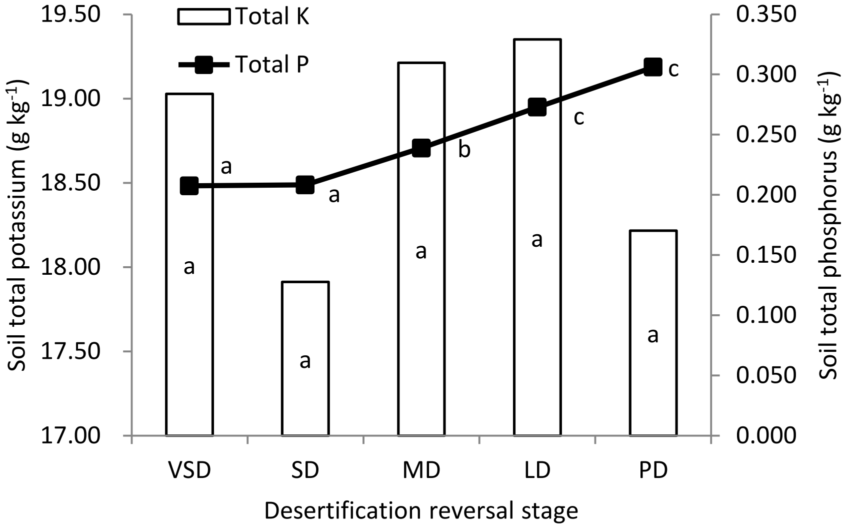

Fig. 70: Responses of soil total potassium and total phosphorus to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

On the regional scale, soil available nitrogen (AN) increased gradually from VSD to PD (Fig. 71). Soil available phosphorus (AP) also showed an increasing tendency with the reversal sequence, while the trend of AP seemed to be weaker than those of AN. AP decreased at first from VSD to SD and increased very slightly from MD to LD. In spite of these fluctuations, significant differences (P < 0.05) of both AN and AP between different reversal stages were recorded.

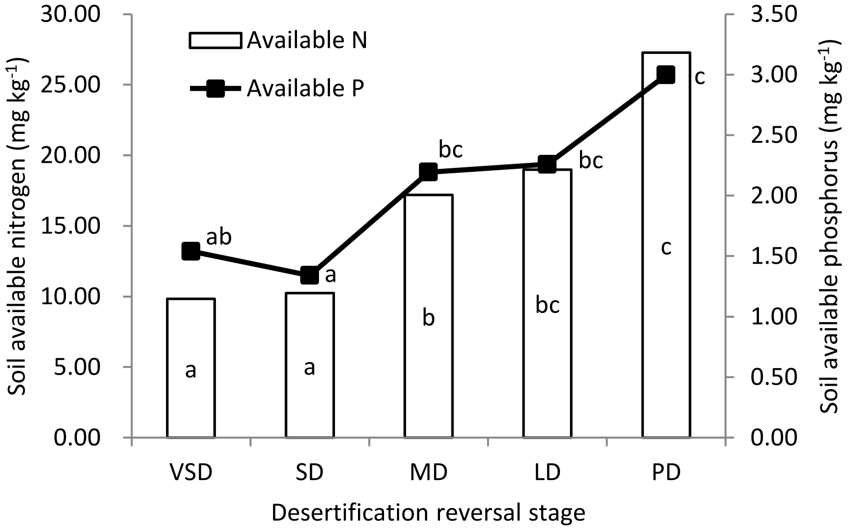

Fig. 71: Responses of soil available nitrogen and available phosphorus to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

Soil available potassium (AK) increased steadily with the reversal of sandy desertification on the regional scale

(Fig. 72). Soil catalase activity (CAT) showed the similar tendency on the regional scale, although there was a slight decrease of CAT from LD to PD. There were significant differences ($P < 0.05$) between different reversal stages for both AK and CAT.

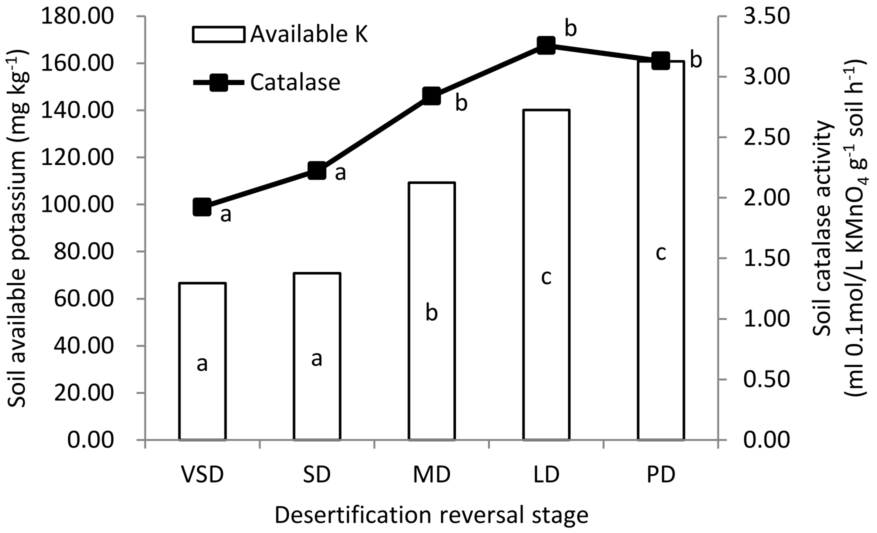

Fig. 72: Responses of soil available potassium and catalase activity to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

Soil pH mostly decreased with the reversal of sandy desertification on the regional scale, although a non-significant increase from LD to PD occurred (Fig. 73). There were significant differences ($P < 0.05$) of soil pH between different reversal stages. Soil electrical conductivity (EC) on the regional scale increased significantly ($P < 0.05$) at first from VSD to MD and then decreased insignificantly ($p > 0.05$) from MD to PD (Fig. 73).

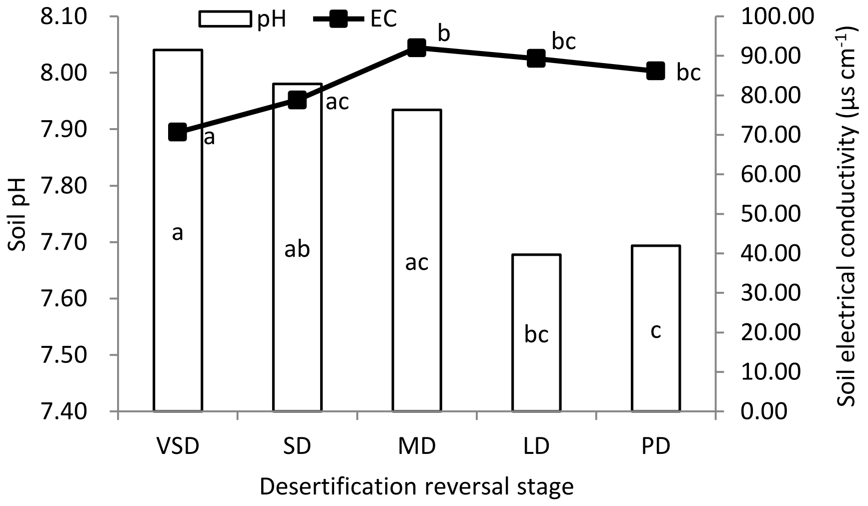

Fig. 73: Responses of soil pH and electrical conductivity to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

On the regional scale, both soil urease activity (URE) and soil phosphatase activity (PHO) increased dramatically from VSD to PD (Fig. 74). Differences of both URE and PHO between different reversal stages were significant ($P < 0.05$), especially for PHO.

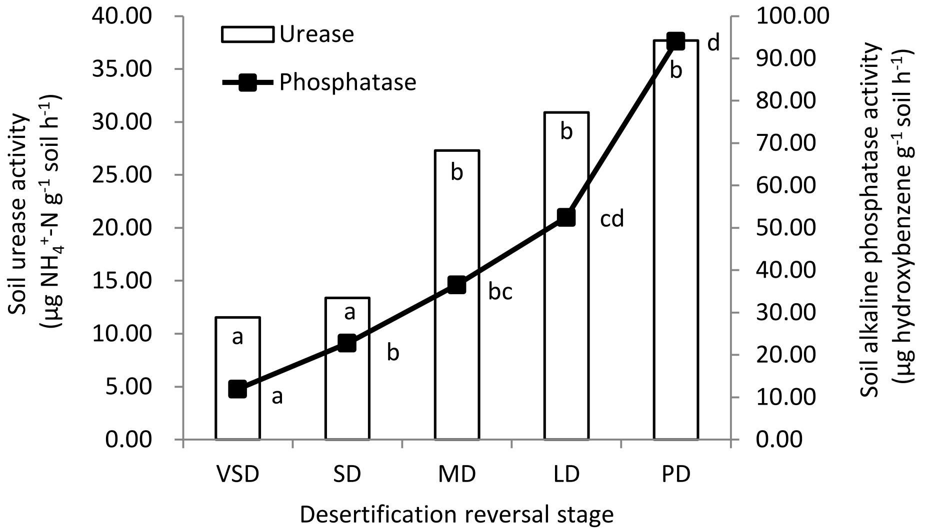

Fig. 74: Responses of soil urease and alkaline phosphatase activity to the reversal of sandy desertification on the regional scale in southern "Mu Us Sandy Land", China

Soil invertase activity (INV) increased significantly ($P < 0.05$) with the reversal of sandy desertification on the regional scale (Fig. 75). Significant differences of INV occurred between VSD and any of MD, LD and PD, between SD and any of MD, LD and PD and between MD and PD. Soil protease activity (PRO) also showed an increasing tendency on the regional scale, although it decreased from VSD to SD and from LD to PD (not significantly), respectively. There were also significant differences ($P < 0.05$) of PRO between different reversal stages.

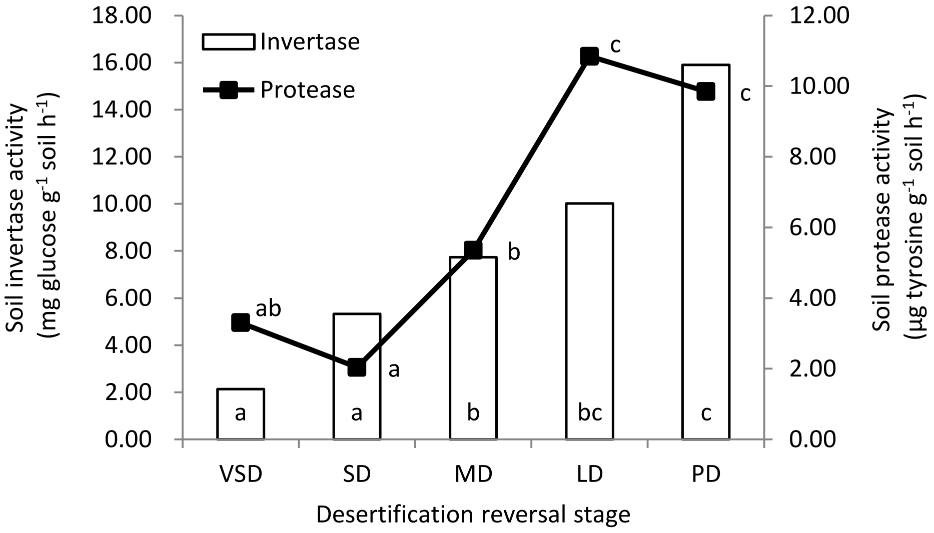

Fig. 75: Responses of soil invertase and protease activity to the reversal of sandy desertification on the regional scale

in southern "Mu Us Sandy Land", China

4.8 Responses of micrometeorological indices to the reversal of sandy desertification

This section will introduce changes in micrometeorological indices including air temperature, wind speed, illumination, and soil temperatures at different depth, with the reversal of desertification. Results will be shown at each full hour in day time.

4.8.1 Air temperature

Air temperature (TEM) generally increased with the reversal of sandy desertification in every daytime before 15:00, but after that it decreased slightly in the main along the reversal sequence (Fig. 76). TEM in each reversal stage increased at first and then decreased in daytime hours from 8:00 to 19:00. TEM in VSD and SD both fluctuated as it changed from 8:00 to 19:00, whereas TEM in MD and PD increased and then decreased steadily along the time sequence, without any fluctuation. The highest TEM were at around 14:00.

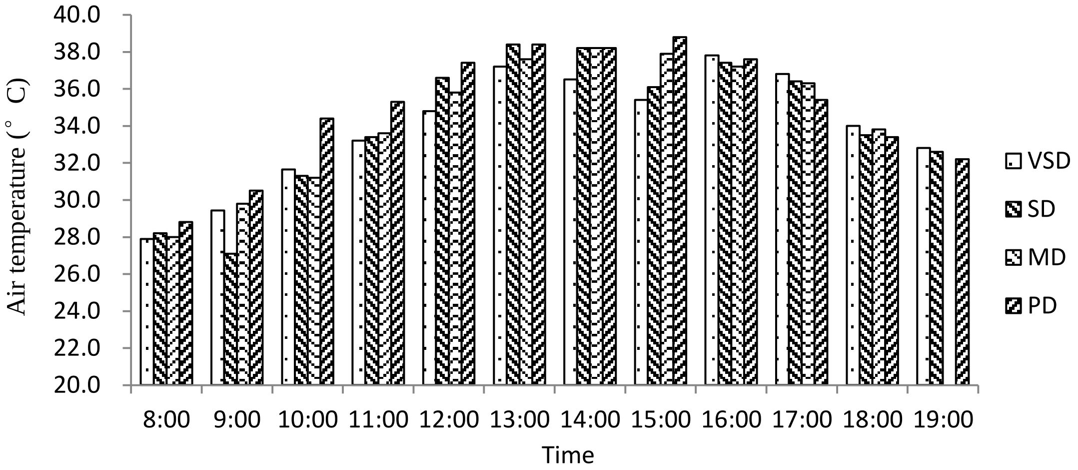

Fig. 76: Responses of air temperature on sunny day to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

4.8.2 Wind speed

Wind speed decreased in general with the reversal of sandy desertification in each hour except for 8:00, 13:00, 16:00, and 18:00 (Fig. 77). Large wind speed happened mainly in the afternoon.

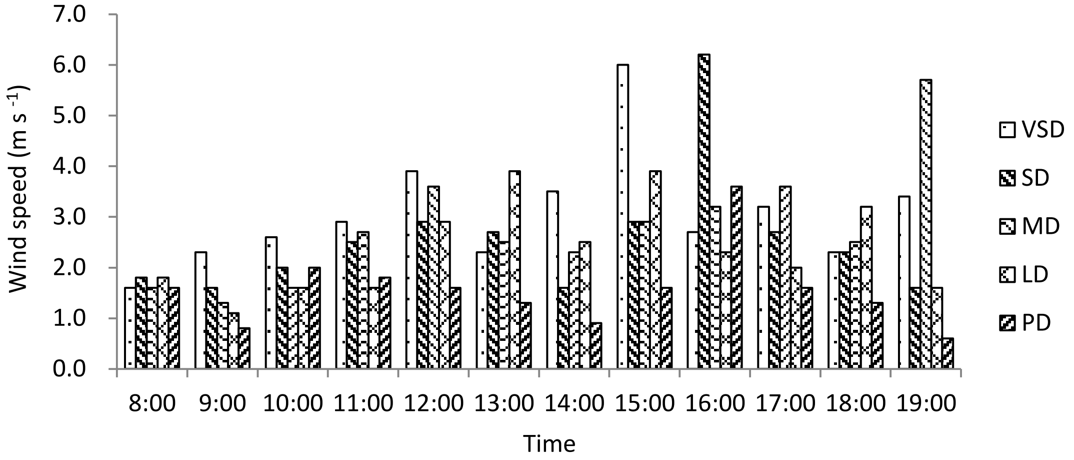

Fig. 77: Responses of wind speed on sunny day to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

4.8.3 Illumination

Solar illumination showed an increased tendency with the reversal of sandy desertification at 8:00, 9:00, 15:00, 16:00, 17:00 and 18:00 (Fig. 78). However, solar illumination fluctuated from VSD to PD at each daytime from 10:00 to 14:00, and it decreased from VSD to SD, then increased from SD to LD, and then decreased again in PD. Solar illumination in SD and MD were almost the lowest in all reversal stages at each daytime during this period.

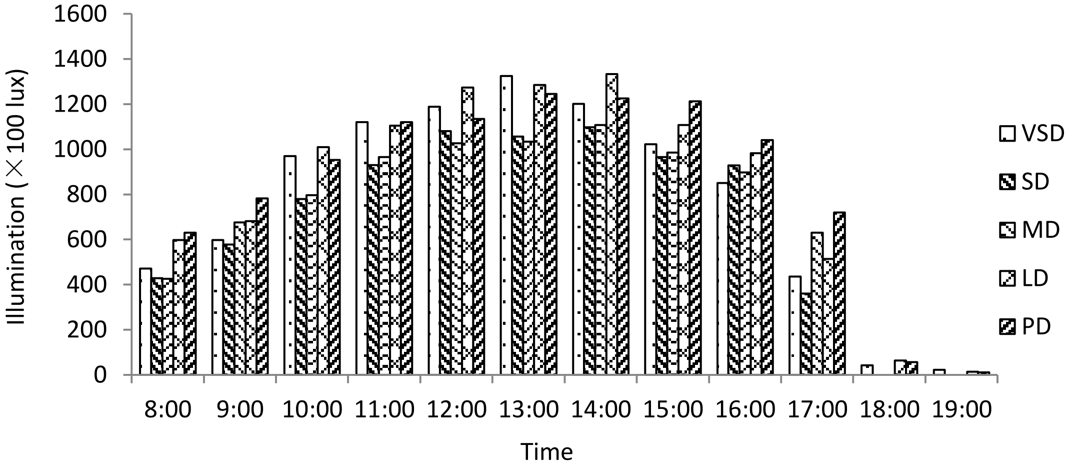

Fig. 78: Responses of solar illumination on sunny day to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

4.8.4 Soil temperature

Soil temperature at 5cm depth (TEM5) showed a decrease tendency with the reversal of sandy desertification at each daytime from 8:00 to 13:00, whereas at each daytime from 14:00 to 19:00, TEM5 decreased at first from VSD to SD, then increased from SD to MD, decreased again from MD to LD and increased at last from LD to PD (Fig. 79).

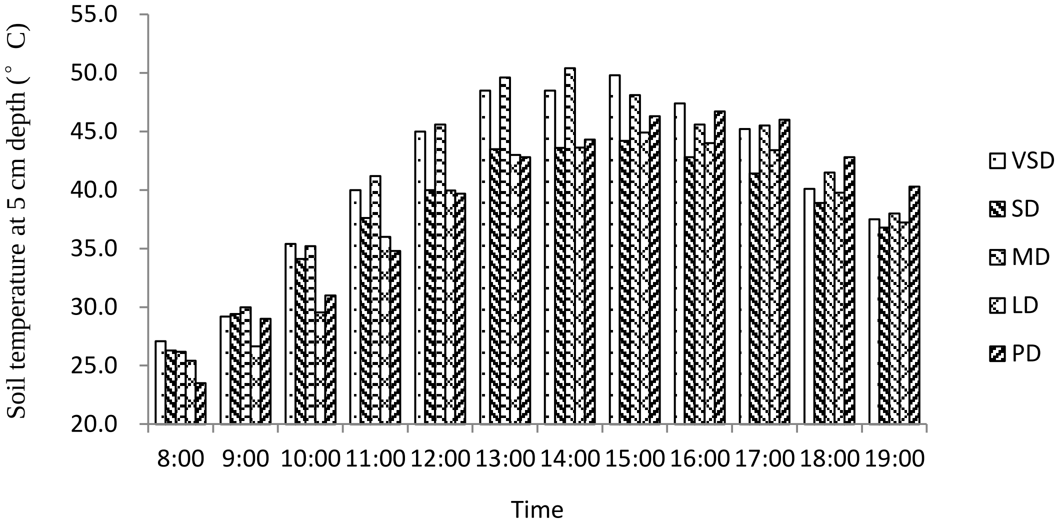

Fig. 79: Responses of soil temperature at 5 cm depth on sunny day to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

Soil temperature at 10 cm depth (TEM10) decreased in general with the reversal of sandy desertification at each daytime, except for 18:00 and 19:00 (Fig. 80), at which TEM10 decreased from VSD to SD, then increased from SD to LD, and decreased at last from LD to PD.

TEM10 in VSD, SD, MD, and LD were all highest at 16:00, but TEM10 in PD was highest at 17:00. TEM10 in VSD, SD and MD decreased steadily from 16:00 to 19:00, whereas TEM10 in LD and PD kept almost unchanged from 16:00 to 19:00.

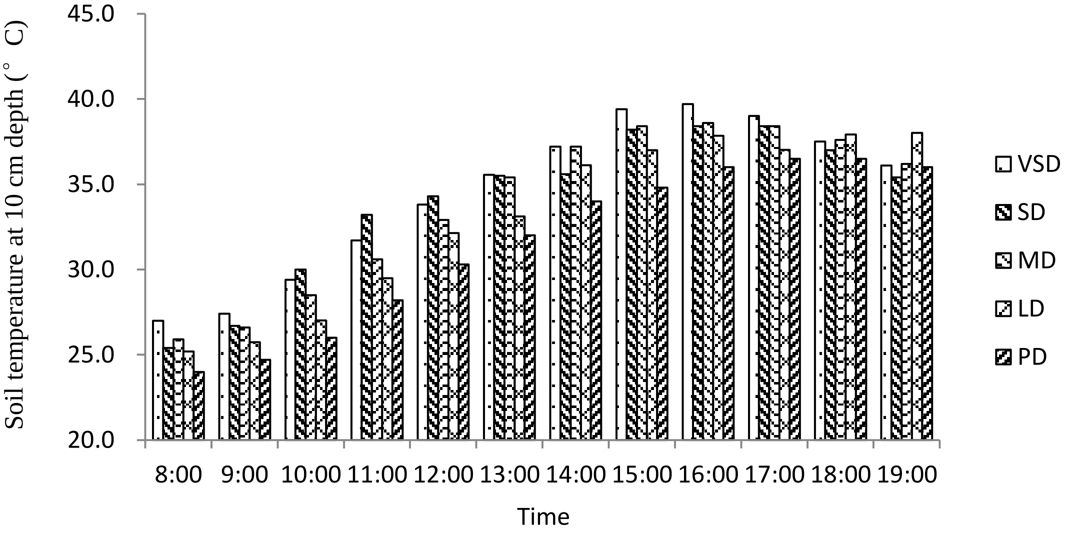

Fig. 80: Responses of soil temperature at 10 cm depth on sunny day to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

Soil temperature at 15cm depth (TEM15) decreased in the main with the reversal of sandy desertification at each daytime from 8:00 to 12:00 (Fig. 81). However, TEM15 increased with the desertification reversal sequence at each daytime from 13:00 to 19:00. The highest TEM15 in SD, MD, and LD were all at 19:00, and in PD it was at 18:00.

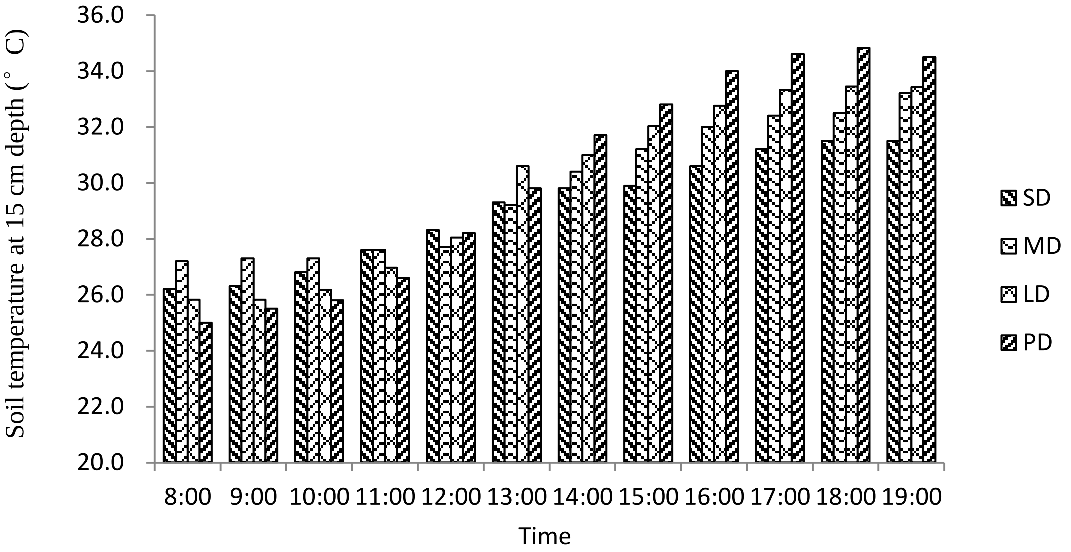

Fig. 81: Responses of soil temperature at 15 cm depth on sunny day to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

Soil temperature at 20cm (TEM20) showed a tendency of decrease with the reversal of sandy desertification at each daytime from 8:00 to 12:00 (Fig. 82), whereas TEM20 fluctuated strongly between different reversal stages at each daytime after 12:00. At 13:00 and 16:00, TEM20 increased from VSD to SD, and decreased from SD to MD, and then increased from MD to LD, and lastly decreased from LD to PD; TEM20 at 14.00 kept the same between SD and MD, and changing tendency between other reversal stages were the same as TEM20 at 13:00. TEM20 at 15:00 decreased from VSD to SD, and then increased from SD to LD, and lastly decreased dramatically from LD to PD. TEM20 at each daytime from 17:00 to 19:00 all decreased from VSD to MD, and then increased from MD to LD, and lastly decreased from LD to PD.

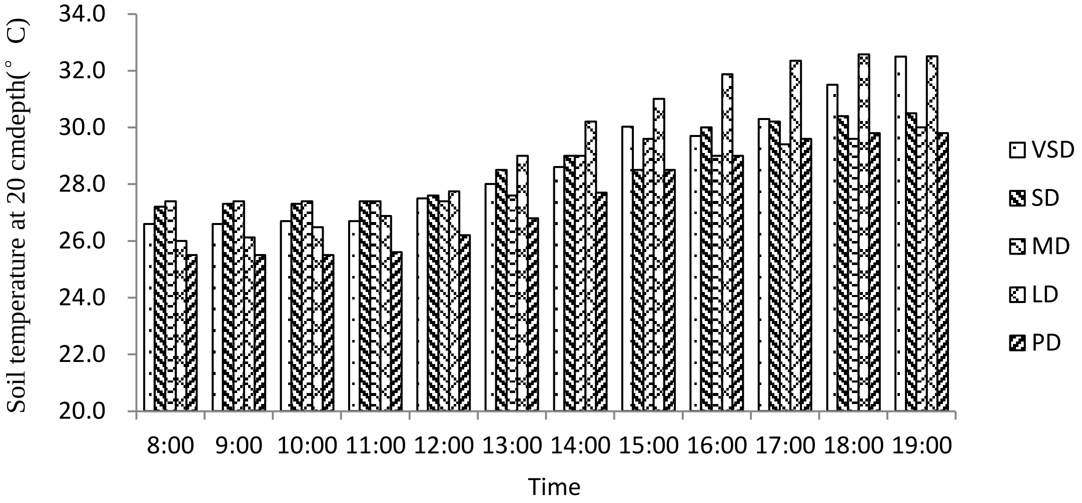

Fig. 82: Responses of soil temperature at 20 cm depth on sunny day to the reversal of sandy desertification in a typical desertification area (Lijihaizi) in southern "Mu Us Sandy Land", China

4.9 Relationships between vegetation and soil

4.9.1 Correlation analyses between vegetation characteristics and soil properties

Close relationships between vegetation characteristics and soil physical properties were detected (Tab. 8). A positively significant correlation ($P < 0.01$) between any two variables of plant cover, aboveground biomass, species richness, diversity, clay and silt, and very fine sand existed. In addition, a positively significant correlation ($P < 0.01$) between any two variables of species diversity, species evenness, and soil water content occurred. A positively significant correlation was also found between species evenness and coarse sand ($P < 0.05$), and between soil bulk density and any of the variables of fine sand and coarse sand ($P < 0.01$).

Any variable of plant cover, aboveground biomass, species richness, clay and silt, and very fine sand was negatively and significantly correlated ($P < 0.01$) with soil fine sand, coarse sand, and bulk density (Tab. 8). Additionally, species evenness was negatively and significantly ($P < 0.01$) correlated with very fine sand.

Tab. 8: Spearman’s rank correlation coefficients between vegetation characteristics and soil physical properties in typical desertification areas in southern "Mu Us Sandy Land", China

	C	B	R	D	E	CLS	VFS	FS	CS	BD	SW
C	1.00										
B	0.92**	1.00									
R	0.63**	0.60**	1.00								
D	0.38**	0.35**	0.64**	1.00							
E	-0.12	-0.14	-0.02	0.73**	1.00						
CLS	0.61**	0.62**	0.60**	0.38**	-0.05	1.00					
VFS	0.59**	0.51**	0.56**	0.21*	-0.28**	0.73**	1.00				
FS	-0.30**	-0.30**	-0.30**	-0.16	0.02	-0.54**	-0.39**	1.00			
CS	-0.47**	-0.44**	-0.47**	-0.15	0.25*	-0.65**	-0.86**	0.04	1.00		
BD	-0.55**	-0.53**	-0.47**	-0.20	0.17	-0.76**	-0.65**	0.33**	0.63**	1.00	
SW	-0.05	-0.01	0.24*	0.31**	0.31**	0.23	-0.09	0.05	-0.09	-0.12	1.00

C Plant Cover; *B* Total Plant Aboveground Biomass; *R* Plant Species Richness; *D* Plant Species Diversity; *E* Plant Species Evenness; *CLS* Clay and Silt; *VFS* Very Fine Sand; *FS* Fine Sand; *CS* Course Sand; *BD* Bulk Density; *SW* Soil Water Content.

* Correlation is significant at the $P< 0.05$ level (two tailed);

** Correlation is significant at the $P< 0.01$ level (two tailed).

Spearman's rank correlation analyses between vegetation characteristics and soil chemical properties are shown in Tab. 9. There was a positively significant correlation ($P < 0.05$) between the following variables: plant cover, aboveground biomass, species richness, diversity, SOC, TN, TP, AN, AP, AK, and EC. Furthermore, there was also a positively significant correlation ($P < 0.05$) between TK, AK, and EC.

Simultaneously, there were also negatively significant correlations between vegetation characteristics and soil chemical properties. Plant cover, species diversity, and AK were all negatively and significantly correlated with soil pH value (Tab. 9).

Tab.9: Spearman's rank correlation coefficients between vegetation characteristics and soil chemical properties in typical desertification areas in southern "Mu Us Sandy Land", China

	C	B	R	D	E	OC	TN	TP	TK	AN	AP	AK	pH	EC
C	1.00													
B	0.92**	1.00												
R	0.63**	0.60**	1.00											
D	0.38**	0.35**	0.64**	1.00										
E	-0.12	-0.14	-0.02	0.73**	1.00									
OC	0.52**	0.52**	0.42**	0.24*	-0.09	1.00								
TN	0.66**	0.68**	0.72**	0.41**	-0.07	0.63**	1.00							
TP	0.54**	0.58**	0.54**	0.26*	-0.10	0.49**	0.78**	1.00						
TK	0.10	0.02	0.19	0.06	-0.07	-0.01	0.17	0.04	1.00					
AN	0.57**	0.60**	0.59**	0.39**	0.04	0.57**	0.84**	0.76**	0.04	1.00				
AP	0.30**	0.31**	0.34**	0.26*	0.13	0.32**	0.51**	0.53**	-0.03	0.58**	1.00			
AK	0.75**	0.70**	0.51**	0.47**	0.09	0.31**	0.56**	0.46**	0.22*	0.57**	0.34**	1.00		
pH	-0.41**	-0.36	-0.12	-0.25*	-0.10	-0.02	0.01	-0.03	0.15	-0.03	0.12	-0.49**	1.00	
EC	0.42**	0.39**	0.56**	0.31**	-0.10	0.49**	0.63**	0.32**	0.26*	0.46**	0.21*	0.35**	0.03	1.00

C Plant Cover; *B* Total Plant Aboveground Biomass; *R* Plant Species Richness; *D* Plant Species Diversity; *E* Plant Species Evenness; *OC* Soil Organic Carbon; *TN* Soil Total Nitrogen; *TP* Soil Total Phosphorus; *TK* Soil Total Potassium; *AN* Soil Available Nitrogen; *AP* Soil Available Phosphorus; *AK* Soil Available potassium; *EC* Soil Electrical Conductivity.

* Correlation is significant at the $P< 0.05$ level (two tailed);

** Correlation is significant at the $P< 0.01$ level (two tailed).

There was a positively significant correlation ($P < 0.05$) between any two of the variables: plant cover, aboveground biomass, species richness, diversity, CAT, URE, PHO, INV, and PRO (Tab. 10). In addition, there was also a positively significant correlation ($P < 0.05$) between species evenness and PRO.

To summarize, vegetation characteristics were mainly positively and significantly correlated with clay and silt, very fine sand, SOC, TN, TP, AN, AP, AK, EC, CAT, URE, PHO, INV, and PRO, and negatively and significantly correlated with fine sand, coarse sand, soil bulk density, and pH value.

Tab. 10: Spearman’s rank correlation coefficients between vegetation characteristics and soil enzyme activities in typical desertification areas in southern "Mu Us Sandy Land", China

	C	B	R	D	E	CAT	URE	PHO	INV	PRO
C	1.00									
B	0.92**	1.00								
R	0.63**	0.60**	1.00							
D	0.38**	0.35**	0.64**	1.00						
E	-0.12	-0.14	-0.02	0.73**	1.00					
CAT	0.53**	0.35**	0.50**	0.33**	-0.08	1.00				
URE	0.35**	0.36**	0.61**	0.26*	-0.12	0.59**	1.00			
PHO	0.46**	0.56**	0.44**	0.32**	0.05	0.47**	0.41**	1.00		
INV	0.38**	0.50**	0.35**	0.35**	0.09	0.27**	0.37**	0.26*	1.00	
PRO	0.46**	0.35**	0.39**	0.46**	0.24*	0.54**	0.38**	0.22*	0.43**	1.00

C Plant Cover; *B* Total Plant Aboveground Biomass; *R* Plant Species Richness; *D* Plant Species Diversity; *E* Plant Species Evenness; *CAT* Soil Catalase Activity; *URE* Soil Urease Activity; *PHO* Soil Phosphatase Activity; *INV* Soil Invertase Activity; *PRO* Soil Protease Activity.

* Correlation is significant at the $P< 0.05$ level (two tailed);

** Correlation is significant at the $P< 0.01$ level (two tailed).

4.9.2 Stepwise regression analyses between vegetation characteristics and soil properties

Stepwise regression analyses between plant cover and soil properties were conducted in four steps and one model was produced in each step (Tab. 11). Three soil variables were selected as the predictors of plant cover after the stepwise analyses finished. Selected soil variables were available K, SOC, and coarse sand. Both R square and adjusted R square increased, as predictors in the model increased. Standard error of the estimate decreased, however, along with the number of predictors. Model 3 is the best model for plant cover, as R, R square and adjusted R square in model 4 were all the largest in these three models (Tab. 11). In model 3, the R square was 0.698.

Tab. 11: Model summary of stepwise analyses between plant cover and soil properties [d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.732 [a]	0.536	0.530	13.411	
2	0.804 [b]	0.646	0.637	11.785	
3	0.836 [c]	0.698	0.686	10.950	1.240

a. Predictors: (Constant), Available K

b. Predictors: (Constant), Available K, SOC

c. Predictors: (Constant), Available K, SOC, Coarse Sand

d. Dependent Variable: Cover

The analyses of variance in every step in the process of model simulation for plant cover are shown in Tab. 12. Regression sum of squares increased, as the predictors in the model increased, whereas, the residual sum of squares, mean square, and F value all decreased with the increase of the predictors in the model. The significance level for each model was less than 0.001 (Tab. 12).

Tab. 12: Analyses of variance in the process of stepwise regression analyses between plant cover and soil properties [a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15972.656	1	15972.656	88.813	0.000 [b]
	Residual	13848.192	77	179.847		
	Total	29820.848	78			
2	Regression	19264.935	2	9632.468	69.351	0.000 [c]
	Residual	10555.912	76	138.894		
	Total	29820.848	78			
3	Regression	20828.838	3	6942.946	57.909	0.000 [d]
	Residual	8992.010	75	119.893		
	Total	29820.848	78			

a. Dependent Variable: Cover

b. Predictors: (Constant), Available K

c. Predictors: (Constant), Available K, SOC

d. Predictors: (Constant), Available K, SOC, Coarse Sand

Coefficients of models for plant cover are shown in Tab. 13. Absolute values of t for soil variables in all models were larger than 2.0, indicating soil variables selected in all models can predict plant cover effectively. Significance levels of all soil variables selected in all models were less than 0.01. If we define plant cover as $y_{1,}$ available K as x_1, SOC as x_2, and coarse sand as x_3, then the predictive model of plant cover can be expressed as the following equation: (Equation 10)

$$y_1 = 0.198x_1 + 4.579x_2 - 0.422x_3 + 7.060 \qquad (10)$$

R^2=0.698

$P < 0.001$

DW=1.240

No very small tolerance values (close to 1.0 and far from 0.0) and also no very large VIF (variance inflation factor) values (very close to 1.0) existed in each model (Tab. 13), indicating that there were no collinearity problems between soil variables selected in each model.

Tab. 13: Coefficients of models produced in the process of stepwise regression analyses between plant cover and soil properties [a]

Model		Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Tolerance	VIF
1	Constant	1.155	3.364		0.343	0.732		
	Available K	0.267	0.028	0.732	9.424	0.000	1.000	1.000
2	Constant	-6.862	3.384		-2.028	0.046		
	Available K	0.226	0.026	0.619	8.597	0.000	0.897	1.115
	SOC	5.071	1.042	0.351	4.869	0.000	0.897	1.115
3	Constant	7.060	4.974		1.419	0.160		
	Available K	0.198	0.026	0.545	7.777	0.000	0.819	1.221
	SOC	4.579	0.977	0.317	4.686	0.000	0.880	1.137
	Coarse Sand	-0.422	0.117	-0.247	-3.612	0.001	0.863	1.159

a. Dependent Variable: Cover

The lower limit of the DW statistic checked in the Durbin-Watson table for equation (10) is $d_L = 1.60$, and the upper limit of that is $d_U = 1.73$, with the checking condition of $n = 95$, $k = 3$, $\alpha = 0.05$ (n is the number of samples; k is the independent variables in the equation; α is the significance level. They are in the same meanings below.).As DW < d_L, first-order autocorrelation between residuals in equation (10) was implicated. The results of further autocorrelation diagnostics in EViews showed that there was none high-order autocorrelation between residuals. The model of equation (10) was modified in EViews as the following model (equation (11)) to eliminate the autocorrelation:

$$y'_1 = 0.151x_1 + 2.801x_2 - 0.445x_3 + 16.212 \qquad (11)$$

$$R^2 = 0.746 \qquad \text{Adjusted } R^2 = 0.734 \qquad P < 0.001$$

$$DW = 2.083 \qquad AR\ (1) = 0.513$$

where y'_1 is plant cover; x_1, x_2, and x_3 denote the same meanings as in equation (10); AR (1) is the estimated value of the first-order autocorrelation coefficient.

In equation (11), $d_U < DW = 2.083 < 4 - d_U$, there was therefore no more autocorrelation between residuals. Further autocorrelation diagnostics with the methods of Correlogram-Q-Statistics and Breusch-Godfrey Serial Correlation TM test in EViews showed that there were also no high-order autocorrelations between residuals in equation (11)

Stepwise analyses between plant aboveground biomass and soil properties were conducted in three steps and each step produced one model (Tab. 14). All of R, R square, and adjusted R square increased with the increase of the number of predictors in the model. The standard error of the estimate decreased to the lowest value in model 3. Model 3 is, therefore, the best model for plant aboveground biomass. Soil variables selected in model 3 included avail K, Total N, and pH value. R square in model 3 was 0.523.

Tab. 14: Model summary of stepwise analyses between plant aboveground biomass and soil properties [d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.613 [a]	0.376	0.368	0.408	
2	0.700 [b]	0.490	0.477	0.371	
3	0.723 [c]	0.523	0.504	0.361	1.295

a. Predictors: (Constant), Available K

b. Predictors: (Constant), Available K, Total N

c. Predictors: (Constant), Available K, Total N, pH

d. Dependent Variable: Log (Aboveground biomass)

The analyses of variance for every step of stepwise regression analyses between plant aboveground biomass and soil properties are shown in Tab. 15. Regression sum of squares increased along with the number of predictors, whereas residual sum of squares, mean square, and F value all decreased. The significance level in each model was less than 0.001, indicating that all the three soil variables should be included in the model.

Tab. 15: Analyses of variance in the process of stepwise regression analyses between plant aboveground biomass and soil properties [a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	7.822	1	7.822	46.946	0.000 [b]
	Residual	12.995	78	0.167		
	Total	20.817	79			
2	Regression	10.209	2	5.105	37.055	0.000 [c]
	Residual	10.608	77	0.138		
	Total	20.817	79			
3	Regression	10.889	3	3.630	27.785	0.000 [d]
	Residual	9.928	76	0.131		
	Total	20.817	79			

a. Dependent Variable: Log (Aboveground biomass)

b. Predictors: (Constant), Available K

c. Predictors: (Constant), Available K, Total N

d. Predictors: (Constant), Available K, Total N, pH

Coefficients of models for plant aboveground biomass in the process of stepwise regression analyses are shown in Tab. 16. All absolute values of t for soil variables in each model were larger than 2.0, suggesting that all soil variables selected in each model can predict plant aboveground biomass effectively. The significance levels of all soil variables were less than 0.05. Model 3 is the best model as mentioned above. If we define the log (aboveground biomass) as y_2, Total N as x_4, and soil pH value as x_5, then log (aboveground biomass) can be predicted with the following equation (available K was defined as x_1 above): (Equation 12)

$$y_2 = 0.003x_1 + 1.747x_4 - 0.322x_5 + 3.504 \qquad (12)$$

$R^2 = 0.523$

$P < 0.001$

$DW = 1.295$

There were no very low tolerance value and all VIF values were small (close to 1.0) in each model (Tab. 16), indicating that there was no collinearity problems between soil variables selected in the stepwise analyses between log (aboveground biomass) and soil properties.

Tab. 16: Coefficients of models produced in the process of stepwise regression analyses between plant aboveground biomass and soil properties [a]

Model		Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Tolerance	VIF
1	Constant	0.944	0.102		9.275	0.000		
	Available K	0.006	0.001	0.613	6.852	0.000	1.000	1.000
2	Constant	0.862	0.095		9.105	0.000		
	Available K	0.004	0.001	0.446	4.917	0.000	0.804	1.243
	Total N	1.465	0.352	0.378	4.163	0.000	0.804	1.243
3	Constant	3.504	1.162		3.015	0.003		
	Available K	0.003	0.001	0.298	2.725	0.008	0.523	1.911
	Total N	1.747	0.364	0.450	4.795	0.000	0.712	1.404
	pH	-0.322	0.141	-0.224	-2.280	0.025	0.650	1.539

a. Dependent Variable: Log (Aboveground biomass)

The lower limit d_L and the upper limit d_U of the DW statistic checked in Durbin-Watson Table for equation (12) were $d_L = 1.60$ and $d_U = 1.73$ (with the checking condition of $n = 96$, $k = 3$, $\alpha = 0.05$). As $DW < d_L$, there was first-order autocorrelation between residuals in equation (12). Further autocorrelation diagnostics with EViews showed that there were 2-order, 9-order, and 11-order autocorrelations except for first-order autocorrelation. The model was modified to the following equation (equation (13)) with generalized difference method in EViews to eliminate the autocorrelations:

$$y'_2 = 0.003x_1 + 0.576x_4 - 0.075x_5 + 1.853 \quad (13)$$

$R^2 = 0.601$ Adjusted $R^2 = 0.550$ $P < 0.001$

$DW = 1.956$ $AR(1) = 0.088$ $AR(2) = 0.298$

$$AR(9) = 0.257 \qquad AR(11) = -0.246$$

where y'_2 is log (plant aboveground biomass); x_1, x_4, and x_5 represent the same meanings as in equation (12); AR (1), AR (2), AR (9), and AR (11) are the estimated values of the first-order, 2-order, 9-order, and 11-order autocorrelation coefficients, respectively.

In equation (13), $d_U < DW = 1.956 < 4 - d_U$, there was therefore no more first-order autocorrelation between residuals. Further autocorrelation diagnostics with the methods of Correlogram-Q-Statistics and Breusch-Godfrey Serial Correlation TM test in EViews showed that there were no more high-order autocorrelations between residuals in equation (13).

Stepwise analyses between plant species richness and soil properties were conducted in seven steps and each step produced one model (Tab. 17). R, R square, and adjusted R square all increased from model 1 to model 5, then decreased in model 6, and lastly increased to the highest values in model 7. At the same time, the standard error of the estimate decreased steadily from model 1 to model 7. Therefore, model 7 is the best model for the estimation of plant species richness. The R square of model 7 is 0.607. Total N, very fine sand, EC, pH, soil urease activity were selected as the predictors for plant species richness in model 7.

Tab. 17: Model summary of stepwise analyses between plant species richness and soil properties [h]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.661 [a]	0.438	0.430	2.209	
2	0.697 [b]	0.485	0.472	2.127	
3	0.717 [c]	0.515	0.496	2.079	
4	0.743 [d]	0.552	0.528	2.011	
5	0.765 [e]	0.585	0.557	1.949	
6	0.763 [f]	0.583	0.561	1.940	
7	0.779 [g]	0.607	0.580	1.897	1.611

a. Predictors: (Constant), Total N

b. Predictors: (Constant), Total N, Very Fine Sand

c. Predictors: (Constant), Total N, Very Fine Sand, EC

d. Predictors: (Constant), Total N, Very Fine Sand, EC, pH

e. Predictors: (Constant), Total N, Very Fine Sand, EC, pH, Urease

f. Predictors: (Constant), Total N, EC, pH, Urease

g. Predictors: (Constant), Total N, EC, pH, Urease, Clay + Silt

h. Dependent Variable: Plant species richness

The analyses of variance in each step of stepwise regression analyses between plant species richness and soil properties are shown in Tab. 18. The regression sum of squares increased gradually from model 1 to model 7, whereas it decreased slightly in model 6. The residual mean square decreased steadily in this process. The residual sum of squares, regression mean square and F value decreased from model 1 to model 5, then increased in model 6, and lastly decreased in model 7. The significance level for each model was less than 0.001, which indicated that each model has the statistical significance.

Tab. 18: Analyses of variance in the process of stepwise regression analyses between plant species richness and soil properties [a]

Model		Sum of Squares	df	Mean Square	F	Sig.
	Regression	296.020	1	296.020	60.667	0.000 [b]
1	Residual	380.595	78	4.879		
	Total	676.615	79			
	Regression	328.399	2	164.199	36.309	0.000 [c]
2	Residual	348.217	77	4.522		
	Total	676.615	79			
	Regression	348.239	3	116.080	26.866	0.000 [d]
3	Residual	328.377	76	4.321		
	Total	676.615	79			
	Regression	373.418	4	93.354	23.092	0.000 [e]
4	Residual	303.197	75	4.043		
	Total	676.615	79			
5	Regression	395.651	5	79.130	20.841	0.000 [f]
	Residual	280.964	74	3.797		
	Total	676.615	79			
6	Regression	394.352	4	98.588	26.196	0.000 [g]
	Residual	282.263	75	3.764		

	Total	676.615	79			
7	Regression	410.429	5	82.086	22.820	0.000 [h]
	Residual	266.186	74	3.597		
	Total	676.615	79			

a. Dependent Variable: Species Richness

b. Predictors: (Constant), Total N

c. Predictors: (Constant), Total N, Very Fine Sand

d. Predictors: (Constant), Total N, Very Fine Sand, EC

e. Predictors: (Constant), Total N, Very Fine Sand, EC, pH

f. Predictors: (Constant), Total N, Very Fine Sand, EC, pH, Urease

g. Predictors: (Constant), Total N, EC, pH, Urease

h. Predictors: (Constant), Total N, EC, pH, Urease, Clay + Silt

Coefficients of models for plant species richness are shown in Tab. 19. Absolute value of t for soil variables in all models were larger than2.0, except for the t value of very fine sand in model 4 and 5. The significance level for soil variables in all models were less than 0.05, except for the significance level of very fine sand in model 4 and 5. Model 7 is the best model for the estimation of plant species richness as mentioned above. If we define plant species richness as y_3, soil electrical conductivity as x_6, soil urease activity as x_7, and soil clay + silt as x_8, then the predictive model of plant species richness can be expressed as the following equation (As mentioned above, total N was defined as x_4; pH value was defined as x_5): (Equation (14))

$$y_3 = 9.973x_4 - 2.586x_5 + 0.044x_6 + 0.049x_7 - 0.123x_8 + 20.790 \qquad (14)$$

$R^2 = 0.607$

$P < 0.001$

$DW=1.611$

There were no very small tolerance value for soil variables in each model and all VIF values were small (close to 1.0), suggesting that there were no collinearity problems between soil variables selected as the predictors for plant species richness.

Tab. 19: Coefficients of models produced in the process of stepwise regression analyses between plant species richness and soil properties [a]

Model		Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Tolerance	VIF
1	Constant	3.794	0.407		9.326	0.000		
	Total N	14.633	1.879	0.661	7.789	0.000	1.000	1.000
2	Constant	3.311	0.431		7.680	0.000		
	Total N	11.849	2.087	0.536	5.679	0.000	0.751	1.331
	Very Fine Sand	0.080	0.030	0.252	2.676	0.009	0.751	1.331
3	Constant	1.451	0.965		1.504	0.137		
	Total N	10.045	2.207	0.454	4.552	0.000	0.642	1.558
	Very Fine Sand	0.070	0.030	0.221	2.368	0.020	0.733	1.364
	EC	0.028	0.013	0.199	2.143	0.035	0.742	1.347
4	Constant	14.063	5.139		2.737	0.008		
	Total N	10.215	2.135	0.462	4.783	0.000	0.641	1.559
	Very Fine Sand	0.054	0.029	0.169	1.823	0.072	0.696	1.437
	EC	0.035	0.013	0.250	2.712	0.008	0.706	1.417
	pH	-1.653	0.662	-0.202	-2.496	0.015	0.916	1.092
5	Constant	18.840	5.357		3.517	0.001		
	Total N	6.001	2.705	0.271	2.219	0.030	0.375	2.664
	Very Fine Sand	0.019	0.032	0.059	0.585	0.560	0.554	1.806
	EC	0.037	0.012	0.267	2.987	0.004	0.701	1.426
	pH	-2.271	0.691	-0.277	-3.287	0.002	0.791	1.265
	Urease	0.042	0.018	0.319	2.420	0.018	0.324	3.087
6	Constant	19.955	4.984		4.004	0.000		
	Total N	5.964	2.692	0.270	2.215	0.030	0.376	2.662
	EC	0.039	0.012	0.278	3.200	0.002	0.735	1.361
	pH	-2.414	0.643	-0.294	-3.752	0.000	0.904	1.106

	Urease	0.047	0.016	0.353	3.022	0.003	0.407	2.457
7	Constant	20.790	4.889		4.253	0.000		
	Total N	9.973	3.244	0.451	3.074	0.003	0.247	4.044
	EC	0.044	0.012	0.316	3.639	0.001	0.703	1.422
	pH	-2.586	0.634	-0.315	-4.078	0.000	0.889	1.125
	Urease	0.049	0.015	0.371	3.236	0.002	0.405	2.470
	Clay + Silt	-0.123	0.058	-0.265	-2.114	0.038	0.339	2.953

a. Dependent Variable: Species richness

The lower limit d_L and the upper limit d_U of the DW statistic checked in Durbin-Watson Table for equation (14) were $d_L = 1.56$ and $d_U = 1.78$ (with the checking condition of $n = 96$, $k = 6$, $\alpha = 0.05$). As $d_L < DW < d_U$, it cannot be determined whether first-order autocorrelation between residuals in equation (14) existed or not. Further autocorrelation diagnostics with EViews showed that there was first-order autocorrelation. The model was modified to the following equation (equation (15)) with generalized difference method in EViews to eliminate the autocorrelation:

$$y'_3 = 7.710x_4 - 0.510x_5 + 0.030x_6 + 0.046x_7 - 0.084x_8 + 5.922 \qquad (15)$$

$$R^2 = 0.568 \qquad \text{Adjusted } R^2 = 0.533 \qquad P < 0.001$$

$$DW=2.124 \qquad AR\ (1) = 0.345$$

where y'_3 is plant species richness; x_4, x_5, x_6, x_7, and x_8 represent the same meanings as in equation (14); AR (1) is the estimated value of the first-order autocorrelation coefficient.

In equation (15), $d_U < DW = 2.124 < 4 - d_U$, no more first-order autocorrelation between residuals exists. Further autocorrelation diagnostics with the methods of Correlogram-Q-Statistics and Breusch-Godfrey Serial Correlation TM test in EViews showed that there were also no high-order autocorrelations between residuals in equation (15).

Stepwise analyses between plant species diversity and soil properties were accomplished in 3 steps and each step produced one model (Tab. 20). All of R, R square and adjusted R square increased from model 1 to model 3. However, the standard error of the estimate decreased from model 1 to model 3. Model 3 is therefore the best model for plant species richness. R square of model 3 was 0.346. Soil protease activity, soil water, and available K were selected as the predictors for plant species diversity in model 3.

Tab. 20: Model summary of stepwise analyses between plant species diversity and soil properties [d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.458 [a]	0.210	0.200	0.462	
2	0.522 [b]	0.273	0.254	0.446	
3	0.588 [c]	0.346	0.320	0.426	1.633

a. Predictors: (Constant), Protease Activity

b. Predictors: (Constant), Protease Activity, Soil Water

c. Predictors: (Constant), Protease Activity, Soil Water, Available K

d. Dependent Variable: Species diversity

Analyses of variance in each step of stepwise regression analyses between plant species diversity and soil properties are shown in Tab. 21. The regression sum of squares increased, as model number increased. However, both of mean square and F value decreased with the increase of model number. The significance levels for all three models were less than 0.001 (Tab. 21).

Tab. 21: Analyses of variance in the process of stepwise regression analyses between plant species diversity and soil properties [a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.429	1	4.429	20.732	0.000 [b]
	Residual	16.663	78	0.214		
	Total	21.092	79			
2	Regression	5.748	2	2.874	14.422	0.000 [c]
	Residual	15.344	77	0.199		
	Total	21.092	79			
3	Regression	7.303	3	2.434	13.418	0.000 [d]
	Residual	13.789	76	0.181		
	Total	21.092	79			

a. Dependent Variable: Species Diversity

b. Predictors: (Constant), Protease Activity

c. Predictors: (Constant), Protease Activity, Soil Water

d. Predictors: (Constant), Protease Activity, Soil Water, Available K

The coefficients of models for plant species diversity are shown in Tab. 22. T values for all soil variables in each model were higher than 2.0, except for the t value of protease activity in model 3. All significance levels of soil variables were less than 0.05, except for the significance level of protease activity in model 3. Nevertheless, the significance level of soil water and available K were both less than 0.01, and so model 3 is still statistically significant.

As mentioned above, model 3 is the best model for the estimation of plant species diversity. If we define plant species diversity as y_4, soil protease activity as x_9, soil water content as x_{10}, then the predictive model of plant species diversity can be shown as the equation bellow (available K was defined as x_1 above): (Equation (16))

$$y_4 = 0.004x_1 + 0.018x_9 + 0.129x_{10} + 0.143 \qquad (16)$$

$R^2 = 0.346$ Adjusted $R^2 = 0.320$

$P < 0.001$ DW=1.633

There was no very low tolerance value for soil variables in each model and all VIF values were small (close to 1.0) (Tab. 22), so there was no collinearity problems between soil variables selected as predictors for plant species diversity in the stepwise regression analyses.

Tab. 22: Coefficients of models produced in the process of stepwise regression analyses between plant species diversity and soil properties [a]

Model		Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Tolerance	VIF
1	Constant	0.718	0.074		9.677	0.000		
	Protease Activity	0.040	0.009	0.458	4.553	0.000	1.000	1.000
2	Constant	0.476	0.118		4.027	0.000		
	Protease Activity	0.039	0.008	0.454	4.665	0.000	1.000	1.000
	Soil Water	0.097	0.038	0.250	2.573	0.012	1.000	1.000
3	Constant	0.143	0.160		0.891	0.376		
	Protease Activity	0.018	0.011	0.209	1.679	0.097	0.553	1.809
	Soil Water	0.129	0.038	0.332	3.429	0.001	0.916	1.092
	Available K	0.004	0.001	0.373	2.928	0.005	0.529	1.890

a. Dependent Variable: Species Diversity

The lower limit d_L and the upper limit d_U of the DW statistic checked in Durbin-Watson Table for equation (16) were $d_L = 1.56$ and $d_U = 1.73$ (with the checking condition of $n = 96$, $k = 3$, $\alpha = 0.05$). As $d_L < DW < d_U$, it cannot be determined if first-order autocorrelation between residuals in equation (16) existed. Further autocorrelation diagnostics with EViews showed that there was no autocorrelation.

So, for species diversity, the original model of equation (16) was unchanged. Because it is not a modified model with the generalized difference method, it is necessary to test the normality and homoscedasticity of the residuals.

Fig. 83 showed that the residual from the model of equation (16) is normal, as most of the points in the figure are on or very close to the assumed line for normal distribution.

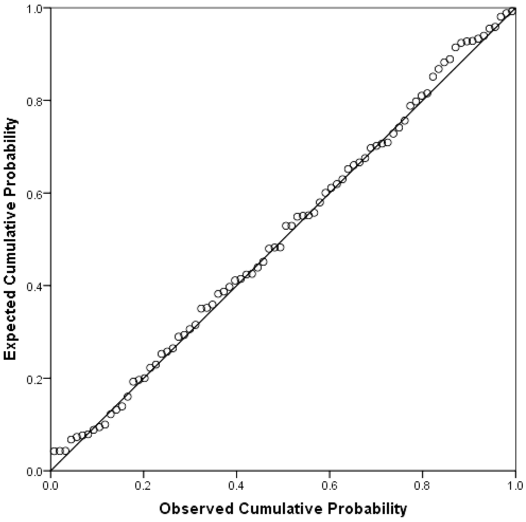

Fig. 83: Normal P-P plot of regression standardized residual in the multiple regression analyses between plant species diversity and soil properties

Fig. 84 showed that the residual from the model of equation (16) fulfills the assumption of homoscedasticity, as most standardized predicted values in the figure distributed randomly within the value of ± 2 of the standardized residual and so the residual is independent from the predicted value.

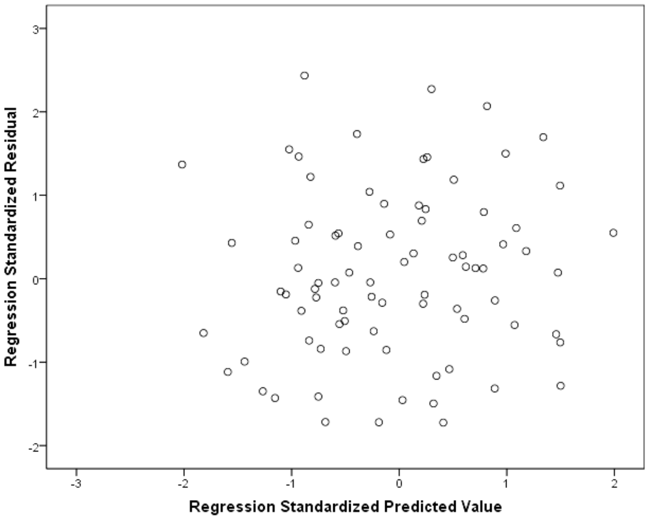

Fig. 84: Scatter plot of standardized predicted value and standardized residual in the multiple regression analyses between plant species diversity and soil properties

Stepwise regression analyses between plant species evenness and soil properties were carried out in two steps and two models were produced in this process (Tab. 23). R, R square and adjusted R square were all larger in model 2 than those in model 1. However, the standard error of the estimate in model 2 is smaller than that in model 1. Hence, model 2 is the better model for the estimation of plant species evenness. Selected predictors in model 2 included very fine sand and soil protease activity. The R square of model 2 is 0.148.

Tab. 23: Model summary of stepwise analyses between plant species evenness and soil properties [d]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.236 [a]	0.056	0.044	0.229	
2	0.384 [b]	0.148	0.126	0.219	1.400

a. Predictors: (Constant), Very Fine Sand

b. Predictors: (Constant), Very Fine Sand, Protease Activity

c. Dependent Variable: Species Evenness

The analyses of variance in the process of stepwise regression analyses between plant species evenness and soil properties are shown in Tab. 24. The regression sum of squares, regression mean square, and F value were all greater in model 2 than those in model 1. Only the residual sum of squares in model 2 was lower than that in model 1. The significance levels in both models were less than 0.05.

Tab. 24: Analyses of variance in the process of stepwise regression analyses between plant species evenness and soil properties [a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	0.241	1	0.241	4.611	0.035 [b]
	Residual	4.083	78	0.052		
	Total	4.325	79			
2	Regression	0.639	2	0.320	6.677	0.002 [c]
	Residual	3.685	77	0.048		
	Total	4.325	79			

a. Dependent Variable: Species Evenness

b. Predictors: (Constant), Very Fine Sand

c. Predictors: (Constant), Very Fine Sand, Protease

The coefficients of models for the estimation of plant species evenness are shown in Tab. 25. The absolute values of t for soil variables selected in each model were all greater than 2.0 and the significance level for all soil variables were less than 0.005.

As mentioned above, model 2 is better than model 1. If we define plant species evenness as y_5 and very fine sand as x_{11}, then the predictive model for plant species evenness can be shown as the following equation (soil protease activity was defined as x_9 above): (Equation (17))

$$y_5 = 0.012x_9 - 0.008x_{11} + 0.588 \qquad (17)$$

$R^2 = 0.148$

$P < 0.01$

$DW = 1.400$

The tolerance value for both soil variables in model 2 were close to 1.0 and both VIF values were very small (close to 1.0). There was consequently no collinearity problems between soil variables selected in model 2.

Tab. 25: Coefficients of models produced in the process of stepwise regression analyses between plant species evenness and soil properties [a]

Model		Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
		B	Std. Error	Beta	t	Sig.	Tolerance	VIF
1	Constant	0.639	0.042		15.159	0.000		
	Very Fine Sand	-0.006	0.003	-0.236	-2.147	0.035	1.000	1.000
2	Constant	0.588	0.044		13.333	0.000		
	Very Fine Sand	-0.008	0.003	-0.314	-2.888	0.005	0.939	1.065
	Protease	0.012	0.004	0.313	2.883	0.005	0.939	1.065

a. Dependent Variable: Species Evenness

The lower limit of DW statistic checked in the Durbin-Watson Table for equation (17) is $d_L = 1.62$, and the upper limit of that is $d_U = 1.71$, with the checking condition of $n = 96$, $k = 2$, $\alpha = 0.05$. Then $DW < d_L$, there was first-order autocorrelation between residuals in equation (17). The result of further autocorrelation diagnostics in EViews showed that there was none high-order autocorrelation between residuals. The model of equation (17) was modified in EViews to the following model (equation (18)) to eliminate the autocorrelation:

$$y'_5 = 0.010x_9 - 0.009x_{11} + 0.644 \qquad (18)$$

$$R^2 = 0.269 \qquad \text{Adjusted } R^2 = 0.238$$

$$P < 0.001 \qquad DW=2.055$$

$$AR\ (1) = 0.275$$

where y'_5 is plant species evenness; x_9 and x_{11} denote the same meanings as in equation (17); AR (1) is the estimated value of the first-order autocorrelation coefficient. Further autocorrelation diagnostics with the methods of Correlogram-Q-Statistics and Breusch-Godfrey Serial Correlation TM test in EViews showed that there were also no high-order autocorrelations between residuals in equation (18)

In equation (18), $d_U < DW = 2.055 < 4 - d_U$, there was therefore no more autocorrelation between residuals.

5 Discussion

5.1 Changes in vegetation condition and plant community characteristics with desertification reversal

The species importance value (IV) of both pioneer plant species (*Artemisia ordosica* and *Agriophyllum squarrosum*) for sand fixation decreased dramatically along the desertification reversal sequence, indicating a reversal process of sandy desertification. This result is consistent with the desertification classification in this study based on bare sand area proportion and plant cover. This agreement showed that plant community structure can be also an index for desertification reversal. Plant community structure consists of species composition and the corresponding IVs.

Changes in IVs of *Agriophyllum squarrosum* and *Artemisia scoparia* occurred in opposite directions. *A. squarrosum* disappeared suddenly in Moderate desertification areas (MD), where its IV was 0, whereas the IV of *A. scoparia* increased abruptly in MD. These two plant species are both annual forbs. Reason for the observed change may be competition between plant species with the same life form. The environment in MD was not suitable for *A. squarrosum anymore* and it was replaced by *A. scoparia* and some other plant species. *A. scoparia* is a species which does not live well in extremely harsh environment like the VSD areas. In addition, Du et al. (2013) showed that growth of *A. scoparia* significantly benefited from higher nitrogen concentrations, which is well reflected by our data.

Sub-shrubs, together with shrubs accounted for a substantial amount of IV Very severe desertification areas (VSD), severe desertification areas (SD), and moderate desertification areas (MD), indicating an importance of the existence of sub-shrubs and shrubs in the process of desertification reversal. In accord with this study, Maestre et al. (2009) showed that the establishment of shrubs was an important step for desertification reversal, and the number of vascular plant species increased due to shrub establishment

This may be due to the positive effects of organic matter provided by perennial shrubs on microbial activity (Berg and Steinberger 2010) and the effects of shrub rhizosphere components on microbial diversity (Diedhiou et al. 2009), which both contribute to ameliorate soil conditions and be further beneficial to the re-establishment of perennial grasses. The establishment of shrubs also leads to substantial changes in plant community composition (Maestre et al. 2009), as was shown by this study, too. One related mechanism that changes plant species diversity and plant community composition might be the inhabitation of shrubs by seed spreading birds, other comprehensive factors may include mycorrhizas and symbionts (Maestre et al. 2009). Moreover, soil properties in shifting sand dunes were improved by shrub establishment and sand immobilization. This process facilitated the establishment of further herbaceous plant species in the ecosystem (Su and Zhao 2003). Consequently, the growth of shrubs and sub-shrubs in desertified grasslands may be an advantage for the initiation of the reversal of sandy desertification. However, shrubs and sub-shrubs will be replaced gradually by perennial grasses and other herbaceous taxa during the process of desertification reversal.

Changes in IVs of *Leymus secalinus*, *Pennisetum centrasiaticum*, *Cleistogenes squarrosa*, *Agropyron mongolicum* and *S. bungeana* suggested that the importance of perennial grasses as plant group gradually increased in communities with the reversal of sandy desertification. This plant group may play an important role in communities, especially in Potential desertification areas (PD). Changes in perennial grasses, forbs, sub-shrubs, and annual forbs indicated that plant communities developed gradually from sub-shrub and annual forb dominated communities to perennial grass dominated communities. Previous studies also suggested a re-establishment of perennial grasses as a consequence of desertification reversal (Allington and Valone 2010), which is consistent with our results.

Perennial grasses reestablish with the reversal of sandy desertification, which is probably affected by the interactions between three factors including soil nutrient, compaction and infiltration (Allington and Valone 2010). Soil compaction is the decrease of soil porosity or increase of soil bulk density caused by internal or external loads (Alakukku 2012). Water infiltration is the capability of soil in absorbing irrigation or rainfall. The soil nutrients tested in our study generally increased on both the local scale and the regional scale with the reversal of sandy desertification. The accumulation of soil nutrients is affected by changes in soil infiltration and compaction (Allington and Valone 2010). Although we did not test water infiltration in this study, past work has suggested that increased infiltration was significantly related to decreased soil compaction (Valone 2008). Soil bulk density, which is an indicator of soil compaction, decreased in general on both studied scales with the reversal of sandy desertification in our study. This suggests an increase of water infiltration in the process of desertification reversal. An increase in infiltration and a decrease in soil compaction were reported as a consequence of long-term livestock removal (Steffens et al. 2008), which supported the accumulation of soil nutrients with time (Allington and Valone 2010). This result will further affect the reestablishment of perennial grasses, which will provide a good environment for further reversal of sandy desertification.

5.2 Responses of vegetation characteristics to the reversal of sandy desertification

In this section, changes in vegetation characteristics, including plant species diversity, plant cover and biomass, with the reversal of sandy desertification will be discussed. Vegetation is the essential factor for an ecosystem. A study of the changes in vegetation characteristics is important for the understanding of desertification reversal.

5.2.1 Plant species diversity and the reversal of sandy desertification

Species richness and diversity generally increased on both site and regional scales with the reversal of sandy desertification. Plant species diversity was found to be strongly related to chemical and soil physical properties, which resulted in different habitats (de Carvalho et al. 2014). As is reported in this study, most physical, chemical and biological soil properties changed significantly in the process of desertification reversal. Soil quality improved with higher content of clay and silt, lower content of sand, higher content of nutrients, enzyme activities and other factors during the reversal of sandy desertification. The ameliorated soil conditions in less desertificated grasslands can lead to a higher species diversity due to the relatively sufficient soil fertility (Fang and Peng 1997) and other improved soil properties (Chawla et al. 2010). Hence, plant biodiversity responds positively to the reversal of sandy desertification.

Plant species diversity increased not only in natural processes of desertification reversal described in this study, but also during ecological restoration management by planting artificial shrubs in mobile sand dunes (Su and Zhao 2003). On the other hand, changes in plant species diversity will also influence the reversal of sandy desertification. Higher plant species diversity yields more differences in litter components in both physical and chemical aspects, which will be beneficial to soil formation and nutrient cycling (Millennium Ecosystem Assessment 2005). Soils in areas reversed from desertification therefore have better conditions and higher rates of nutrient cycling due to higher species diversity. This will in turn promote the further reversal of sandy desertification.

Moreover, soil microbial communities responded rapidly to changes in plant species diversity in grassland ecosystems, and higher plant diversity resulted in higher bacterial activity and diversity (Loranger-Merciris et al. 2006), which is important for litter decomposition and other biogeochemical processes in the reversal of sandy desertification. To summarize, there are close interactions between species diversity and the reversal of sandy desertification. Any changes in one part will lead to responses in the other through the effects on soil properties, decomposition components, and soil microbial communities.

5.2.2 Plant cover, aboveground biomass and the reversal of sandy desertification

Beneath plant species diversity, plant cover and aboveground biomass both increased significantly with the reversal of sandy desertification in this study, especially on the regional scale. Plant cover and biomass are two important vegetation characteristics reflecting plant growth status. Changes in plant cover and aboveground biomass in this study are probably influenced by an amelioration of soil quality, as mentioned above, in the process of the reversal of sandy desertification. Plants grow better in the reversed grasslands than in the desertificated grasslands, due to higher nutrient concentrations and improved soil conditions in the former.

Increments in plant cover and biomass will in turn contribute to the further reversal of sandy desertification. Plant cover is of key importance for the accumulation of organic matter and fine particles in the soil, providing a physical barrier (Berg and Steinberger 2010). The accumulation of organic matter will enhance soil fertility and provide the original medium for microbial communities, which will improve soil quality by a series of biogeochemical processes including organic matter decomposition, element conversion and nutrient cycling. The physical barrier provided by plant cover will prevent aeolian soil erosion. Both the organic matter accumulation and physical barrier function caused by plant cover will promote the further process of desertification reversal.

5.3 Responses of plant physiological properties to the reversal of sandy desertification

Leaf traits, leaf chlorophyll, and photosynthetic characteristics are all important physiological properties of the plants. Changes in any part are closely related to the growth of the plant, which may further affect plant distribution and species allocation. Adaptive changes in physiological properties of common plant species are therefore significant for the reversal of sandy desertification.

5.3.1 Leaf traits of common plant species

On both individual and organ levels, terrestrial plant growth depends on the size for a series of ecological and physiological reasons (Milla and Reich 2007), such as gas exchange (Koch et al. 2004) and biomass partitioning (Enquist and Niklas 2002). Leaf size is a key aspect of plant size on organ level, as it controls important physiological processes as photosynthesis and transpiration in plants. In addition, changes in leaf size were reported to indirectly result in the fruit size variation (Herrera 2002). Leaf size was documented to be correlated (positively or negatively) with plant height on both global and local scales, but the drivers of changes in leaf size still need a further study (Price et al. 2014). Previous studies have focused on the relations between leaf size and environmental factors, such as elevation (Li and Bao 2014), temperature (Purohit and Dhyani 1988) and precipitation (Dilcher 1973). However, the responses of leaf size to desertification reversal are, unfortunately, still not well understood.

Results in this study showed that all analyzed leaf traits (relating to leaf size) of *Leymus secalinus* increased significantly with the reversal of sandy desertification, indicating that leaf size of *L. secalinus* (Fig. 85a) becomes larger in the process of desertification reversal. All leaf traits except leaf width of *Pennisetum centrasiaticum* (Fig. 85b) showed an increasing tendency, but there were only significant differences between light desertification areas (LD) and any of severe desertification areas (SD) and moderate desertification areas (MD), and also between SD and potential desertification areas (PD). For leaf area, a significant difference was also found between LD and very severe desertification areas (VSD). This suggests that the leaf size of *P. centrasiaticum* is less strongly controlled by processes related to desertification reversal as the one of *L. secalinus*.

The increase in leaf size is probably related to an improvement of soil resources in areas reversed from desertification. Higher nutrients and other soil resources may facilitate lager leaf size in reversed areas. Numerous studies have shown positive relations between leaf size and soil nutrients (Cunningham et al. 1999; Fonseca et al. 2000).Smaller leaves tend to be found in sites scarce in nutrients, as nutrient depletion leads to difficulties in nutrient absorption and a limitation in leaf photosynthetic enzymes with obvious effects on photosynthesis rate (Givnish 1987). In addition, in severely desertified areas the low concentrations of soil nutrients may hamper root growth; a limitation of root growth further causes drought and this directly minimizes the leave size to reduce water loss (Cunningham et al. 1999).

The increase in leaf size in reversed area may in turn affect soil nutrients. Larger leaves have probably higher capacity of photosynthesis and support the growth of plant. The plant thus contributes more litter to the soil, which promotes an accumulation of soil nutrients.

Fig. 85: Photo of *Leymus secalinus* (a) and *Pennisetum centrasiaticum* (b)

5.3.2 Leaf chlorophyll content and photosynthetic rate of common plant species

Results in this study showed a significant ($P < 0.05$) increase in leaf total chlorophyll content (Chl content) with the reversal of sandy desertification for both *L. secalinus* and *P. centrasiaticum*, although significant differences were only found between any of very severe desertification areas (VSD), severe desertification areas (SD) and any of light desertification areas (LD), potential desertification areas (PD) for *P. centrasiaticum*. At the same time, the

Photosynthetic rate (P_n) of *L. secalinus* increased significantly ($P < 0.05$) along the reversal sequence. Both P_n of *L. secalinus* and Chl content of *P. centrasiaticum* can be predicted by soil available nitrogen (AN) or soil available phosphorus (AP) with regression models, but they had no significant relationships with soil water content (SW). The increase in leaf Chl content and P_n in areas reversed of desertification is probably directly related to the increase in soil nutrient availability.

The availability of soil phosphorus is important for plants to take up and to use soil nitrogen (Vafadar et al. 2014). The available P in this study site increased significantly along the reversal sequence. At the same time, soil total and available N both increased significantly in the reversal process. The uptake and utilization of soil N is thus improved in reversed areas, which lead to a higher biomass production. Soil N availability is important for plants; a low level in N availability may pose a low N stress to plants and lead to a reduction in leaf Chl content (Peñuelas et al. 1993) and photosynthetic rate (Shangguan et al. 2000). Generally, a reduction in leaf Chl content during low N level conditions is often suggested to be the reason of a low rate of photosynthesis (Dordas and Sioulas 2008; Fredeen et al. 1991).

On the other hand, for many plant species not only a high N level(Ibrahim et al. 2011; Mauromicale et al. 2006; Zhang X. et al. 2013) but also P_n is important in triggering a higher leaf Chl content (Cechin and de Fátima Fumis 2004; Dordas and Sioulas 2008; Li et al. 2009; Mohammad et al. 1997; Ohsumi et al. 2007). In addition, the increase of total Chl content with the reversal of desertification observed in this study might be related to less competition of leaf Chl with secondary metabolites in reversed areas with higher N content (Ibrahim et al. 2011). Simultaneously, high N nutrition may accelerate the photosynthetic rate by generating a higher yield of Photosystem II photochemical efficiency and a higher potential quantum conversion efficiency of photosynthesis in leaves (Shangguan et al. 2000). Moreover, a higher N content leads to a larger chloroplast size, resulting in a higher mesophyll conductance, which is associated with an increase in the concentration of CO_2 in the chloroplast. This increase further caused the acceleration of P_n in leaves (Li et al. 2009). The reversed areas with higher N level had therefore higher P_n.

Despite the significant increase in P_n for *L. secalinus*, other photosynthetic characteristics measured in this study decreased from SD to PD, indicating that the reversed areas with higher level of N had lower levels of transpiration rate (Tr), stomatal conductance (G_s), and intercellular CO_2 concentration (C_i). There have been some other studies showing negative effects of N level on G_s and C_i (Ciompi et al. 1996; Ohsumi et al. 2007; Wang et al. 2014), which support our results. This indicates that the increase of P_n in reversed areas is caused by increased mesophyllic activity, rather than by stomatal factors (Ciompi et al. 1996). Peri et al. (2002) also reported a poor relationship between G_s and P_n at different N contents. This suggests that although G_s is an important limiting factor (Wong et al. 2014), which represents the resistance for CO_2 diffusing into mesophyll cells in photosynthesis (Li et al. 2009), a reduction in G_s does not necessarily cause a decrease in P_n. The decrease of C_i in reversed areas with high N concentrations in this study is in consistent with results found by (Dordas and Sioulas 2008; Li et al. 2009), where C_i is lower at higher N levels than at lower N levels. This may be related to a higher mesophyll conductance with higher N supply, as higher C_i is taken as an indicator of higher mesophyll resistance (Dordas and Sioulas 2008).

Some studies attributed changes in leaf Chl content (Dalil et al. 2010; Hussain and Jaloud 2011; Zgallai et al. 2006) and P_n (Lawlor and Tezara 2009; Rekika et al. 1998; Sanchez et al. 1983) to changes in soil water availability. Drought stress results in significant reduction not only in leaf Chl content, but also in P_n, transpiration rate and stomatal conductance (Zhang et al. 2011). Under drought stress, leaf Chl content decreases due to the destruction in the structure of the slice layer in chloroplasts (Li et al. 2012). On the other hand, leaf P_n decreases under water deficient conditions due to reductions in leaf photosynthetic metabolic potential and C_i (Lawlor and Tezara 2009).

However, changes in leaf Chl content and P_n in the process of desertification reversal in this study seem to not be a result of changes in soil water availability. The field measurements of leaf Chl content were conducted at the study site of Lijihaizi. Changes in soil water content between different reversal stages in this study site were not regular and the differences between reversal stages were not significant ($P > 0.05$). There were no significant correlations between Chl content and SW, and also between P_n and SW. Soil water content in this study may be low enough to pose a drought stress to the two investigated species. Soil water content is thus probably not the reason for the changes in leaf Chl content and P_n in this study. On the other hand, the one-time measurement of soil water content may not be a good estimation for the variable on longer timescales, and thus existing gradients in SW were eventually not detected.

5.4 Responses of soil physical properties to the reversal of sandy desertification

Soil particle size distribution and soil bulk density analyzed in this study are two important physical properties of the soil. Soil particle size distribution analysis is a useful method for identifying different properties in soil organic matter, whose turnover is closely related to the cycling of soil nutrients (Christensen 1987). The coarsening of soil particle has been regarded as an indicator for wind erosion (Su et al. 2004b) and also for land desertification (Su et al. 2004a). Soil bulk density is reported to be closely related to the development of desertification in several studies (Chen X. et al. 2014; Taghizadeh-Mehrjardi and Akbarzadeh 2014; Zhang F. et al. 2013) and is likely to be an indicator of the status of desertification. The interactions between soil particle size distribution, bulk density and the reversal of sandy desertification is therefore a valuable topic for discussion.

5.4.1 Soil particle size distribution

Soil particle size distribution is used to estimate many related soil properties (Hillel 1980); it influences the motion and storage of soil water, soil solute, heat and air (Su et al. 2004a). Soil particle size distribution is therefore an important property in regulating nutrient cycling and other processes in the soil, especially for desertified grasslands.

Results in our study showed that the fraction of soil clay + silt and very fine sand increased with the reversal of sandy desertification, whereas that of fine sand and coarse sand decreased on both the local and regional scale. Soil particle composition showed a clear fining tendency in the desertification reversal process, indicating an accumulation of fine particles in the soil due to less wind erosion (Su et al. 2004b; Zuo et al. 2009a), which was reduced by a denser plant cover in areas reversed from sandy desertification (Chen and Duan 2009).

The most apparent change in soil particles occurred in clay + silt fraction. This result suggests that this fraction has probably special effects on the reversal of sandy desertification. The finest particle fraction promotes not only the formation of biological crusts to fix shifting sand on the soil surface (Li et al. 2002), but also an improvement in soil properties like water holding capacity, organic carbon and nutrients (Su et al. 2005). This supports the idea that the clay fraction controls the soil quality in large parts (Chen et al. 2014) and that the reduction in fine particle fraction leads to losses in soil nutrients (Fu et al. 2009).

In agreement with previous studies, our results showed that the accumulation of clay + silt in the soil resulted in an increase of soil organic carbon and total nitrogen in reversed areas from sandy desertification. This is due to the fact that soil C and N are often adjoined to clay and silt particles (Christensen 1987). Finer soil was proved to support the mineralization of soil organic nitrogen in studies based on laboratory incubation (Cameron and Posner 1979; Chichester 1969; Chichester 1970; Lowe and Hinds 1983). The degradation of soil organic matter is faster in the fine particle fraction of the soil (Clemente et al. 2012). These studies confirm our results of an increase of soil available nutrients with increasing clay + silt content in areas reversed from sandy desertification.

5.4.2 Soil bulk density

Our results showed that soil bulk density decreased in general with the reversal of sandy desertification on both local and regional scales. This is probably due to higher content of soil organic matter (associated with soil organic carbon) and more fine roots (related to grass species) (Su et al. 2004b) in the areas reversed from sandy desertification. More soil organic carbon and fine roots in the soil may increase soil porosity and therefore reduce the bulk density.

It has been suggested that soil bulk density is highly associated with the grade of land degradation;

desertification often leads to an increase in soil bulk density (Zhang et al. 2013). Larger soil bulk density was found in a desert area than that in non-desert area (Taghizadeh-Mehrjardi and Akbarzadeh 2014), which supports the result of our study. A parallel comparison between meadow and desert ecosystems also showed much lower values of soil bulk density in the former (Fu et al. 2009). All these results suggest that soil bulk density is closely related to desertification in both processes of development and reversal.

The relation between soil bulk density and desertification reversal is probably triggered by the establishment and development of vegetation in the reversal process. Su et al. (2005) proved that soil bulk density in the topsoil in open dunes is significantly larger than that in stabilized, vegetated areas. With the establishment and development in reversed areas from desertification, plant cover and biomass increased significantly and so generate more soil organic C in the soil by providing more plant litter. The increased soil organic C further leads to a decrease in soil bulk density.

5.5 Responses of soil chemical properties to the reversal of sandy desertification

Soil chemical properties are important in regulating soil environment, which poses an effect on plant growth and vegetation development. Soil chemical properties analyzed in this include soil nutrients, pH value and electrical conductivity. We discussed changes in soil chemical properties with the reversal of sandy desertification from the following two aspects.

5.5.1 Soil nutrients

Previous studies have revealed that higher concentrations of soil nutrients are related to desertification reversal (Allington and Valone 2010). Results of our study also showed that soil nutrient concentrations increased significantly with the reversal of sandy desertification. Changes in the content of soil nutrients may be driven by series of biogeochemical processes with the desertification reversal. The content of soil organic carbon increased dramatically in the process of desertification reversal, indicating a significant accumulation of organic matter in the soil. This is related to an increase in vegetation cover and biomass with the desertification reversal (Chen and Duan 2009). A higher vegetation cover and biomass in the areas reversed from sandy desertification will provide the soil with more plant litter, which is the main source of soil organic matter.

Plant litter turnover is an important source of soil nutrients (Hu et al. 2006). Plant litter is decomposed and mineralized by soil microbes; the further breakdown of plant litter and the nutrient recycling is facilitated by detritus-feeding consumers (Kuehn et al. 2011). The input of plant litter into the soil will produce a great mobile carbon and nitrogen pool (Scheu 1997). Hence, the increase in plant litter in the soil also promotes an increase in soil total nitrogen, as plant litter include many nitrogen compounds.

At the same time, as mentioned above, soil particle size got finer in the process of desertification reversal. The finer soil particle results in a larger surface area per unit volume for soil mineral weathering; the release and storage capacity of soil nutrients is enlarged due to an increase in the weathering surface area (Chen and Duan 2009). Fine particle-ion complexes in addition hamper the depletion of nutrients during precipitation events (Pott and Hüppe 2007). This is a possible reason for the increase of soil nutrients with the reversal of sandy desertification.

It has been shown in previous studies that the composition and structure of plant litter has great effects on decomposition processes (Hu et al. 2006) and increases the leaching element cations including PO_4^{3-}- P and K^+ (Scheu 1997). The structure of plant litter is often "improved" by a mixture of litters from different species. Results in this study showed that plant species composition got more complex with the reversal of sandy desertification. Plant litter in areas reversed from desertification consists of a higher degree of mixture from different plant species. So we supposed that soil available nutrients are much higher in the reversed areas than those in severe desertified areas due to an improvement in the composition and structure of plant litter in the areas reversed from sandy desertification. A systematic study concerning on the effects of plant litter material on soil nutrient cation leaching would help confirming this assumption.

In spite of the general trends of changes in soil nutrients with the reversal of sandy desertification, some irregular changes were found by this study. On the local scale, we found the values of several soil nutrients and vegetation characteristics were higher in moderate desertification areas (MD) than those in light desertification areas (LD) at the study site of Nanhaizi, indicating that the plot of MD in Nanhaizi may reflect special conditions. Although MD in Nanhaizi was actually an area undergoing moderate desertification, trees occurring in this area may lead to a considerable changes in content of some soil nutrients (Kellman 1979). In addition, on the local scale, the values of some soil nutrients were higher in MD than those in LD at the study site of Machang, which may be due to the large amounts of *Artemisia ordosica* in MD.

Furthermore, on the local scale, the values of some soil nutrients were higher in VSD than those in SD, which may be related to only minor differences between very severe desertification areas (VSD) and severe desertification areas (SD) in these study sites, and thus the random error may exceed the difference between VSD and SD and lead to a higher value in VSD. In spite of all these irregular changes, the general trend of changes in soil nutrients with the reversal of sandy desertification is clear on the local scale.

5.5.2 Soil pH and electrical conductivity

Soil pH value is an important indicator and trigger of processes in the soil (Li X. et al. 2006), changes in soil pH value may indicate ecological shifts. On the local scale, soil pH value showed a decreasing tendency in this study, whereas soil electrical conductivity (EC) showed an increasing tendency with the reversal of sandy desertification. However, there were several irregular fluctuations along the desertification reversal sequence for both soil pH and EC (especially for soil pH), suggesting that changes in pH were not stable with the reversal of sandy desertification on the local scale. Changes in soil pH value were also shown fluctuate strongly between different stages of desertification development (Xu et al. 2012; Zuo et al. 2009a), suggesting that soil pH value is a soil property which responses not so directly to both processes of desertification development and reversal on a relatively small spatial scale.

In contrast to the local scale, changes in soil pH along the desertification reversal were much clearer on the regional scale. It decreased significantly with the reversal of sandy desertification. This result is in agreement with (Fu et al. 2009), who found soil pH values to be much lower in desert than that in meadow on a relatively large spatial scale. The higher soil pH values in areas reversed from sandy desertification resulted probably from an increase in soil organic C and cations (Fu et al. 2009).

In contrast, EC increased from VSD to MD, and then decreased slightly from MD to PD, indicating that only minor changes in EC occurred. Nevertheless, EC still showed an increasing tendency during the process of desertification reversal. The increase of EC in areas reversed from sandy desertification may be related to a decrease in sand movement and accumulation on the ground surface, which results in an increase in soil evaporation on the ground surface, and more salts rise to the top soil (Li X. et al. 2006). In addition, EC may be influenced by the higher cation storage capacity in soils with fine particle content (Pott and Hüppe 2007). EC was also found to decrease with the expansion of sandy desertification (Li X. et al. 2006; Zuo et al. 2009a), indicating that changes in this soil property have a similar regularity in the process of desertification development and that of desertification reversal.

5.6 Responses of soil enzyme activities to the reversal of sandy desertification

Soil enzyme activities play an important role in nutrient cycling and catalyze the biochemical reactions in the soil; they were considered to be an useful indicator of soil quality, productivity and microbial activity (Acosta-Martínez and Tabatabai 2000; Alef 1995; Bandick and Dick 1999; Weaver et al. 1994.). Soil enzyme activities have close relationships with soil biology and respond quickly to changes in land management (Acosta-Martínez and Tabatabai 2000; Dick et al. 1988). Soil enzyme activities were therefore supposed to have significant responses to the reversal of sandy desertification. Our results confirmed the assumption that enzyme activities increase dramatically in the process of desertification reversal.

Previous studies showed that soil enzyme activities increase with the accumulation of plant litter as food for decomposers to generate more microbial biomass (Song Y. et al. 2014; Wang B. et al. 2012), indicating that an increase in available plant litter will lead to an increase in soil enzyme activities. This provides a reasonable interpretation for our results. As mentioned above, plant litter increased strongly with the reversal of sandy desertification. The increase in plant litter contributes to the increase in soil enzyme activities in the areas reversed from sandy desertification.

In contrast to the generally clear trend of the changes in soil enzyme activities, there were also some abnormal changes. Soil catalase activity (CAT) decreased (but insignificantly) from light desertification areas to potential desertification areas in both study sites of Habannong and Lijihaizi, indicating that light desertification may have minor effects on CAT, and CAT can tolerate some degrees of desertification in these two study sites.

Soil urease activity (URE) decreased significantly from moderate desertification areas to light desertification areas and from very severe desertification areas to severe desertification areas, at the study site of Nanhaizi, Haba, respectively, suggesting that URE can be changed easily by other factors. For example, Chernysheva et al. (2014) showed that URE is strongly influenced by livestock faeces and can maintain stable over very long time scales.

5. 7 Responses of micrometeorology to the reversal of sandy desertification

The increase in plant cover caused a reduction of land-surface albedo (Millennium Ecosystem Assessment 2005), which further results in a relative higher temperature on the ground surface under sunshine conditions (Otterman 1974). This may contribute to the increase of ground surface temperature with desertification reversal. However, plant cover also limits the short-wavelength radiation and hinders the incoming energy on the ground surface (Atchley and Maxwell 2011). The reduction of land-surface albedo and the limitation of incoming energy exert their effects together and may partly neutralize each other. This explains why soil temperature showed a tendency to decrease with the reversal of sandy desertification but the regularity was not definitely clear, with many fluctuations. The limitation of incoming energy showed greater effects on soil temperature, but had less effect on the ground surface temperature. Simultaneously, the effects of these two factors are not always unchanged. For example, soil temperature at 15 cm depth decreased in general with desertification reversal at each hour of the daytime during 8:00 to 11:00, but it increased obviously with desertification reversal at each hour of the daytime during 14:00 to 19:00. In addition, one should consider that the pattern in micrometeorological data measured in our study may considerably be affected by local site and short-time weather characteristics, and a higher number of sites and measurements would probably be needed to observe clearer trends.

Plant cover also resists to evapotranspiration (Atchley and Maxwell 2011), which may lead to a reduction of air humidity. A lower evapotranspiration may also lead to a higher air temperature because of the reduction of air humidity. But this is the case under sunshine conditions, when the sunshine gets weakness after 17:00, the reduction of evapotranspiration may influence little on the air temperature, as showed in this study.

5.8 Relationships between soil and vegetation on the background of desertification

Stepwise regression analysis is a suitable method to build proper models for vegetation characteristics. The process of stepwise regression analysis makes it possible to select the most important and non redundant independent soil variables to predict vegetation variables. Residual diagnostics are an important part of a regression model but are often neglected. A model with autocorrelation between residuals has several disadvantages, e.g. the estimation of the parameters will not be ideal (Sun 2005). Hence, the model needs to be modified to eliminate the autocorrelation.

The detection of autocorrelation between residuals can be performed in SPSS by checking the DW option. However, there are two intervals, i.e. $d_L \leq DW \leq d_U$, and $4 - d_U \leq DW \leq 4 - d_L$, where it cannot determine whether there is autocorrelation or not. At the same time, the method of DW test is only valid for first-order autocorrelation detection, and not for the detection of high-order autocorrelation. Moreover, it is inconvenient or impossible to modify the model with the generalized difference method in SPSS, if the model is detected to possess autocorrelation between residuals. All these disadvantages can be overcome with EViews. However, SPSS is powerful for stepwise regression analysis, especially in selecting independent variables for vegetation variables. So, we combined the advantages of these two pieces of software packages. Results showed that this method can get optimal and high quality models.

As a requirement for expression, we defined the modified models for plant cover, aboveground biomass, plant species richness, plant species evenness and the original model for plant species diversity as the final models. The P value of the F test in each final model was less than 0.001, indicating a high and significant degree of effects of the selected independent variables on their corresponding dependent variables, and the selected variables should be included in the relevant models.

The adjusted R^2 for the model of plant cover, aboveground biomass, and plant species richness was 0.734, 0.550, and 0.533, respectively. These values were larger than those for the model of plant species diversity and evenness, indicating that the goodness of the regression fit in the former three models was better than that in the latter two models. One reason may be that the data of plant cover, aboveground biomass, plant species richness and all soil variables used for modeling were the original data, whereas those of plant diversity and evenness used in modeling were calculated from the original data according to a specific formula. Although the adjusted R^2 for the models of plant diversity and evenness was relatively small, these two models were still valid based on the series of analyses mentioned above.

The regression models built in this study suggested not only the most important soil variables for different vegetation characteristics, but also estimate the quantitative relationships between soil and vegetation variables. Eleven soil variables in total were selected as predictive variables in the five models. Soil available K had the closest relationship to vegetation characteristics. It was the most important independent variable in three models including the models for plant cover, aboveground biomass, and plant species diversity. Plant species distribution is mathematically related to plant species diversity; they are significantly and negatively linear correlated on the plot scale (Arita et al. 2008). So species diversity indicates plant distribution in some extent. Moreover, as soil available K always played a positive effect on predicting the vegetation characteristics in this study, this nutrient is therefore rather important for both plant growth and species distribution in the process of desertification reversal and may represent one of the limiting factors of plant growth in the study area.

Besides, both soil total N and pH value were selected as the predictive variables in two models, and they were both selected in the models for plant aboveground biomass and species richness, suggesting that soil total N and pH values are the second important soil factors for both plant growth and species distribution. But they predicted plant aboveground biomass and species richness in the reverse direction, as they were correlated with the vegetation characteristics positively and negatively, respectively. Soil protease activity was selected in both the models for plant species diversity and evenness, indicating that it is an important variable for plant species distribution.

In addition, plant cover was also positively predicted by soil organic C, and negatively predicted by soil coarse sand; plant species richness was also positively predicted by soil electrical conductivity and soil urease activity, but negatively predicted by soil clay and silt content; plant species diversity was also positively predicted by soil water content; plant species evenness was also negatively predicted by very fine sand. These results suggest that in addition to soil available K, total N, pH value and protease activity other soil properties including organic carbon and coarse sand are also important factors for plant growth; soil properties such as electrical conductivity, urease activity, clay and silt, very fine sand and soil water content are also important factors determining the plant species distribution in the reversal of desertified grassland.

Soil nutrients such as organic C and total N were found to be positively correlated to plant cover and aboveground biomass in the process of desertification development (Zuo et al. 2009a). This confirms the results found in our study, which indicates that soil organic C and total N are important environmental factors for plant cover and aboveground biomass for both development and reversal processes of desertification. A specific study of the vegetation restoration of mobile dunes suggested that soil properties such as organic C, total N, electrical conductivity, pH value, very fine sand, and soil water content play a key role in regulating plant growth and species distribution (Zuo et al. 2009b).

Most of the soil properties found as the main factors for plant distribution in Zuo et al. (2009b) are the same as those found in this study, indicating an agreement of the study results with different methods, i.e. canonical correspondence analysis and stepwise regression analysis. However, soil available K, urease activity and protease activity were also determined to be the main factors for plant distribution in this study, whereas they were not found in Zuo et al. (2009b). This may be related to the difference at the study sites. Our study sites include all the five stages of land desertification; whereas those in Zuo et al. (2009b) include 0-year, 11-year, and 20-year enclosed formerly mobile dunes. In this example, soil available K may not represent a very important factor in early stages of desertification reversal. As available K is easy to leach from plant bodies and there is more plant biomass in the latter stages of desertification reversal, so available K can exert its advantages in the latter stages. Soil enzyme activities were not analyzed in Zuo et al. (2009b), so they were not determined to be the main factors for plant distribution.

This study showed that vegetation and soil properties have intimate relationships, which is in accord with previous results (Abd el-Ghani and Amer 2003; Aweto 1981), indicating that soil properties are important factors for vegetation development in all kinds of ecosystems. However, specific soil properties such as soil available K, total N, pH value and protease activity found in this study are the most important soil factors for vegetation characteristics and play important roles in the process of desertification reversal.

Soil and vegetation characteristics are highly inter-correlated to each other and causal relationships between these two elements are extremely difficult to determine (Zuo et al. 2009b). Changes in vegetation with the reversal of sandy desertification affect the changes in soil properties; at the same time, any changes in soil properties will in turn influence on the vegetation development. Increased soil nutrients and enzyme activities in areas reversed from sandy desertification will further ameliorate the vegetation environment, which will promote the further development of vegetation, e.g. a higher plant cover will be triggered by this process. An area with higher plant cover has a lower risk of soil erosion than those with lower plant cover have (Wijitkosum et al. 2013), which will be beneficial for the further reversal of sandy desertification. Furthermore, an improvement in vegetation characteristics will further affect on the soil properties and a virtuous circle begins. In this way, vegetation and soil strongly interact during the process of sandy desertification reversal. A disturbance to any segment of the soil-vegetation complex will break the circle and a further reversal of desertification will be prevented or delayed. In conclusion, to recognize the interactions between soil and vegetation is important for the designing of strategies for land management and our understanding on desertification reversal.

6 Conclusions

This study carried out a series of investigations into the changes in soil properties, vegetation characteristics, plant physiological properties, micrometeorological indices, and the relationships between soil properties and vegetation characteristics, with the reversal of sandy desertification. Based on the study results and the literature analyses, we put forward the following conclusions from eight aspects with regard to the reversal of sandy desertification.

6.1 Changes in vegetation and quantitative plant characteristics with the reversal of sandy desertification

Plant communities changed dramatically with the reversal of sandy desertification. Sub-shrubs and annual forbs were replaced gradually by perennial grasses and perennial forbs in the process of desertification reversal. Pioneer species for sand fixation declined sharply with the progressive reversal of sandy desertification, whereas perennial grasses spread out. Sub-shrubs and shrubs in very severe desertification areas, severe desertification areas and moderate desertification areas may be of benefit to the reversal of desertification. As a result of desertification reversal, the re-establishment of perennial grasses was affected by the interactions between soil properties, such as soil nutrients and bulk density.

6.2 Relationships between vegetation characteristics and the reversal of sandy desertification

Plant diversity mainly increased on both local and regional scales in the process of desertification reversal, affected by a better soil quality in areas reversed from desertification. Increased species diversity can in turn promote the further reversal of sandy desertification through affecting litter components, soil formation, microbial communities, and soil nutrient cycling. Plant cover and aboveground biomass both increased with the reversal of sandy desertification on both local and regional scale due to an improvement of soil quality in the process of desertification reversal. Enhanced plant cover in turn contributes to the reversal of sandy desertification through providing organic matter and acting as physical barrier preventing erosion.

6.3 Responses of plant physiological properties to the reversal of sandy desertification

Leaf traits including leaf area, leaf length, and leaf perimeter of *Leymus secalinus* increased dramatically with desertification reversal; leaf width of *L. secalinus* also increased in this process but there were no significant differences between very severe desertification areas, severe desertification areas, and moderate desertification areas. All the four leaf traits of *Pennisetum centrasiaticum* changed slightly from very severe desertification areas to potential desertification areas and increased in general with the exception of leaf width. The leaf size of the two common species was shown to adapt by expansion in areas reversed from sandy desertification, but the adaptive changes were in different magnitudes for the two species. The leaf chlorophyll content of *L. secalinus* increased significantly ($P < 0.05$), whereas that of *P. centrasiaticum* increased slighter in the process of desertification reversal.

The photosynthetic rate of *L. secalinus* increased significantly with the reversal of sandy desertification; while transpiration rate, stomatal conductance, and intercellular CO_2 concentration all decreased from severe desertification areas to potential desertification areas. The increase in leaf Chl content and photosynthetic rate is probably related to enhanced soil nutrients, especially to the increased soil nitrogen content in the process of sandy desertification, rather than to changes of soil water content.

6.4 Responses of soil physical properties to the reversal of sandy desertification

The soil clay + silt and very fine sand fraction increased significantly ($P < 0.05$) with the reversal of sandy desertification, whereas fine sand and coarse sand fraction decreased significantly along the reversal sequence. Soil particle size got finer in the process of sandy desertification reversal. Soil bulk density decreased significantly ($P < 0.05$) with the reversal of sandy desertification, whereas soil water content changed in a relatively ambiguous tendency, i.e. increased at first and then decreased slightly.

6.5 Responses of soil chemical properties to the reversal of sandy desertification

Soil chemical properties including organic carbon, total nitrogen, total phosphorus, available nitrogen, available phosphorus and available potassium increased significantly ($P < 0.05$) with the reversal of sandy desertification. The concentrations of most soil nutrients increased strongly in the process of sandy desertification reversal. Soil electrical conductivity also showed an increasing tendency from very severe desertification areas to potential desertification areas, but it decreased slightly from moderate desertification areas to potential desertification areas and changed mildly along the whole reversal sequence. Soil total potassium changed irregularly with the reversal of sandy desertification. Soil pH value decreased significantly ($P < 0.05$) along the desertification reversal sequence.

6.6 Responses of soil biological activities to the reversal of sandy desertification

Soil enzyme activities including catalase activity, urease activity, phosphatase activity, invertase activity, and protease activity increased significantly ($P < 0.05$) with the reversal of sandy desertification. The increase in soil enzyme activities may be related to an improvement in structure and composition of plant litter material in the reversed areas from sandy desertification. Soil respiration rate increased significantly ($P < 0.05$) with the reversal of sandy desertification at each daytime analyzed.

6.7 Responses of micrometeorology to the reversal of sandy desertification

Soil temperature showed a decreasing tendency with the reversal of sandy desertification, probably related to a combination of the effects of albedo reduction and incoming energy limitation, which both resulted from the increase in plant cover. Air temperature increased in general with the reversal of desertification, which is associated with the resistance of evapotranspiration in reversed areas. Large wind was mainly in the afternoon and those areas without reversal were more likely to be exposed to large wind. Illumination changed irregularly between different stages of desertification reversal and illumination in severe and moderate desertification areas often had lowest values in day time.

6.8 Relationships between vegetation and soil with desertification reversal

Vegetation characteristics analyzed in this study, except for species evenness, were all significantly and positively correlated with soil clay and silt, very fine sand, organic carbon, total nitrogen, total phosphorus, available nitrogen, available phosphorus and available potassium content plus electrical conductivity, catalase activity, urease activity, phosphatase activity, invertase activity and protease activity. In contrast, plant species evenness was significantly and positively correlated with coarse sand and soil water content plus protease activity, and negatively correlated with very fine sand content. Plant cover, aboveground biomass, and richness were all significantly and negatively correlated with soil fine sand and coarse sand content plus bulk density.

However, only a few soil properties were selected as predictive variables for vegetation characteristics in the multiple stepwise regression analyses. Plant cover was predicted by soil available K, organic carbon and coarse sand; aboveground biomass was predicted by soil available K, total nitrogen and pH value; species richness was predicted by soil total nitrogen, pH value, electrical conductivity, urease activity and clay and silt content; species diversity was predicted by soil available K, protease activity and soil water content; species evenness was predicted by soil protease activity and very fine sand. Soil available K, total nitrogen, pH value and protease activity are therefore the most important soil factors for vegetation characteristics in the process of desertification reversal.

While our study showed extremely clear and strong relations between vegetation and soil characteristics during the process of desertification reversal, it remains difficult to identify direct causal relationships due to the strong interactions and mutual influences between both groups of factors.

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Curriculum Vitae

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Thesis Title:	Study on properties and spatial heterogeneity of vegetation and soil in the critical area of desertification in South Edge of Mu Us Sandy Land	
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09.2004-07.2008	**Fujian Normal University, College of geographical sciences**	**Bachelor**
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List of Publications

1. Xie Y Z*, **Qiu K Y***, Xu D M, Shi X F, Qi T Y, Pott R*. 2015. Spatial heterogeneity of soil and vegetation characteristics, and soil–vegetation relationships along an ecotone in Southern Mu Us Sandy Land, China. Journal of Soils and Sediments, 15: 1584-1601 (* corresponding author).
2. **Qiu K Y**, Xie Y Z*, Matthew C*, Xu D M, Qi T Y, Pott R*. (in review). Responses of vegetation characteristics to the reversal of sandy desertification. Journal of Vegetation Science.
3. **Qiu K Y**, Xie Y Z*, Chen T W, Xu D M, Pott R*. (in review). Changes in plant physiological properties with the reversal of sandy desertification and the potential mechanisms in relation to soil water content and P, N availability. Plant, Cell & Environment.
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9. Liu G H, Li K, Peng H, **Qiu K Y**, Qian W, Ma H L, Gao R. 2014. An in situ Approach for Measuring Fine Root Respiration for Loquat Trees (*Eriobotrya japonica* (Thunb.) Lindl). Journal of Anhui Agriculture Science. 42(1): 12-14.
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12. Li Y, **Qiu K Y**, Song N P. 2010. Restoration approaches of degraded ecosystem in southern region of Ningxia. Journal of Agricultural Sciences. 31(3): 65-68.
13. Shi X F, Xu D M, **Qiu K Y**, Xie Y Z. 2010. Application of moving split-window technique in quantitative methodologies for edge influence of landscape boundary: a case study of *Lespedeza potaninii-Artemisia ordosica* community. Pratacultural Science. 27(4): 30-33.