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COMBATING AEOLIAN DESERTIFICATION IN NORTHERN CHINA

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ABSTRACT

Progress in combating aeolian desertification (land degradation resulting from wind erosion) has been achieved in an agro-pastoral ecotone of northern China since the mid-1980s. This paper reviews three common measures used to combat and control aeolian desertification in such regions. In addition, it introduces a case study on the recovery of a degraded semi-arid ecosystem to provide regional lessons and support theoretical and practical approaches to desertification prevention and reversal on a global scale. On the basis of the analysis and evaluation of three kinds of typical measures and one regional scale case, this study shows that human-caused aeolian desertified land can be rehabilitated. Although the technologies and management of combating aeolian desertification in an agro-pastoral ecotone of northern China still need further improvement through more experimentation and practical application in the future, the experience gained to date contains important lessons for the recovery of degraded land on a global scale. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: aeolian desertification; agro-pastoral ecotones; degraded ecosystem; northern China; rehabilitation; measures

INTRODUCTION

Land degradation/desertification occurs widely and is one of the most important social, economic and environmental problems in the world today. It is most damaging in drylands, which cover approximately 41 per cent of the land surface of the world (hyper-arid areas included) and are home to more than 38 per cent of the total global population of 6·5 billion (Reynolds *et al*., 2007; UNCCD, 2008). According to the Millennium Ecosystem Assessment (MEA, 2005), 10–20 per cent of the drylands are already moderately degraded, and over 250 million people are already directly affected by land degradation in the developing world, an estimate likely to expand substantially in the face of climate change and population growth (Reynolds *et al*., 2007; UNCCD, 2008). Therefore, the control and rehabilitation of desertified land is crucial if the needs of the growing human population for food, feed, biomass energy, fiber and timber are to be met (Daily, 1995). It is also crucial if the stability of dryland ecosystems in the face of global climate change is to be maintained.

For the past 20 years, there have been efforts across the world to combat desertification. The United Nations has periodically focused on desertification and drylands, notably adopting the Convention to Combat Desertification in 1992 (UNCCD, 1994) and designating 2006 as the International Year of the Desert and Desertification. The immediate goals of the UNCCD (1994) are as follows: (i) prevention and/or reduction of land degradation; (ii) rehabilitation of partly degraded land; and (iii) reclamation of desertified land. Recent advances in preventing and reversing desertification are embedded in the integrative and systematic theory approaches and analysis of multiple causal factors (Geist and Lambin, 2004; MEA, 2005). For example, through the study of coupled human–environmental (H-E) systems, Reynolds *et al*. (2007) presented a new synthetic framework, the Drylands Development Paradigm, which consists of five principles and is supported by a growing and well-documented set of tools for policy and management action. This framework helps navigate the inherent complexity of desertification and dryland development, identifying and synthesizing those factors that are important to the research, management and policy communities.

Desertification plagues almost all arid, semi-arid and sub-humid areas of northern China and has become a challenge facing more than 1·6 million km^2 and 200 million people (Zhu and Wang, 1993; Zhu and Chen, 1994; Wang *et al*., 2008b). There are three different desertification processes in China (Zhu and Wang, 1993). The first process is land degradation that results from wind erosion (called aeolian desertification in this paper), the second is water and soil loss resulting from water erosion, and the third is salinization caused by unsustainable irrigation and management. Of the three processes, aeolian desertification is dominant and accounted for 46 per cent of the total desertified area in the early-1990s (Zhu and Chen, 1994) and for more than 84 per cent of the total desertified area in the early-2000s (SFAC, 2005; Wang *et al*., 2008c). Aeolian desertification has developed mainly in the agro-pastoral ecotones, nomadic zones and inland river basins and oases of northern China over the past 50 years (Xue *et al*., 2005). The total aeolian

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desertified area in northern China was 0·137 million km^2 in 1955, which increased to 0·176 million km^2 in 1975, 0·334 million km^2 in 1987 and reached 0·386 million km^2 in 2000 (Wang *et al*., 2004a). On average, aeolian desertified land developed at a rate of 1560 km^2 y^{-1} from 1955 to 1975, 2100 km^2 y^{-1} from 1976 to 1987 and 3600 km^2 y^{-1} from 1988 to 2000 (Wang *et al*., 2004b). Although aeolian desertification in northern China still remains a major environmental problem that impedes local development, there are some projects and community-based initiatives that have successfully addressed these problems (Mitchell *et al*., 1998; Gerile and Wulantuya, 2004; Piao *et al*., 2005; Zhao *et al*., 2010). For example, in the past 20 years, some reversal of aeolian desertification has occurred in parts of the agro-pastoral zone as a result of sustainable and effective measures that were adopted and implemented in local regions (Fullen and Mitchell, 1994; Xue *et al*., 2005; Qi *et al*., 2012; Zhou *et al*., 2012).

This paper reviews the development and rehabilitation processes that have been undertaken in aeolian desertified lands in the agro-pastoral ecotone of northern China, evaluates three typical measures used in the study area and presents a case study that highlights the benefits of an integrated model for controlling aeolian desertification. The objective of this paper was not to provide a template for combating desertification but to provide regional scale case studies that support theoretical approaches to desertification prevention and reversal on a global scale.

AEOLIAN DESERTIFICATION IN THE AGRO-PASTORAL ECOTONE OF NORTHERN CHINA

Study Area Description

The agro-pastoral ecotone of northern China is the transition zone from cropping to grazing (Figure 1). It is interlaced spatially with pasture and cropland and overlaps temporally with agriculture and animal husbandry. Throughout different historical periods, the location of the agro-pastoral ecotone has shifted constantly because of climate change and alternating control by Han and nomadic minority nationalities (Zhu and Chen, 1994). The Great Wall, stretching along the 400 mm rainfall isohyet in northern China, marks the boundary between the semi-arid zone and the sub-humid zone and between loess soil and sandy soil. Historically, Han and minority nationalities practiced sedentary agriculture and nomadic pasturing, and the Wall was always the north boundary of the agro-pastoral ecotone before 1800 AD (Zhao *et al*., 2003). At present, the agro-pastoral ecotone is mainly located to the north of the Great Wall, between the 200 and 450 mm isohyets of northern China, and consists of the following: (i) the Horqin region, located in southeastern Inner Mongolia and western Jilin and Liaoning Provinces, including 13 counties in Inner Mongolia, two counties in Jilin Province and two counties in Liaoning Province; (ii) the regions in southern Inner Mongolia and northern Hebei Province (SIM & NH), including 12 counties in Inner Mongolia and six counties of Hebei Province; and (iii) the Ordos region located in southwestern Inner Mongolia, northern Shanxi Province and eastern Ningxia Province, including eight counties in Inner Mongolia, seven counties in Shanxi Province and one county in Ningxia Province (Figure 1). Almost all of these regions were nomadic pasture 200 years ago.

Physical Features and Climate Change

In the agro-pastoral ecotone of northern China, 80 per cent of the rainfall is concentrated in summer (June, July and August), and annual rainfall varies from 150–200 mm in the west to 400–450 mm in the east. Strong winds with velocities above the threshold for blown sand (≥ 5 m s^{-1}) (Zhu *et al*., 1980), and drought occur simultaneously during spring and winter. A major part of the soil consists of loose Quaternary sandy deposits from ancient river courses, which are very prone to wind erosion once the original vegetation has been removed (Zhu and Liu, 1981). The natural

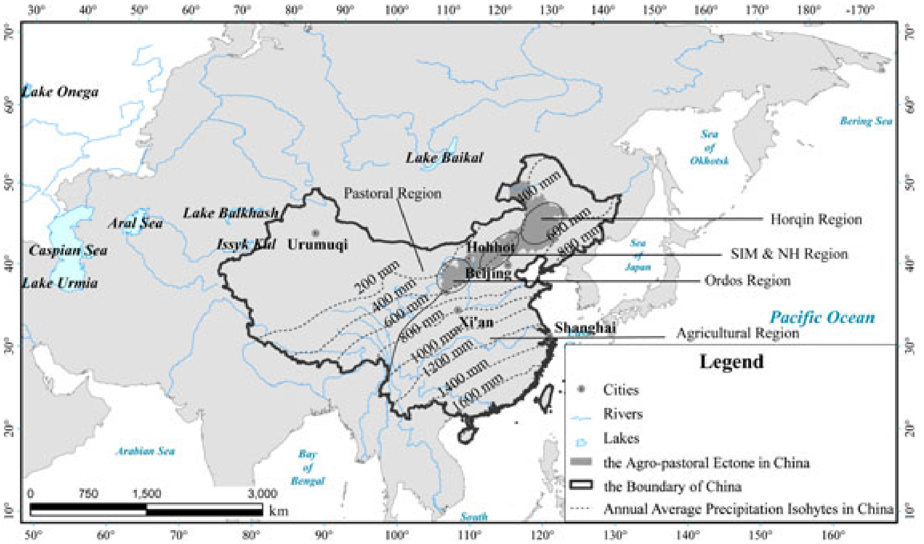

Figure 1. Location of the study area. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

vegetation gradually transitions from typical temperate grassy steppes in the eastern parts of the study area into temperate desert steppes with drought-tolerant vegetation in the west (Figures 2a and 2b).

Meteorological data recorded by 31 local meteorological stations reveal that the same climate trend toward warming and aridity has occurred in all three regions of the study area in the past half century (Figure 3). From 1950 to 2011, air temperature showed a significant linear increase of 0·8 °C; precipitation showed a non-significant decrease of 30 mm, and average relative humidity significantly decreased by about 4 per cent. Average wind speeds in the study area also showed a significant downward trend from 1955 to 2011.

Human Activity

The inhabitants of the agro-pastoral ecotone 200 years ago were pastoral minority people and grazing dominated because strong winds, drought and a loose soil surface were not conducive to sedentary cultivation. In the early Qing Dynasty, the steppes in the study area were royal rangeland and were kept in good condition as farming was forbidden in these areas by central government, although scattered conversions to farmland also occurred at that time (Zhu and Chen, 1994). However, from the 18th century to the present day, farmland landscapes gradually became dominant in the study area after several large-scale conversion events (Table I). In Inner Mongolia alone, farmland increased from 50,200 km^2 in 1952 to 82,000 km^2 in 1998. In the Ordos region, the farmland area increased by 1150 km^2 from 1915 to 1928 and reached 13,330 km^2 in 1949 (Yang and Ta, 2002). In north Hebei Province, farmland increased from ,700 km^2 in 1948 to 7300 km^2 in the late-1980s, and natural pasture area decreased from 8700 to 2700 km^2 in the same period (Han and Han, 2003; Sheng *et al.*, 2003). Because of wind erosion, farmland

Figure 2. The temperate desert steppe with xeric shrubs in the western part of Ordos region. Photo was taken in July 2010 (a). The temperate typical steppe with *Leymus chirensis and Stipa* spp. community in the Xilinguole steppe. Photo was taken in May 2012 (b). Erodible dry farmland in north Hebei Province. Photo was taken in August 2002 (c). Initial stage of shrub sand dunes showing sand moving downwind and accumulating near the shrubs in Shangdu County of Inner Mongolia. Photo was taken in August 2002 (d). Coarse gravel surface due to wind erosion in Shangdu County of Inner Mongolia. Photo was taken in August 2002 (e). Yadang caused by wind erosion in Horiqn Region. Photo was taken in August 2002 (f). This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

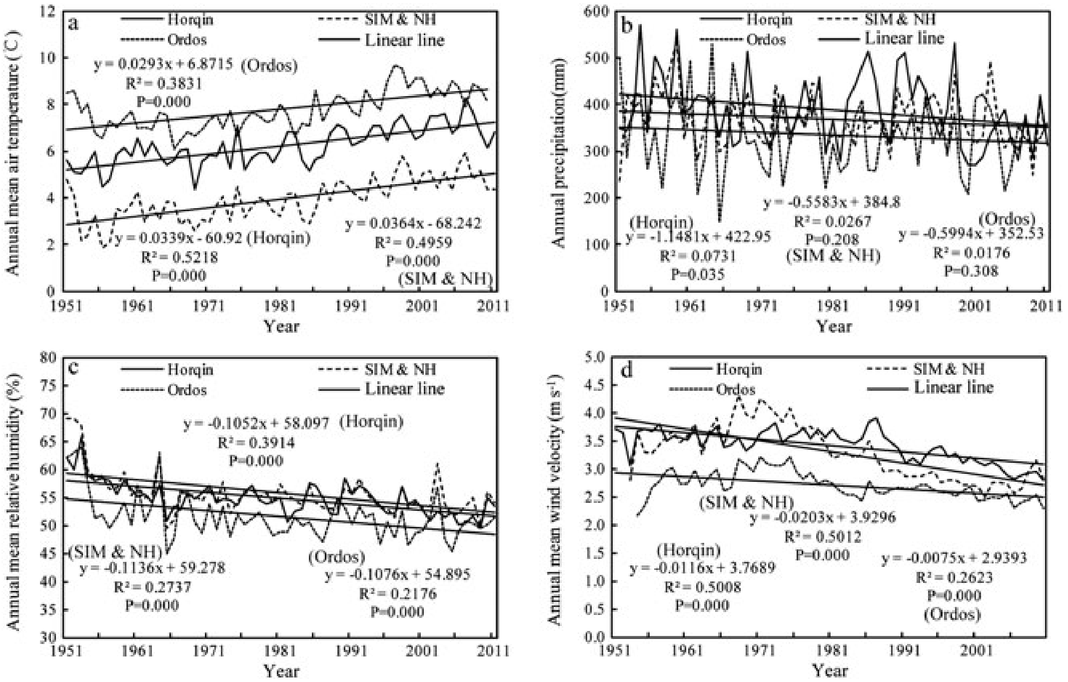

Figure 3. Trends in annual average air temperature (a), annual precipitation (b), annual average relative humidity (c) and annual average wind speed (d) in the study area.

had to be abandoned after several years of cultivation (Zhu and Liu, 1981). For example, in Yijinhuoluo County in the Ordos region, the total area converted from pasture to farmland was 700 km^2, but only 300 km^2 of farmland remained after the three conversion programs between 1955–1956, 1958–1962 and 1970–1973 (Jia *et al*., 2003). As a consequence, land use conversion extended the farmland northwestwards and pushed northwards the boundary of the historical agro-pastoral ecotones by an average of 180–220 km into the typical steppe or desert steppe (Wang *et al*., 2008b).

Aeolian Desertification Processes

The human-induced changes in the land use patterns destroyed steppe vegetation and created favorable conditions for the erosion of the loose, sandy soil under the strong winds and droughts during spring in the study area (Zhu and Liu, 1981). Spring plowed in sandy steppe in particular allowed the fine soil particles and soil organic matter to be eroded by the strong winds (Figure 2c), resulting in the formation and exacerbation of aeolian desertified farmland, which has a rough surface and infertile soil (Zhang *et al*., 2011). During the land use conversions of the mid-1970s to the 1980s, farmlands suffering wind erosion in the study area increased at a rate of 387·2 km^2 y^{-1} (Zhu and Chen, 1994).

Land use conversion not only induced the formation of aeolian desertified farmlands but also caused overstocking of rangelands due to the gradually diminished grassland area and increased livestock number. According to the statistical data, the overstocking of rangelands reached over 50 per cent in the study area (Zhu and Chen, 1994). One mature sheep unit requires 0·04 km^2 of temperate steppe, predominantly covered by species of *Gramineae*, for grazing (Zhao *et al*., 2003). In the early-1950s, each mature sheep unit occupied 0·03 km^2 of grassland, and this declined in the late-1970s to 0·01 km^2 (Zhu and Chen, 1994). Such livestock pressure resulted in the pure steppe pastoral region becoming the second largest aeolian desertified region in north China (Xue *et al*., 2004; Wang *et al*., 2004a).

The particles eroded by wind can be transported and accumulate several meters to hundreds meters downwind. The fine silt and clay particles easily become airborne and form dust storms in downwind areas (Liu *et al*., 2008). Although there is not yet conclusive evidence, the study area might be one of the principal dust sources for the Beijing area, which now has frequent dust storms. Furthermore, sand particles move downwind along the land surface and form sand patches or active dunes when they encounter barriers (Figure 2d). After long periods of wind erosion, only coarse gravel, which has no productive value, or some aeolian landforms, such as gravel lands or yardangs, remain (Figures 2e and 2f). The aeolian desertified land in the study area increased at an annual mean rate of 2103·2 km^2 between the 1970s and the 1980s, reaching a total of 121,900 km^2 in 1987, 40·5 per cent of the total aeolian desertified land area in northern China (Zhu and Chen, 1994).

INTRODUCTION AND EVALUATION OF MEASURES FOR COMBATING AEOLIAN DESERTIFICATION

Many measures have been taken to control aeolian desertification in the agro-pastoral ecotone since the mid-1980s. Three effective measures are introduced and evaluated in this paper. The first measure is stabilization of dunes with straw checker-boards (SCM) (Shapotou Desert Research

Table I. Several large-scale conversion events in the study area

Regions	Dates	Counties	Sponsors	Motivation	Consequences	Citation
Horqin	1750–1876	Kulun, Kezuohou, Tongliao	Qing Dynasty government	Increase national income	North boundary of agro-pastoral ecotone has moved northwards by 390 km in the western part and 244 km in the eastern part of this region since the 1700s.	Zhao *et al.*, 2003
	1877–1911	Kezuozhong, Keyouzhong, Zhalute	Qing Dynasty government	Resolved the huge international war debt		
	1912–1925	Aluhorqin, Balinzuo, Balinyou	Minguo government	Increase national income		
	1931–1945	Southeastern places	Private companies	Increase private income		
	1949–1952	Wongniute, Aohan, Naiman	Chinese central government	Resolved the problem of food		
	1958–1960	Whole region	Chinese central government	Implemented the policy of increasing land productivity		
	1966–1976	Whole region	Chinese central government	Implemented the policy of converting pasture into agriculture		
	1982–	Whole region	Chinese central government	Implemented the policy of the household contract responsibility		
SIM & NH	1877–1911	Kangbao, Kuyuan, Shangyi, Zhangbei, Fengning, Weichang	Qing Dynasty government	Increase national income	Farmland percentage increased from 5 per cent in the 1700s to above 60 per cent in the 1980s in this region.	Zhu and Chen, 1994
	1912–1925	Huade, Shangdu, Chayouhou, Chayouzhong, Siziwang, Damao, Wuchuan, Taibushi,	Private companies and catholic churches	Increase private income		
	1937–1945	Duolun, Zhenglan, Zhengxiangbai, Xianghuang	Japanese government	Provided food provision for the Japanese army in China		
	1953–1956	Whole region	Chinese central government	Implemented State policies for the cooperative transformation of agriculture		
	1958–1960	Whole region	Chinese central government	Implemented the policy of increasing land productivity		
	1966–1976	Whole region	Chinese central government	Implemented the policy of converting pasture into agriculture		
Ordos	1902–1911	Dalate, Hangjin	Qing dynasty government	Resolve military requirements	Conversion rate from grassland to farmland increased from 0·85 per cent in late-1900s to 11·11 per cent in 1949 and the total conversion area was 1 333 000 ha	Song and Zhang, 2007
	1912–1922	Yijinhuoluo, Wushen, Etuoke	Minguo government	Increase national income		
	1953–1956	Whole region	Chinese central government	Implemented state policies for the cooperative transformation of agriculture		
	1958–1960	Whole region	Chinese central government	Implemented the policy of increasing land productivity		
	1966–1976	Whole region	Chinese central government	Implemented the policy of converting pasture into agriculture		

Station, 1986; Mitchell *et al*., 1998; Zhang *et al*., 2004a); the second measure is controlling wind erosion in farmland by planting wind-shelter forests (SFM) (Mitchell *et al*., 1998; Wang *et al*., 2003; Yasuhito *et al*., 2004); the third measure is the protection of grassland using enclosures (EM) (Zhao *et al*., 1998; Yasuhito *et al*., 2005).

Stabilizing Mobile Dunes Using Straw Checker-boards

As an engineering methodology for preventing wind erosion, SCM has been extensively adopted to protect transportation infrastructure and cultural heritage from wind erosion and sand burial in arid regions where ecological measures were not available because of extreme drought (left panel of Figure 4a). Along with other measures, this method has also been used in semi-arid and sub-humid parts of the agro-pastoral ecotone to effectively stabilize mobile sand dunes. Straw checker-boards are usually built using wheat straw because wheat straw has good flexibility, can effectively decrease wind velocity and can be easily collected in the north of China. The size of each checker-board depends on the angles of the dune slopes. Generally, 1 m × 1 m checker-boards have been installed on the flat sand areas, and gentle slopes and smaller straw checker-boards have been installed on the steep slopes. The height of the straw above the ground surface varies from 0·15 to 0·2 m. The orientation of the checker-boards is perpendicular to the local prevailing wind direction (right panel of Figure 4a).

Experimental results have shown that straw checker-boards can increase the aerodynamic roughness of the sand surface by factors of 400–600 and decrease wind velocity by 20–40 per cent at a height of 0·5 m above the surface (Zou *et al*., 1981; Shapotou Desert Research Station, 1986; Liu, 1987). The quantity of sand transported over straw checker-boards is only 1 per cent of that transported over uncovered mobile sand dunes (Zhu *et al*., 1992). Straw checker-boards can also change the microclimate by increasing air humidity and by lowering the albedo and the air and soil temperatures (Li *et al*., 2002; Hao *et al*., 2005a). It has been shown that by reducing the wind velocity, checker-boards not only fixed sand dunes by inhibiting wind erosion but also trapped fine particles from the atmosphere and incorporated them into the land surface in the form of a soil physical crust, which is a thin layer with reduced porosity and increased density at the surface of the soil (Mitchell *et al*., 1998; USDA, 2001). Along with the development of soil physical crusts, clay content (Figure 5a), soil nutrients and organic matter (Figures 5b and 5c) in the topsoil inside, the checker-boards gradually increased (Li *et al*., 2003, 2007; Su and Zhao, 2003; Xiao *et al*., 2003; Duan *et al*., 2004; Zhang *et al*., 2004a, 2004b; Zhao *et al*., 2004a; Su *et al*., 2005a). The increase in soil nutrients can enhance porosity and the water-holding capacity of soil (Duan *et al*., 2004), providing an environment conducive to natural plant growth in the semi-arid and sub-humid regions with yearly precipitation above 200 mm. Xerophytic shrubs, such as *Calligonum mongolicum*, *Caragana microphylla*, *Salix gordejevii*, *Hedysarum leave*, *Haloxylon ammodendron (C. A. Mey.) Bunge*, *Nitraria tangutorum Bobr*. and *Tamarix*

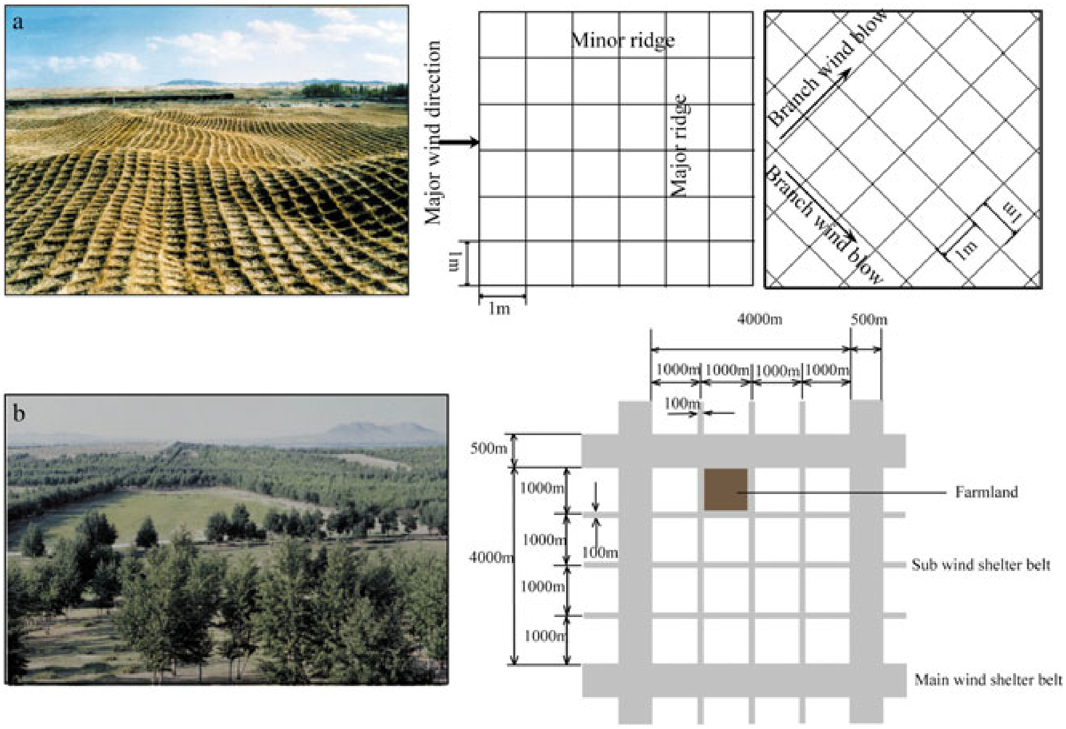

Figure 4. Photograph and arrangements of the straw checker-boards near the railway (a) and a photograph and sketch map of wind-shelter forest around farmland in Shangdu County (b). In the left panel of (a), the sketch map shows the prevailing wind direction. The orientation of the checker-boards was perpendicular to the prevailing wind direction. In the right panel of (a), the sketch map shows two prevailing wind directions, and the orientation of the two ridges of checker-boards were placed parallel to the two prevailing wind directions. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

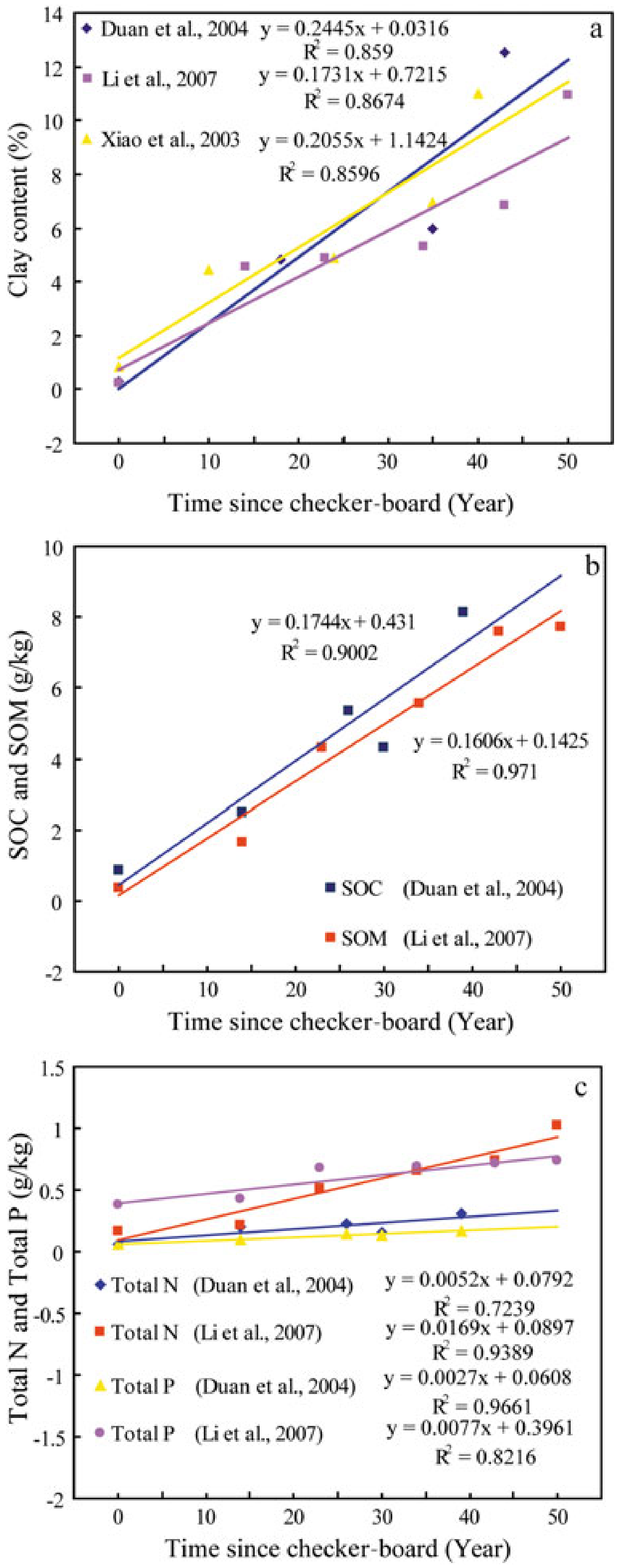

Figure 5. Changes in the topsoil (0–5 cm) clay content (a), SOC and SOM (b), and Total *N* and Total *P* (c) over the period that straw checker-boards were used to stabilize mobile sand dunes. Data were taken from a number of different results. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

hohenackeri Bunge, were the first pioneer plants to appear on the mobile sand dunes (Figures 6a and 6b), and they can lead to further improvements in soil properties and facilitate herbaceous growth (Zhao *et al*., 2007; Guo *et al*., 2008). The xerophytic shrubs were gradually replaced by herbaceous plants after living on the mobile sand dunes for between 10 and 30 years (Figures 7a, 7b and 7c). Finally, a stabilized natural ecosystem consisting of herbaceous plants and biological crusts formed, resulting in mobile sand dunes developing into fixed sand dunes. This process led to the control of aeolian desertification in the area.

Natural rehabilitation of aeolian desertified land is an extremely slow process because of the low levels of soil nutrients and moisture during the preliminary stage. For example, experimental results from the Horqin region showed that the fine fractions, water-holding capacity and organic matter in the 0–5 cm topsoil layer started to increase significantly after around 20 years of stabilizing shifting sand dunes using straw checker-boards (Su and Zhao, 2003; Zhang *et al*., 2004a, 2004b; Su *et al*., 2005a). Therefore, artificial measures were taken to accelerate the process after the straw checker-boards were installed in many regions (Fearnehough *et al*., 1998). One measure was to transplant artificial vegetation inside the checker-boards to trap atmospheric dust and maintain the stability of the sand surface (Mitchell *et al*., 1998; Zhang *et al*., 2004a, 2004b). The vegetation transplanted was mainly native xerophytic shrub species that were tolerant of drought, wind erosion and being covered by sand. They survived without irrigation because the straw remained intact and continued stabilizing the sand dunes for 4–5 years (Mitchell *et al*., 1998). After it had grown for several years, the artificial vegetation gradually replaced the straw checker-boards in stabilizing the sand dunes. The other measure taken was aerial seeding of native xerophytic herbs and vascular plants prior to the rainy season after the straw checker-boards were installed (Shen, 1998; Li *et al*., 2010). In eastern regions of the agro-pastoral ecotone, with a mean yearly precipitation of around 400 mm, xerophytic shrubs were directly transplanted into the sand dunes in the shape of the checker-boards to replace the straw (Zhang *et al*., 2005a). The vegetation cover has been known to reach 70 per cent after 7 years (Zhang *et al*., 2007), at which time young shoots were cut from the living plants and transplanted into the other mobile sand dunes as new checker-boards. This kind of measure has been transferred successfully to many regions of the eastern agro-pastoral ecotone and has provided considerable economic and environmental benefits.

Protecting Farmlands Using Wind-shelter Forests

The practice of protecting farmlands using SFM in northern China emerged in the 1940s, developed in 1960s–1970s and has been incorporated in the ‘Three-North Shelterbelt Development Programme’, which was initiated by the Chinese government in 1978 and aimed to form a 700 km environmental screen across northern China (Yu *et al*., 2006). Although the real achievements of the ‘Three-North Shelterbelt Development Program’ and its impact on the

Figure 6. The initial stage (a) and mature stage (b) of straw checker-boards used to fix mobile sand dunes at Shapotou Station. The farmland without wind-shelter forest in 1982 (c) and with wind-shelter forest (d) in 2002 in Shangdu County of Inner Mongolia. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

groundwater table have been questioned (Mitchell *et al*., 1998; Wilske *et al*., 2009; Wang *et al*., 2010), a farmland wind-shelter forest system, one part of the program, has been recognized by many researchers as an effective method for reducing wind velocity, inhibiting wind erosion and restoring degraded farmland ecosystems (Mitchell *et al*., 1998; Hao *et al*., 2005b).

Farmland wind-shelter forest grids consist of main zones and sub-zones (Figure 4b). Their size depends on the local environment, yearly mean wind velocity and the shelter forest species used. Usually, the size changes from 50 to 100 m in the western regions of the agro-pastoral ecotone to 400–600 m in the eastern regions (Zhao, 2002; Zhu *et al*., 2003; Wang *et al*., 2008a). Correspondingly, the width of the forest zones and the number of rows also increases from 4 to 6 m and two rows to 20–30 m and more than 16 rows as the size of the grid increases (Zhu *et al*., 2002a; Guo, 2002; Wang *et al*., 2008a). The orientation of the main zones is perpendicular or oblique with a 45 degree angle, to the local prevailing wind direction (Zhu *et al*., 2003). As a shelter forest consisting of a single species is liable to have diseases and has a decreased wind-proof effect during the leaf-off period, mixed broadleaf-conifer forest and mixed tree-shrub forest are now being used as shelter in SFM (Duan *et al*., 2008; Wang *et al*., 2008a). In eastern regions with sufficient precipitation, trees, such as *Populus* spp., *Salix* spp., *Pinus sylvestris* var. and *Picea asperata*, and shrubs, such as *Hippophae rhamnoides* L., *Prunrs sibirica* L., *Caragana microphylla* and *Amorpha fruticosa* L.,. are usually selected for the main part of the wind-shelter forest grids (Xiao *et al*., 1983; Dong *et al*., 2011). In the western regions, where there is less precipitation, trees, such as *Ulmus pumila* and *Pinus sylvestris* var., and shrubs, such as *Caragana microphylla*, *Amorpha fruticosa*, *Astragalus adsurgen*s and *Agropyron cristatum*, are selected for the main part of the wind-shelter forest grids (Hu *et al*., 2001; Wang *et al*., 2003; Wang *et al*., 2008a). The initial and terminal protective maturity ages of wind-shelter grids depends on the maturity height and optimal porosity of the shelter forests, which change depending on the trees and shrubs species used. Usually, they are 8–10 years and 33–37 years, respectively, for local *populus* shelter zones (Zhu *et al*., 2002b). The initial protective maturity ages for shrubs are smaller (Wang *et al*., 2008a). An update on the wind-shelter forest needs to be considered, on the basis of the protective ages of the forest.

Observations in the field have shown that a wind-shelter forest can reduce the wind velocity and increase the roughness length (Wang and Takle, 1996; Cornelis and Gabriels, 2005). The reduction in wind velocity depends on the porosities of the wind-shelter forest (Hao *et al*., 2005b; Ma *et al*., 2010). The wind velocity decreased with decreasing porosity of the shelter forests and became stable when the porosity reached 20–35 per cent (Figure 8a). The wind reduction effect of shelter forest rose as the height of the shelter forests increased (Figure 8b), and the protection range of wind-shelter forest grids were in proportion to the height of the forest (Zhao, 2002; Wang *et al*., 2008a; Li *et al*., 2009). In addition, wind-shelter forest grids can affect the local micrometeorological environment. Research in arid Ningxia Province showed that the average temperature

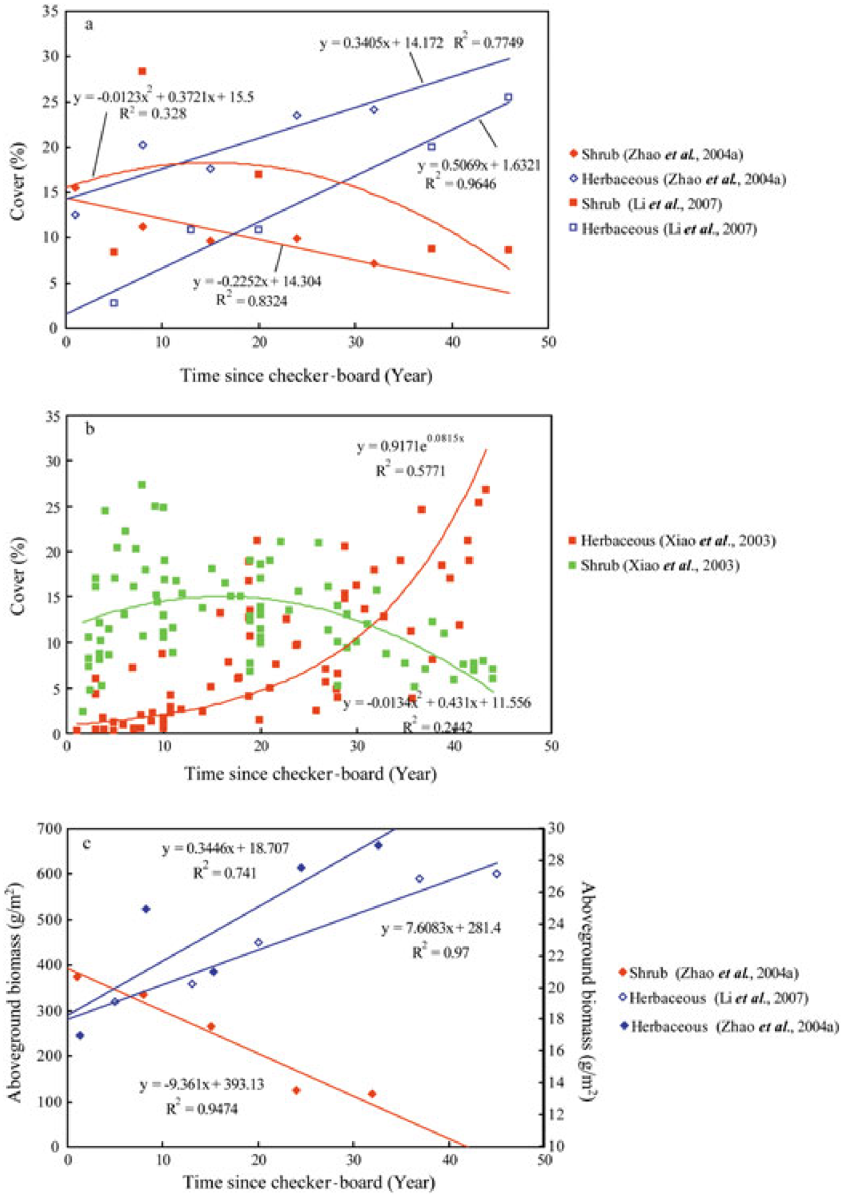

Figure 7. Changes in vegetation cover (a and b) and aboveground biomass (c) for shrubs and herbaceous plants over the period that straw checker-boards were used to stabilize mobile sand dunes. Data were taken from a number of different results. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

of the soil surface was 24·5 °C (SD ± 7·87) inside the shelter forest and 39·6°C (SD ± 6·20) outside the shelter forest and that the shelter forest can reduce air temperature by 14–40 per cent, increase air moisture by 25 per cent and increase soil moisture (0–10 cm depth) by 30 per cent (Zha *et al*., 2004).

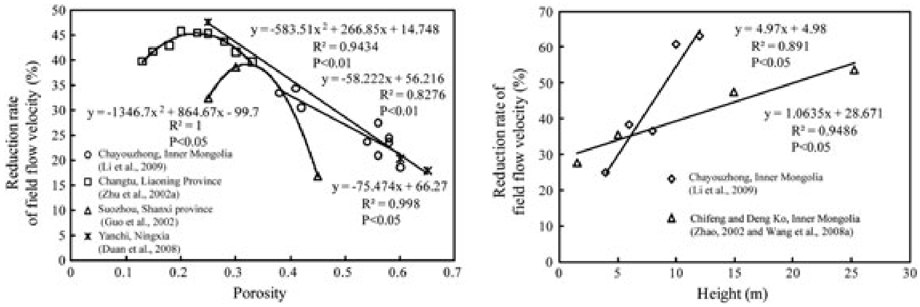

Figure 8. The effect of reducing the wind velocity on the porosity (a) and height (b) of wind-shelter forest. Data were taken from a number of different results.

Establishing a wind-shelter forest can effectively protect the farmland inside the forest grids from wind erosion, change the microclimate and enhance crop production (Figures 6c and 6d). Therefore, the soil physical and chemical properties inside the forest belt and the forest grids were superior to the properties of the soil found in the outer forest girds without protection (Wang *et al*., 2003; Yasuhito *et al*., 2004, 2005). For example, observations in Dengkou, located in the western part of agro-pastoral ecotone, showed that the field moisture capacity, soil moisture content, soil porosity, volume weight of soil, soil compactness, clay particle content, total salt content and pH on the farmland in the wind-shelter forest grids were higher than those in the fields without wind-shelterbelt forest protection by 26·69 per cent, 14·75 per cent, 7·97 per cent, $-0{\cdot}23\,\mathrm{g\,cm^{-3}}$, $-1{\cdot}2\,\mathrm{kg\,cm^{-2}}$, 36·1 per cent, –0·0711 per cent and –0·5, respectively (Wang *et al*., 2003). Usually, the changes to the soil physical and chemical properties in the surface layers following the planting of wind-shelter forest are slow in the first 9–10 years and then are rapid between 10 and 20 years in the eastern part of the agro-pastoral ecotone (Yasuhito *et al*., 2004). However, the significant change occurred after 15 years in the western part of the agro-pastoral ecotone (Mao *et al*., 2009).

Protecting Grassland Using Enclosure Measures

Overgrazing is one of the main factors causing aeolian desertification in the grasslands of the agro-pastoral ecotone (Zhu and Wang, 1993; Zhu and Chen, 1994; Zhang *et al*., 2004b). Prohibiting grazing or introducing rotational grazing inside enclosed grasslands have been used to recover Aeolian desertified grasslands in China for over 10 years (Pei *et al*., 2008; Zhou *et al*., 2012). For example, grazing has been completely prohibited in Beijing, Qinghai Province, Ningxia Hui Autonomous Region, Shannxi Province and Hebei Province since 2005. In Inner Mongolia and some other regions, moderately and severely aeolian desertified grasslands have also been enclosed to prevent grazing to allow native vegetation to regenerate and reduce soil erosion (Zhang *et al*., 2004b; Zhang *et al*., 2005b; Pei *et al*., 2008; Xiong *et al*., 2011). Potential and slightly aeolian desertified grasslands have also been enclosed for seasonal and regional rotational grazing (Kazuhiro *et al*., 1998).

Experimental results from different regions showed that the vegetation and soil properties significantly recovered after prohibiting grazing in enclosed grasslands (exclosure) for 2–5 years and enclosure also enhanced the fixation of shifting sand sheets and dunes (Su *et al*., 2004; Zhao *et al*., 2004b; Zhang *et al*., 2005b; Pei *et al*., 2008; Xiong *et al*., 2011). For example, in Horqin region, excluding animals for 1 year increased the vegetation cover, height and above ground biomass by 20–40 per cent, 5–10 cm and 40–45 per cent, respectively. Excluding animals for 2 years increased the parameters by 50–70 per cent, 10–15 cm and 100–110 per cent, respectively, and excluding animals for 3 years increased them by 100–126 per cent, 15–25 cm and 140–150 per cent, respectively (Liu *et al*., 1996). After excluding animals for 3 years, the proportion of the habitat made up by the *Leymus chinensis* community, *Artemisia frigid* community and *Artemisia halodendron Turcz. Ex Bess.* community increased from 2·53 per cent to 10·64 per cent, from 3·53 per cent to 17·56 per cent and from 17·23 per cent to 17·56 per cent, respectively, and the proportion made up by the weed community and bare land decreased from 59·2 per cent to 56·37 per cent and from 17·52 per cent to 5·2 per cent, respectively (Liu *et al*., 1996). As vegetation density, cover and height increase, the wind velocity and wind-blown intensity near surface significantly decrease. For example, in Tengger Desert, after excluding animals for 3 years, the wind velocity at 50 cm above the surface and the sand transportation rate inside the enclosure decreased by 92·7 per cent and 53·4 per cent, respectively, compared with outside the enclosure (An *et al*., 2007).

Field experiments have shown that herb cover usually rises as the number of years of enclosure increases (Figure 9a), but shrub, especially sub-shrub, cover increased at the beginning but then decreased, which indicated that enclosure causes the area to change from shrub-dominated to grass-dominated land (Xiong *et al*., 2011). Linked with the plant cover change, the total biomass also increased at first and then declined. Maximum biomass occurred after about 20 years of enclosure (Figure 9b) because of the reduction in shrub biomass. Litter biomass research has shown that vegetation diversity rose as the enclosure period increased (Figure 9c), but the increase in species number was significantly greater than the increase in the species abundance index (Xiong *et al*., 2011). Prohibiting grazing in an enclosure improves litter accumulation (Su *et al*., 2005b), soil bulk density (Figure 9d), soil organic C (Figure 9e) and total N concentrations (Figure 9f). Soil biological properties, including some enzyme activities and basal soil respiration, also improve (Jia *et al*., 2004; Su *et al*., 2005b) because of a reduction in wind erosion and an increased litter input. However, unlike the rapid recovery seen in degraded vegetation, soil quality recovery in degraded land is relatively slow (Zhao *et al*., 1998, 2004b; Su *et al*., 2004, 2005b).

Although prohibiting grazing in enclosed, grasslands improves the restoration of degraded grassland; long time exclosure harms the economic interests of the herdsmen, which raises dilemmas and conflicts in relation to ecological protection and pastoral household livelihoods (Brown *et al*., 2008). Research into the grazing prohibition policy in Yanci County, located in the Mu Us sandy area, showed that the aeolian desertified grasslands started to recover when the amount of land where grazing was prohibited reached 30 per cent. The speed of restoration increased when the amount of land where grazing was prohibited increased from 30 to 40 per cent, but then kept steady when the amount of land where grazing was prohibited increased from 40 to 100 per cent because of farmers illegally grazing the land (Zhou *et al*., 2012). However, the accumulated litter has been found to cause fire and inhibit vegetation growth in enclosures that were over 5 years old (Wang, 2011). So, seasonal and regional rotational grazing in an enclosure

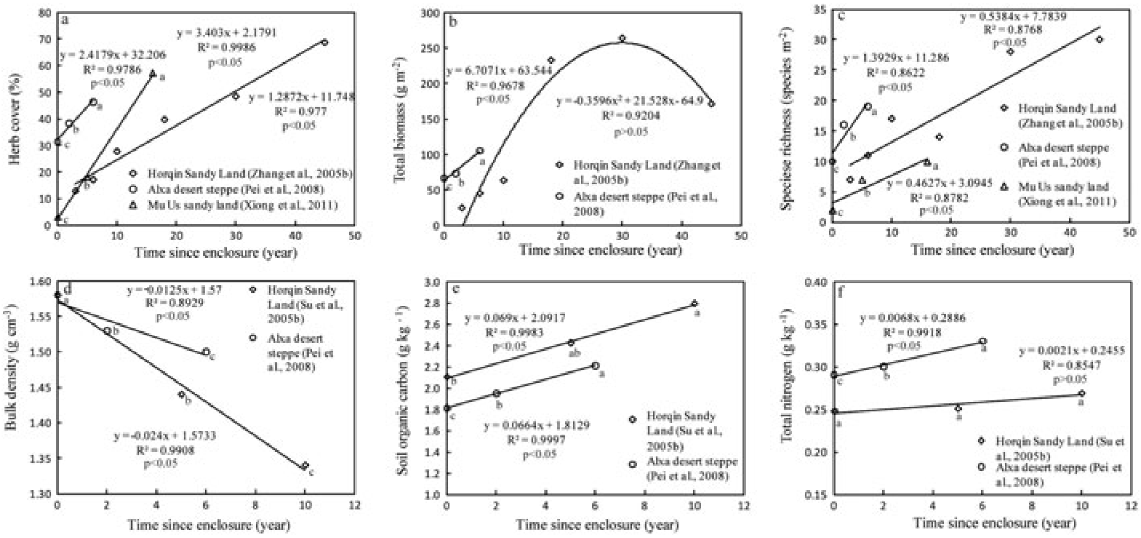

Figure 9. Changes in herb cover (a), total biomass (b), species richness (c), bulk density (d), organic carbon content (e) and total nitrogen (f) in topsoil for the period during which the land had been enclosed. Data were taken from a number of different results.

should be more sustainable when restoring degraded grassland. Results from research on seasonal grazing in the Horqin sandy area showed that vegetation cover, vegetation height and species richness were higher at sites where grazing had been controlled than at sites lacking any control, which suggested that the seasonal exclusion of animals was sufficient to maintain grassland vegetation on formerly degraded grassland (Kazuhiro *et al*., 1998). On the basis of the experimental results from field grazing trials, seasonal enclosure and light grazing with 2–3 sheep or sheep equivalents per hectare was recommended for the recovery of overgrazed grassland and maintenance of plant species diversity in agro-pastoral ecotones with mean yearly precipitation of about 400 mm (Kazuhiro *et al*., 1998; Zhao *et al*., 1998, 2004b). To supply the demand for fodder, enough stable breeding facilities must be established in those regions where enclosure is employed to assure economic benefits to local herdsmen (Zhou *et al*., 2012).

A CASE STUDY ON COMBATING AEOLIAN DESERTIFICATION IN AN AGRO-PASTORAL ECOTONE

On the basis of the results of experimental research into combating aeolian desertification, many measures have been selected, integrated and implemented across much of northern China, and the achievements have been outstanding, especially in agro-pastoral ecotones. The aeolian desertified area in the agro-pastoral ecotone of northern China decreased from 121,900 km^2 in 1987 to 109,900 km^2 in 2000 (Zhu and Chen, 1994; Xue *et al*., 2005). A typical case study, developed for Balinyou County, is presented in this paper to illustrate the integrated application of different measures for combating desertification in the agro-pastoral ecotone.

Balinyou County is located in the western part of the Horqin region in Inner Mongolia. The total land area of Balinyou County is 9909·97 km^2, the yearly average rainfall is 344·4 mm and the yearly average evaporation is 2103 mm. The native vegetation mainly consists of *Ulmus pumila* L., *Prunus sibirica* L., *Artmisia halodendron* and *Filifolium sibiricum*. The soil is classified as being a sandy soil (Wang *et al*., 2005). The aeolian desertified land area, including potential aeolian desertification land, was 6131·67 km^2 in 1975, 5340·37 km^2 in 1987, 5205·17 km^2 in 2000, 3499·28 km^2 in 2005 and 1273 km^2 in 2010 (Wu, 2003; Duan *et al*., in press). The rapid reversal of aeolian desertification after 2000 was attributed to the establishment and implementation of local ecology recovery policies and practices, which were mainly based on previous research result into the three measures mentioned in this paper. In Balinyou County, there are three kinds of aeolian desertified lands: aeolian desertified farmland, aeolian desertified grassland and shifting sand dunes. Since 2002, SCM, SFM and EM have been combined to control and restore these degraded lands (Wang *et al*., 2005).

Restoring Aeolian Desertified Farmland Using Enclosure and Shelter Forest

Farmers left the area before the aeolian desertified farmlands were enclosed as a protection area. Cultivation was forbidden in the enclosed protection areas to restore the vegetation cover and improve soil quality. From 2000 to 2007, 1200 km^2 of aeolian desertified farmlands were converted into protection areas. In the protection areas, mixed plantations of trees, shrubs and grasses were established to replace cultivation and accelerate the recovery of degraded farmland (Figure 10a). Species of trees, shrubs and grasses with economic and commercial benefit were selected as suitable species to promote sustainable development of the environment and the economy in the protection area. During the initial stage (5–10 years), government provided the funds and technological support to ensure the

Figure 10. Mixed tree-shrub-grass planting in previously aeolian desertified farmland. Photo was taken in August 2002 (a). The enclosure pasture. Photo was taken in July 2011 (b). The Quickbird photo for wind-shelter forest grids. Photo was taken in June 2010 (c). The Quickbird photo for *Hedysarum laeve Maxim* checker-boards Photo was taken in June 2010 (d). The middle stage of *Hedysarum laeve Maxim* checker-boards used for binding sand dunes. Photo was taken in August 2002 (e). The late stage of *Hedysarum laeve Maxim* checker-boards used for binding sand dunes. Photo was taken in August 2002 (f). All photos were taken in Balinyou County. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

smooth implementation of the project. As the economic benefits developed in the project area, the funding support was gradually reduced and finally eliminated.

Because of the large area of aeolian desertified farmlands that were enclosed or converted into grassland, only 900 km^2 of farmland now exists in the Balinyou County. These farmlands are mainly located on low-lying alluvial land with good soil moisture and fertility because they are adjacent to a river. All of the farmlands were protected using wind-shelter forest containing trees and shrubs. From 2001 to 2005, 70 km^2 farmland-shelter forest zones and grids were established (Figure 10c). The grain yield increased from 90,000 tons in 2001 to 120,000 tons in 2005.

Restoring Aeolian Desertified Grassland Using Enclosures

Balinyou County is a traditional pastoral region, and grassland occupies a large portion of the whole county. Over-cultivation and overgrazing left the grassland severely degraded. Starting in 2002, enclosure measures were implemented in the aeolian desertified grasslands over an area of 3000 km^2 to recover the productivity and carrying capacity of the pastures (Figure 10b). In severely degraded grasslands, grazing in the enclosures was completely forbidden until the vegetation recovered. In moderately degraded grasslands, grazing was forbidden in spring and winter to help the grass turn green and recover naturally. In lightly degraded grasslands, regional rotation grazing was carried out to prevent grassland degradation and guarantee economic benefits. To accelerate the recovery of aeolian desertified grassland and supply the demands of livestock, artificial planting and aerial seeding were also used in the enclosure grasslands to increase vegetation cover and enhance the productivity of the pasture. From 2001 to 2005, artificial pastures over an area of 2200 km^2 had been established. After enclosure measures had been implemented for 7 years, the average vegetation cover increased from less than 40 to 85 per cent, and the average height of the grass increased from less than 10 to 80 cm. The recovery in the vegetation enhanced the biomass and productivity of the pastures.

Fixing the Shifting Sand Dunes with Straw and Live Checker-boards

Overgrazing destroyed the vegetation, causing a large area of fixed sand dunes to be activated in Balinyou County over time. In 2000, the areas of mobile and semi-mobile sand dunes were 673 and 439 km^2, respectively (Wang *et al.*, 2005). From 2000 to 2007, 282 km^2 of mobile sand dunes were fixed by straw and live checker-boards. In 2000, live *Hedysarum laeve Maxim* plots, $4 \times 4\,m^2$ in size, were planted in the shape of checker-boards in mobile sand dunes that had an average relative height of 20 m (Figures 10d and 10e). After the checker-boards had been in place for 7 years, the vegetation cover of the sand dunes reached 100 per cent, and the sand dunes were completely fixed (Figure 10f). A majority of the branches of *Hedysarum laeve Maxim* were harvested in Balinyou County and sold to nearby counties to fix their mobile sand dunes, not only bringing added benefit to local people but also helping to combat aeolian desertification in nearby regions.

From the case study, it can be seen that the three measures and technologies described in this paper were combined to rehabilitate the local aeolian desertified land. The Balinyou County measures used to combat aeolian desertification have been certified as effective in local and nearby counties and in recent years have been popularized and improved upon in other regions of the agro-pastoral ecotone of northern China.

SUMMARY

On the basis of the analysis and evaluation of three common measures for combating aeolian desertification in the agro-pastoral ecotone of northern China, it can been seen that fixing mobile sand dunes using checker-boards, protecting farmland from wind erosion using wind-shelter forest grids and restoring degraded grassland using enclosure are appropriate approaches for rehabilitating aeolian desertified land. The case-study in Balinyou County also demonstrated that the integrated implication of these three measures is effective and feasible. It can be concluded that the rehabilitation of degraded land can be achieved as long as sustainable land use policies and scientific methodologies are implemented. The selection, combination and implementation of measures and technologies to combat aeolian desertification depend largely on the regional ecosystem characteristics and the aeolian desertification pattern. That is to say, only when measures taken to control aeolian desertified land are working with nature can the measures be effective and sustainable.

This paper presents measures and practices for the recovery of degraded land that could be used on a global scale. However, the technology and management experience for rehabilitating aeolian desertified land is still inadequate because the short history of combatting aeolian desertification. In particular, how to respond to the impacts of climate change and increasing population on the fragile arid ecosystem is a great challenge to the processes that will be used to prevent and control aeolian desertification in the future.

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