Available online at www.sciencedirect.com
ScienceDirect
Journal of Environmental Sciences 19(2007) 470–474
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

Sustainability: A view from the wind-eroded field

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Received 20 August 2006; accepted 24 November 2006

Abstract

This article explores the assessment of sustainability in fields subject to wind erosion. In the first part, simple sustainability audits are examined, as of soil depth and nutrients. Direct measurement of these characteristics has many problems, largely because of huge variability in space and time at all scales. Modelling still has its problems, but it may be possible to overcome many of them soon. It is true that wind erosion preferentially removes soil nutrients, but there are imponderables even here. The nutrient balance in many of these soils includes considerable input from dust. In West Africa, it has been shown that the amounts of calcium and potassium that are added in dust are sufficient to fertilize dispersed crops. In mildly acidic sandy soils, such as those found on the widespread palaeo-aeolian deposits, much of the phosphorus is fixed and unavailable to plants by the time it is removed by wind erosion, so that erosion has no added downside. Most of the nutrients carried by dust have been shown to travel close to the ground (even when they are attached to dust-sized particles), and so are trapped in nearby fallow strips, and are thus not lost to the farming system. Second, the sustainability of a whole semi-arid farming system is explored. Wind erosion in semi-arid areas (like China, the Sahel and Northwestern Europe) generally takes place on aeolian deposits of the recent geological past. Most of these soils are deep enough to withstand centuries of wind erosion before they are totally lost to production, and some of these soils have greater fertility at greater depth (so that wind erosion may even improve the soil). Finally some remarks are made about environmental change in relation to sustainability.

Key words: sustaninability; wind erosion; nutrient budget; environmental change

Introduction

Wind erosion is a threat to sustainable agriculture in most semi-arid parts of the world. Semi-arid agricultural soils are susceptible to wind erosion for five reasons. First, crop cover is difficult to maintain in the early and post-harvest stages of the cropping cycle. Second, soils are dry, and therefore have little cohesion. Third, this poor cohesion is exacerbated by a low content of organic matter. Fourth, fields are generally less well protected by vegetative barriers than in wetter climates. Fifth, many of the soils are sandy, a legacy of the dry periods during and since the last ice age; sandy soils have poor aggregation and lower wind-speed thresholds for erosion.

According to some of the literature, it is known that these soils are extensive in semi-arid China and that “sandy desertification” is a major preoccupation among Chinese agronomists (Li and Zhou, 2001; Li *et al*., 2004a, b; Liu *et al*., 2003; Luo *et al*., 2005; Wang *et al*., 2004; Zhang *et al*., 2004; Zhao *et al*., 2005, 2006). It is also known from Sontag and Hongle (2002) that sustainability in Chinese agriculture, and especially in its semi-arid areas, is widely believed to be threatened by erosion.

The purpose here was to identify problems with the assessment of sustainability. In doing so, I am not dissenting with the general alarm about sustainability, but merely questioning glib judgments about it. I will first look at “sustainability audits” of “soil services”, then move on to look at two much wider-ranging issues about the sustainability of semi-arid agriculture: sustainable economies and environmental change.

1 Resource sustainability

A simplistic, resource-oriented definition of sustainability in this context is the following: rooting depth, moisture, and nutrient supply (i.e. “soil services”) do not degrade.

1.1 Soil depth

Soil depth, or better rooting depth, are themselves not difficult to measure, and the conversion of these depths to soil water-holding capacity has been adequately understood for many years. But there are large uncertainties about the effect of erosion on soil depth. This is true even for soil erosion by water, which is better understood than wind erosion, and even about erosion rates by water in the United States, which must be the best-understood area in the world. Trimble and Crosson (2002) argued that the USA has been basing its strategies on data that came from small plots, and that rates for larger areas, which were not accurately known, were likely to be much lower.

Trimble and Crosson (2002) made brief mention of wind erosion, to which their argument also applies, but concentrated on water erosion. They and the scientific community in general know much less about rates of wind erosion, despite some excellent science in China and in the rest of the world. Trapping sediment is the oldest and most obvious method to measure wind erosion, but trap designs have only recently converged (Goossens and Offer, 1994), so that older methods are not strictly comparable. The main problem with trapping is very high spatial and temporal variability. The problem is at its most acute at the small scale (the field and under a day), although new analytical techniques using geostatistics are producing better analysis of variability at this scale (Sterk and Stein, 1997). One can smooth out small-scale variability with the 137Cs method, but only over a period of about 40 years (Yan and Shi, 2004; Chappell *et al*., 1998). Even these techniques come up against problems of temporal and spatial variability. The next major challenge is to bridge the scale gap between trapping and 137Cs measurement.

Modelling compliments measurement, and although there are still major problems, there have been large advances in modelling. In a recent project (WEELS) with which I was associated, financed by the European Union (Warren, 2002a), Jürgen Böhner, working at Göttingen in Germany, modelled wind erosion on a 5 km×5 km area of Suffolk, in Eastern England, for a period of over 30 years, day-by-day and at even finer temporal scales (Böhner *et al*., 2003; Chappell and Warren, 2003). When we compared his model results with measurements using 137Cs, we found differences in amounts of erosion, but not in timing or spatial pattern. Böhner believed that there were two major problems with the modelling. The most important was the estimation of roughness, which also has large spatial and temporal variability. The second issue was converting a crude measure of erosion to a quantified one. As a team we also ignored soil that left the fields on the sugar-beet crop, which may be a major cause of soil loss.

1.2 Outputs in wind-erosion

Apart from the loss of rooting depth (and thus water-holding capacity), the main negative effect of erosion is the removal of nutrients. The sediment that is taken by wind erosion may carry a high proportion of the soil's clay and organic matter (which together hold nutrients as well as moisture). In southern Alberta, Larney and his colleagues (1998) found that blown soil was between 1.08 and 1.11 times richer in nitrogen than the remaining soil. Nitrogen is conspicuously enriched in material blown from fields in North Dakota and Eastern England (Cihacek *et al*., 1993; Chappell and Thomas, 2001). In a short-term experiment in China the losses of nutrients through wind erosion averaged 4.62 kg/(hm^2·d) of organic matter, 0.31 kg/(hm^2·d) of nitrogen, and 0.13 kg/(hm^2·d) of phosphorus. During the experiment only 0.54, 0.04, and 0.02 kg/(hm^2·d) of organic matter, nitrogen and phosphorus, respectively, were replaced in dust added to the surface (Li *et al*., 2004a, b).

However, these apparent losses are not always as damaging as they appear. First, most of the material taken by the wind does not travel far. In Niger most nutrients blown from a millet field, despite being held in the fine fraction of the soil, were carried in the saltation layer, so that most of the nutrient load was redeposited locally, often in nearby fallow fields, which themselves would be cultivated in a few years (Sterk *et al*., 1996). Second, many of the nutrients may be in forms that are either not available in the long term, or immediately to crops. Nitrogen is a notoriously labile nutrient, being quickly lost in various ways; its role in a sustainability audit is debatable. Mildly acidic sandy soils the phosphorus that is lost may already have been fixed, and so "lost" in an unavailable form.

1.3 Natural inputs

An approach that concentrates on the dynamics of removal (erosion), accounts for only part of the full dynamic of soil formation. In semi-arid areas, even more so than in more humid areas, a sustainability audit must take into account two important inputs to soils. The first of these comes from the above: from dust. In parts of Niger in West Africa, 2 t/hm^2 of dust (0.15 mm of topsoil) is added to the soil each year (Stahr and Herrmann, 1996; Rajot and Valentin, 2001). On the Loess Plateau in China, profiles in soils cultivated for 7500 years show that they developed with fluctuating and sometimes large inputs of new soil material from dust (Huang *et al*., 2002). Perhaps more important, the dust is richer in essential plant nutrients than the parent soil. In West Africa, the dust brings sufficient potassium and calcium to maintain low-output agriculture. Although the input of phosphorus is insufficient even for this form of cropping in West Africa, Okin and his colleagues (2004) found that dust-bourn phosphorus is a significant and often the dominant form of input into many other semi-arid soils.

The second input is from the below (the weathered rock or sediment beneath the soil). To discuss this input we need first to understand the concepts behind productivity/erosion relationships.

1.4 Erosion vs. productivity

It might seem obvious that erosion would damage productivity, but getting empirical proof is another intractable problem. Stripping off a layer of soil before growing a crop and measuring its yield has occasionally been attempted, but it is an expensive and destructive process. One such experiment, on Canadian Prairie soils subject to wind erosion, showed an alarming decrease in productivity on the artificially eroded soils (Larney *et al*., 1995). This catastrophic reaction to erosion may well occur in some areas one is described by Bunn (1997), but the conclusions are unlikely to hold for larger areas. The rapid collapse of production they suggest has not occurred, except occasionally. The main source of the overestimations this method produces is probably that erosion (by wind or water) generally removes soil much more slowly than does the stripping, and slower rates of loss allow organic matter and nutrients from dust to accumulate in the soil and maintain its fertility. Experiments in which productivity is observed on eroded and uneroded parts of the same soil type suffer from the difficulty of filtering out all the other influences on productivity, particularly moisture.

To discover productivity/erosion relationships, we are left with various forms of estimation or modelling. Estimates by acknowledged authorities range from 1.8% of yield over a hundred years to 8% in a single year (Hopkins *et al*., 2001). Some authorities go so far as to claim that the issue is not serious in the United States (Crosson, 1997). The range itself should not be surprising, for soils vary greatly in the way they are degraded by erosion. Soils formed on loess are some of the best soils in North America, Europe and China. They are effectively very deep, and show little loss of productivity even at quite high rates of erosion over very many years, as has been known for a long time (Larson *et al*., 1983). Very many semi-arid agricultural soils are derived from deep alluvium, loess and stabilised sand dunes. Many of these relics of different environmental conditions are deep, providing large reserves of sediment that can be incorporated as soil, as erosion reduces depth by slow increments. It would take years of erosion at current rates to thin most of these soils to the point where they began to lose fertility. Larson and his colleagues (1983) used soils on deep loess as an example that showed little change in productivity under erosion. A similar calculation has been done for soils on stabilised sand dunes in Nigeria, where the conclusion was that the soil life was very many decades (Mortimore, 1998). For an area with deep sands in the Sahel we speculated that high rates of wind erosion (26 to 46 t/(hm^2·a)) were not a major issue for sustainability in many kinds of Sahelian agriculture (even if it was a problem for short-term agriculture at some times and in some places)(Warren *et al*., 2001).

Of course the relationship between productivity and erosion is unlikely to be as linear as in Larson's model. In Niger, some sandy soils, in which nutrients and clay have been washed down in the profile, may even give improved productivity under erosion. More common among these sandy soils may be those in which the uppermost horizon may be enriched with dust and organic matter before cultivation, but where the lower horizons show no change in fertility to great depths. Once the upper horizon has been lost from these soils, there is no strong relationship between erosion and loss of fertility. Hopkins *et al*. (2001) have now modelled these and other likely situations.

2 Whole-system sustainability

The simple definition of sustainability that underlies the first sections of this paper is only part of a fuller definition of sustainability, which is simply stated as: the food production system does not degrade.

2.1 Food production system

This very considerably broadens the argument. A useful model of whole-system sustainability is that of Serageldin (1996), who broadened the argument to include the economic and technical systems of food production. These ideas can be illustrated from my own experience in the Sahel of West Africa. The sustainability of food production in the parts of the Sahel where wind is the main agent of erosion depends not only on the sustainability of its soil resource, but also on the sustainability of agricultural communities. The two (the biophysical and the economic elements) can be at odds. The biophysical argument based on input and output of biophysical elements is what Serageldin called a "hard sustainability": resources should not degrade. Yet to ask Sahelian farmers to maintain their soils intact would be to destroy their economy. They do not have the labour or technical means to do this (Warren *et al*., 2001). A very similar case has been made for agriculture in the Great Plains, where the constraints are less linked to labour (as they are in the Sahel) as to farm economics (Hoag *et al*., 2000).

The differences between the two approaches to sustainability are largely related to scale. At the small scale, few, if any, farmers are concerned about the long-term. The most obvious reason is that the effect of erosion on productivity in most farms is difficult to distinguish, even over decades, from all the other influences on productivity such as rainfall or the varying input of fertilizers. At the average rate of loss in the United States (6.4 t/(acre·a) it would take twenty-five years to lose one inch of soil (Hughes-Popp *et al*., 2000). In Niger, we calculated that over 30 years, at a rate of 26 to 46 t/(hm^2·a), only a few centimetres of soil would have been lost to wind erosion (Warren *et al*., 2001). Farmers can hardly be expected to show concern for these effects. Sustainability, moreover, depends on each farmer having access to a mix of soils: in Niger farmers need all of their soil types: some for very wet years; some for wet years, and some for dry years. Sustainability, it turns out, depends on who you are; particularly on your scale of vision: the wider timescales of national planners may sensitise them to sustainability, where the farmers horizons limit his concerns to many more pressing things (Warren, 2002b). Soil sustainability (except in some cases) is the concern of the community, not of the individual.

There are many other facets to agricultural sustainability, such as energy sustainability, including the energy invested in inputs such as fertilizers, the running of farm machinery and transport to and from the farm. Other criteria, such as substitutability, uncertainty and reversibility would also have to be considered in the evaluation of a wind-eroded site (Hoag *et al*., 2000).

Sustainability trajectories may be best explored with models, and there have now been many attempts to do this, though fewer where wind erosion is concerned (with some exceptions such as Bunn's work (1997) referred to above). Not all sustainability models find that the soil is a critical input as in model by Mantel *et al*. (2000) for Uruguay as a whole, which found that the soil was not a critical determinant of sustainability).

2.2 Environmental change

The last part of a full sustainability audit is to consider the likely trajectory of environmental change. Change could affect all of the processes I have discussed so far, particularly if windspeeds or evaporation were to increase.

Wind erosion of now-stabilized dunes in semi-arid areas would accelerate in a drier, windier world. Chinese scientists expect that any increase in temperature will increase the "sandification" of their now stabilized dunefields (Ci, 2002). Forecasts of Global Climatic Models have been combined with Lancaster's climatic index of dune activity (Lancaster and Helm, 2000) and applied to the Great Plains. In these models many of the now stabilised dune fields become active again (Muhs and Maat, 1993). Modelling the future plant cover of the Nebraska Sandhills shows that they could easily revert to being active (Mangan *et al*., 2004). These predictions, of course, depend on keeping other things equal, where they seldom are. Studies of dune reactivation in semi-arid areas like the Nebraska Sand Hills and southeastern Australia show that reactivation has been controlled partly by drought, and partly by land use (Seevers *et al*., 1975; Ohmori *et al*., 1983), in unpredictable mixtures. Nonetheless, when there were severe enough droughts, as occurred 55–65 years ago in the Great Plains, and may now be expected to be more frequent, reactivation was so widespread that land use could make only a minor impact (Mason *et al*., 2004). Some have seen the Dust Bowl as an analogy of what might occur in many semi-arid areas if climate warming were to continue. The main climatic anomaly in the Great Plains at that time was a higher temperature, rather than lower precipitation, and higher temperatures are more or less assured in most scenarios of global warming (Rosenzweig and Hillel, 1993).

3 Conclusions

Judging sustainability is not easy, even if we restrict an audit to strictly biophysical criteria. Input and output should be balanced for sustainability, but neither is easy to measure, and the measures are scale-dependent. If the audit includes economies and societies, it becomes very much more complex. And in accelerated climate change, such as we are now experiencing, sustainability will be almost impossible to quantify.

References

Böhner J, Schäfer W, Conrad O *et al*., 2003. The WEELS model: methods, results and limitations[J]. Catena, 52(3/4): 289–308.

Bunn J A, 1997. The implications of alternative beliefs about soil-erosion-productivity relationships and conservation treatments for the economic dynamics of soil erosion on the southern Texas High Plains[J]. Journal of Soil and Water Conservation, 52(5): 368–375.

Chappell A, Warren A, Taylor N *et al*., 1998. Soil flux in southwest Niger and its agricultural impact[J]. Land Degradation and Development, 9(4): 295–310.

Chappell A, Thomas A D, 2001. Reconstructing the recent wind erosion history of a field in East Anglia, UK[M]. In: Soil erosion research for the 21st century(Ascough J. C. II, Flanagan D. C., ed.). ASAE (American Society of Agricultural Engineers) Publication, 701P0007. 486–489.

Chappell A, Warren A, 2003. Spatial scales of 137Cs-derived soil flux by wind in a 25 km^2 arable area of eastern England[J]. Catena, 52(3/4): 209–234.

Ci L J, 2002. Disasters of strong sandstorms over large areas and the spread of land desertification in China[M]. In: Global Alarm: Dust and sandstorms from the world's drylands (Yang Y. L., Squires V. R., Lu Q., ed.). United Nations Publication E.02.II.F.50. 215–226.

Cihacek L J, Sweeney M D, Deibert E J, 1993. Characterization of wind erosion sediments in the Red River Valley of North Dakota[J]. Journal of Environmental Quality, 22(2): 305–310.

Crosson P R, 1997. Will erosion threaten agricultural productivity[J]. Environment, 39(8): 4–31.

Escurra E (Ed.), 2006. GEO for deserts[M]. United Nations Environment Programme (UNEP), Nairobi. 148.

Goossens D, Offer Z Y, 1994. An evaluation of the efficiency of some eolian dust collectors[J]. Soil Technology, 7(1): 25–35.

Hoag D L, Hughes-Popp J S, Huszar P C, 2000. Is US soil conservation policy a sustainable development?[M] In: Soil and water conservation policies and programs (Napier T. L., Napier S. M., Tvrdon J., ed.). CRC, Boca Raton, FL. 127–142.

Hopkins J W, Lal R, Wiebe K D *et al*., 2001. Dynamic economic management of soil erosion, nutrient depletion, and productivity in the north central USA[J]. Land Degradation and Development, 12(4): 305–318.

Huang C C, Pang J L, Huang P *et al*., 2002. High-resolution studies of the oldest cultivated soils in the southern Loess Plateau of China[J]. Catena, 47(1): 29–42.

Hughes-Popp J S, Huszar P C, Hoag D L, 2000. Reducing wind erosion damages and the Conservation Reserve Program[M]. In: Soil and water conservation policies and programs (Napier T. L., Napier S. M., Tvrdon J., ed.). CRC, Boca Raton, FL. 143–154.

Lancaster N, Helm P, 2000. A test of a climatic index of dune mobility using measurements from the southwestern United States[J]. Earth Surface Processes and Landforms, 25(2): 197–207.

Larney F J, Izaurralde R C, Janzen H H *et al*., 1995. Soil erosion -crop productivity relationships for six Alberta soils[J]. Journal of Soil and Water Conservation, 50(1): 87–91.

Larney F J, Bullock M S, Janzen H H *et al*., 1998. Wind erosion effects on nutrient redistribution and soil productivity[J]. Journal of Soil and Water Conservation, 53(2): 133–140.

Larson W E, Pierce F J, Dowdy R H, 1983. The threat of soil erosion to long-term crop production[J]. Science, 219(4584): 458–465.

Lefroy E, Rydberg T, 2003. Emergy evaluation of three cropping systems in southwestern Australia[J]. Ecological Modelling, 161(3): 195–211.

Li B L, Zhou C H, 2001. Sandy desertification trend in western Northeast China Plain in the past 10 years[J]. Journal of Geographical Sciences (Beijing), 11(2): 179–186.

Li X Y, Liu L Y, 2003. Effect of gravel mulch on aeolian dust accumulation in the semiarid region of northwest China[J]. Soil and Tillage Research, 70(1): 73–81.

Li F R, Zhao L Y, Zhang H *et al*., 2004a. Wind erosion and airborne dust deposition in farmland during spring in the Horqin Sandy Land of eastern Inner Mongolia, China[J]. Soil and Tillage Research, 75(2): 121–130.

Li X Y, Liu L Y, Wang J H, 2004b. Wind tunnel simulation of aeolian sandy soil erodibility under human disturbance[J]. Geomorphology, 59(1-4): 3–11.

Liu H Q, Xu J W, Lv X M, 2003. Spatial distribution of sandy desertification change in the west of Jilin Province[J]. Journal of Geographical Sciences (Beijing), 13(3): 379–384.

Luo F, Qi S Z, Xiao H L. 2005. Landscape change and sandy desertification in arid areas: a case study in the Zhangye Region of Gansu Province, China[J]. Environmental Geology, 49(1): 90–97.

Mangan J M, Overpeck J T, Webb R S *et al*., 2004. Response of Nebraska Sand Hills natural vegetation to drought, fire, grazing, and plant functional type shifts as simulated by the century model[J]. Climatic Change, 63(1/2): 49–90.

Mantel S, Van-Engelen V W P, Molfino J H *et al*., 2000. Exploring biophysical potential and sustainability of wheat cultivation in Uruguay at the national level[J]. Soil Use and Management, 16(4): 270–278.

Mason J A, Swinehart J B, Goble R J *et al*., 2004. Late-Holocene dune activity linked to hydrological drought, Nebraska Sand Hills, USA[J]. The Holocene, 14(2): 209–217.

Mortimore M J, 1998. Roots in the dust: sustainable development of Africa's drylands[M]. Cambridge: Cambridge University Press. 219.

Muhs D R, Maat P B, 1993. The potential response of eolian sands to greenhouse warming and precipitation on the Great Plains of the United States[J]. Journal of Arid Environments, 25(4): 351–362.

Ohmori H, Iwasaki K, Takeuchi K, 1983. Relationships between the recent dune activities and the rainfall fluctuations in the sourthern part of Australia[J]. Chirigaku Hyoron (Geographical Review of Japan), 56(3): 131–150.

Okin G S, Mahowald N, Chadwick O A *et al*., 2004. Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems[M]. Global Biogeochemical Cycles 18, GB2005, doi:10.1029/2003GB002145.

Rajot J L, Valentin C, 2001. Wind eroded versus deposited mineral dust: A mass budget for a Sahelian village land unit in Niger[M]. In: Soil erosion research for the 21st century(Ascough J. C. II, Flanagan D. C., ed.). ASAE (American Society of Agricultural Engineers) Publication 701P0007. 404–407.

Rosenzweig C, Hillel D, 1993. The dust bowl of the 1930s – analog of greenhouse-effect in the Great-Plains[J]. Journal of Environmental Quality, 22(1): 9–22.

Seevers P M, Lewis D T, Drew J V, 1975. Use of ERTS-1 imagery to interpret the wind erosion hazard in Nebraska's Sandhills[J]. Journal of Soil and Water Conservation, 30(4): 181–183.

Serageldin I, 1996. Sustainability and the wealth of nations: first steps in an ongoing journey, environment and sustainable development studies[M]. Monograph Series 5, World Bank, Washington, DC. 21.

Sontag B, Hongle S, 2002. Agricultural development and environment in critical areas of China[M]. Beijing: Science Press. 140.

Stahr K, Herrmann L, 1996. Origin, deposition and composition of dust and consequences for soil and site properties with special reference to the semi-arid regions of West Africa[M]. In: Wind erosion in Niger: implications and control measures in a millet-based farming system, Developments in Plant and Soil Sciences 67 (Buerkert B., Allison B. E., von Oppen M., ed.). Kluwer Academic Publishers. 45–66.

Sterk G, Hermann L, Bationo A, 1996. Wind-blown nutrient transport and soil productivity change in southwest Niger[J]. Land Degradation and Rehabilitation, 7(4): 325–335.

Sterk G, Stein A, 1997. Mapping wind-blown mass transport by modeling variability in space and time[J]. Soil Science Society of America Journal, 61(1): 232–239.

Trimble S W, Crosson P, 2000. US soil erosion rates–myth and reality[J]. Science NS, 289(5477): 248–250.

Wang T, Wu W, Xue X *et al*., 2004. Study of spatial distribution of sandy desertification in North China in recent 10 years[J]. Science in China D, 47(Supp 1): 78–88.

Warren A, Batterbury S P J, Osbahr H, 2001. Sustainability and Sahelian soils: evidence from Niger[J]. Geographical Journal, 167(4): 324–341.

Warren A, 2002a. Wind erosion on agricultural land in Europe: a review for land managers[M]. Directorate General of Research, European Union, Brussels, EUR 20370. 76.

Warren A, 2002b. Land degradation is contextual[J]. Land Degradation and Development, 13(6): 449–459.

Yan P, Shi P J, 2004. Using the 137Cs technique to estimate wind erosion in Gonghe Basin, Qinghai Province, China[J]. Soil Science, 169(4): 295–305.

Zhang T H, Zhao H L, Li S G *et al*., 2004. A comparison of different measures for stabilizing moving sand dunes in the Horqin Sandy Land of Inner Mongolia, China[J]. Journal of Arid Environments, 58(2): 202–213.

Zhao H L, Yi X Y, Zhou R L *et al*., 2006. Wind erosion and sand accumulation effects on soil properties in Horqin Sandy Farmland, Inner Mongolia[J]. Catena 65(1):71–79.

Zhao H L, Zhao X Y, Zhou R L *et al*., 2005. Desertification processes due to heavy grazing in sandy rangeland, Inner Mongolia[J]. Journal of Arid Environments, 62(2): 309–319.