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Impacts of the local land-use system in a semi-arid region of northeastern China on soil properties, crop growth, and weed communities

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ABSTRACT

We examined changes in soil properties, crop biomass, and weed communities in the Horqin Sandy Land of China to elucidate cropland degradation. We studied three local cropland types having periods of cultivation of up to 20 years: maize cropland on lowlands without irrigation (nonirrigated lowland), maize cropland on flat sandy lands with irrigation (irrigated flatland), and bean-centered cropland on sand dunes without irrigation (nonirrigated dunes). Soil properties and crop biomass were more degraded in nonirrigated lowland and nonirrigated dunes than in irrigated flatland. Weed communities in the nonirrigated croplands were the type that become established in drier conditions, whereas wetland weeds were more abundant on irrigated flatland. Trends of change in each indicator did not always occur in parallel and differed statistically among the cropland types. Monitoring these indicators within the context of local land-use systems can provide scientific evidence on which to base local management practices or recommendations for change.

1. Introduction

A description of existing land-use systems that includes land-use products, locations, periods, and methods is essential in any investigation of land use (Smith and McDonald, 1998). In general, cultivation is accompanied by loss of soil nutrients (e.g., Celik, 2005; Du Preez and Du Toit, 1995; Hajabbasi et al., 1997; Wu and Tiessen, 2002), and this indicates land degradation (Zhao et al., 2005). The rate of such losses, however, is affected by the period of cultivation (Bowman et al., 1990; Davidson and Ackerman, 1993; Lobe et al., 2001; Saggar et al., 2001), the types of crops planted, and the cropping methods used (Reeves, 1997; Unger, 1997). Assessment of cropland degradation as part of the formulation of an appropriate management plan should therefore be based on an understanding of the local land-use system.

Although numerous studies have used soil properties as useful indicators for assessing cropland degradation, interrelated crop growth and weed communities are also practical indicators. Desbiez et al. (2004) stated that although researchers generally take a reductionist approach to assessing soil fertility, often accounting only for the soil's nutrient status or physical characteristics, farmers assess soil fertility on the basis of holistic perceptions, using a range of indicators that they can see or feel. For example, earlier studies reported that farmers use crop growth and the composition of weed communities as indicators of soil fertility (Corbeels et al., 2000; Desbiez et al., 2004; Mango, 1999; Murage et al., 2000). Changes in crop growth and weed communities in individual fields, however, are often regulated more strongly by local land-use systems (Buhler, 1992; de la Fuente et al., 1999) than by soil conditions (Corbeels et al., 2000). Clarifying not only soil properties but also crop growth, weed communities, and their relationships within the context of local land-use systems will therefore provide scientific evidence on which to base local management practices or recommendations for change.

The Horqin Sandy Land, located in a semi-arid region of northeastern China, has become one of the most severely desertified regions in China (Zuo et al., 2008). A combination of increasing population and demand for food has led to the encroachment of cultivation into natural sandy grasslands (Zhao et al., 2007b). Previous studies of cropland degradation have included the effects of wind erosion and/or sand accumulation on cropland soil properties (Li et al., 2004; Zhao et al., 2006a) and crop growth (Zhao et al., 2006b, 2007b), changes in soil properties (especially particle-size distribution) along a degradation gradient in

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croplands (Su et al., 2004b), and differences in soil properties between croplands and lands used for other purposes (Su and Zhao, 2002; Su et al., 2004a). Most of these studies, however, focused only on soil conditions of a limited number of cropland types, which were often artificially chosen or set by researchers in accordance with their specific objectives. In addition, earlier studies rarely examined cropland degradation over time. Thus far, changes in soil, crop, and weed conditions over time in croplands under the land-use systems of this region have not been documented.

The objective of this study was to elucidate the characteristics of cropland degradation under the local land-use systems in the Horqin Sandy Land with reference to the different histories of soil, crop, and weed conditions since the land was placed under cultivation. We hypothesized that the trends of changes in soil, crop, and weed conditions over time differ among the croplands in this area because of differences in local land-use systems. To test the hypothesis, we identified typical cropland types in the area on the basis of the local land-use system and examined soil properties, crop growth, and weed communities of croplands having different cultivation histories in each type.

2. Material and methods

2.1. Study area

The study area was located in the central part of Naiman County, Inner Mongolia Autonomous Region of China (42°55′N, 120°42′E; elevation approximately 360 m above sea level; Fig. 1). Naiman County is situated in the southern part of the Horqin Sandy Land and has experienced some of the worst land degradation in northern China (Andrén et al., 1994). This region is a temperate zone with a continental semi-arid monsoon climate; spring is dry and windy, and more rainfall is received in the summer months than during other times of the year. According to the statistics of the Naiman Weather Station (1961–2000), the mean annual precipitation is about 366 mm, and much of the precipitation falls between June and August. The mean annual temperature is about 6.8 °C, and the coldest and warmest monthly mean air temperatures are −13.1 °C in January and 23.7 °C in July, respectively. The Aeolian sand on which soils have formed is thought to have originated from alluvial and lacustrine deposits formed in the Late Pleistocene period, and fixed sand dunes formed in association with soil development during the Holocene Optimum (Yang and Scuderi, 2010; Yang et al., 2004, 2008). The threshold wind velocity for sand movement (about 4 m s^{-1} at 2 m height; Hu, 1991) is exceeded on more than 200 days each year (Li et al., 2002). Wind erosion is a very serious problem during the period from the thawing of the frozen surface soil in mid-March to the sowing of crops at the end of April (Li et al., 2004).

2.2. Site selection

To identify the typical cropland types in the area and replicate sites of each type, we interviewed 77 farmers in August 2006 and July and August 2007. The survey questions were designed with reference to the land-use description in the framework of land evaluation proposed by the Food and Agriculture Organization (Smith and McDonald, 1998; Smyth and Dumanski, 1993). This land-use description can be categorized into "What," "Where," "When," and "How" components, with the following respective items determined: planted crop species; landform type; cultivation history; and irrigation (frequency and timing), fertilizer (kind, amount, frequency, and timing), and weeding (method, frequency, and timing).

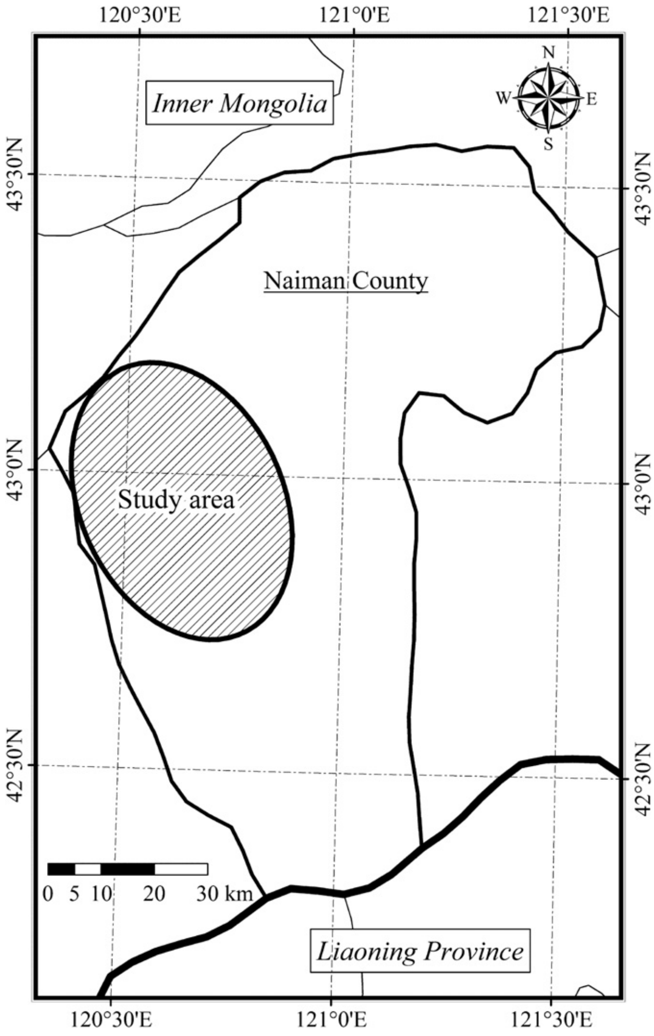

Fig. 1. Location of study area in the Horqin Sandy Land, northeastern China.

The interview surveys revealed that the land-use system in this area is closely related to landform, which is classified into three types by Okuro (1997): lowland, flat sandy land, and sand dunes (sloping sandy land). In this land-use system maize (*Zea mays*) is the preferred crop because of its high and stable productivity. Maize plantations need large fertilizer inputs and are basically restricted to flatland (i.e., lowland and flat sandy land) where irrigation is possible. On the lowland, however, maize is grown with little or no irrigation because of favorable soil moisture conditions; on the sand dunes, bean-centered rotational cropping is practiced with a small amount of fertilizer application supported by the ability of legumes to fix nitrogen. On the basis of the above-mentioned information, we identified three typical cropland types (Fig. 2 and Table 1): maize cropland on lowland (nonirrigated lowland; mainly maize planted on lowland with little or no irrigation and with large amounts of nitrogen and phosphorous fertilizer); maize cropland on flat sandy land (irrigated flatland; mainly maize planted on flat sandy land with irrigation and large amounts of fertilizer [nitrogen and phosphorous]); and bean-centered cropland on sand dunes (nonirrigated dunes; several kinds of beans, including mung bean [*Vigna radiata*] and cowpea [*Vigna unguiculata*], as well as some other crops, including broomcorn millet [*Panicum miliaceum*] and sorghum [*Sorghum bicolor*], were rotationally planted on sand dunes with no irrigation and little fertilizer [only phosphorous]). Although mainly maize is

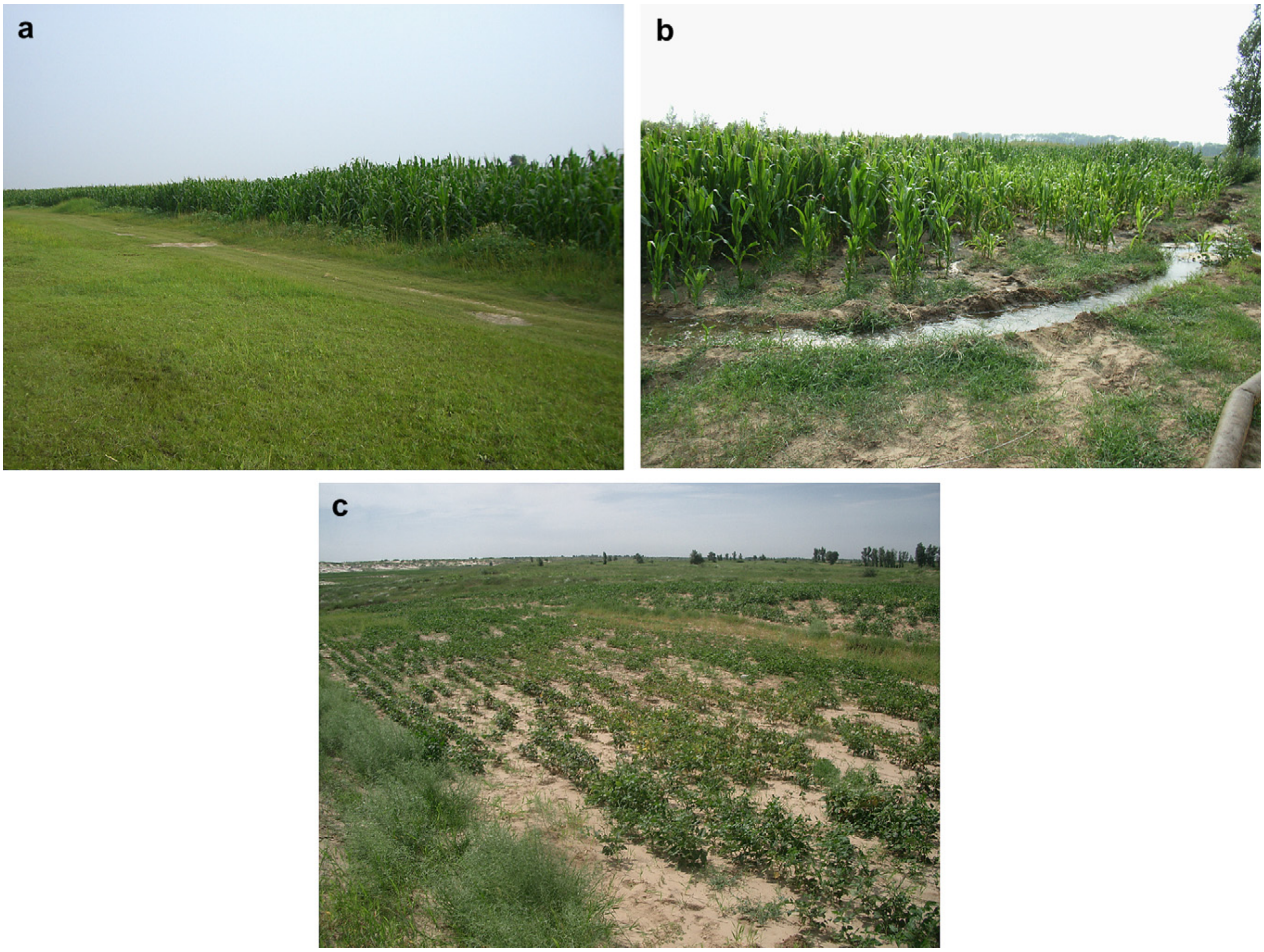

Fig. 2. Photographs of typical cropland types in the Horqin Sandy Land, northeastern China: (a) nonirrigated lowland, (b) irrigated flatland, and (c) nonirrigated dunes. Descriptions of each cropland type are given in Table 1.

planted on nonirrigated lowland and irrigated flatland, other crops are also occasionally planted on these croplands to avoid soil problems caused by continuous cropping (Ventura and Watanabe, 1978) of maize every year. To standardize our comparisons in nonirrigated dunes, we investigated only croplands where mung bean was currently planted.

We selected sampling sites that had had the same continuous land use since the sites were first cultivated. Periods of 1, 5, 10, and 20 years were considered as cultivation histories. We then chose 11 cropland sites of each typical cropland type (giving a total of 33 cropland sites), consisting of two 1-year-cultivated croplands and three 5-, three 10-, and three 20-year-cultivated croplands. We also selected nine grassland sites as 0-year-cultivated lands (i.e., the croplands in their original, uncultivated state). The nine grassland sites consisted of three replicates for each landform type: lowland (corresponding to nonirrigated lowland), flat sandy land (corresponding to irrigated flatland), and sand dunes (corresponding to nonirrigated dunes).

2.3. Data collection and laboratory analysis

We sampled soil and crop biomass and conducted a vegetation survey in mid-August 2007. Six quadrats (1 m^2), which were spaced at least 10 m apart, were established at each sampling site.

Soil samples were collected from 0 to 20 cm depth in three of six quadrats in each site. Each soil sample was obtained by mixing six subsamples collected from six locations in each of the three quadrats. The soil samples were placed in plastic bags and sealed. In the laboratory, each sample was sieved to 2 mm to remove roots and incorporated litter. Part of each sieved sample was air dried and used to determine particle-size distribution and chemical properties. Soil particle-size distribution was determined by the pipette method in a sedimentation cylinder with sodium hexametaphosphate as the dispersing agent (ISSCAS, 1978). Electrical conductivity (EC) was determined in 1:5 soil–water aqueous extract (Multiline F/SET-3, WTW, Weilheim, Germany). Soil organic carbon (SOC) was measured by the $K_2Cr_2O_7$–H_2SO_4 oxidation method of Walkley and Black (Nelson and Sommers, 1982), total nitrogen (TN) by the Kjeldahl procedure (UDK 140 Automatic Steam Distilling Unit, Automatic Titroline 96, Velp Scientifica, Milan, Italy) (ISSCAS, 1978), and total phosphorus (TP) by means of a UV-1601 spectrophotometer (Shimadzu, Kyoto, Japan) after H_2SO_4–$HClO_4$ digestion (ISSCAS, 1978).

We recorded the percentage cover of all plant species in all quadrats. Aboveground biomass of the crops was measured by the clipping method (Zhao et al., 2006b, 2007a, b) in each quadrat of the croplands. The biomass samples were separated based on leaf, stem, and seed and oven dried at 85 °C for 48 h before being weighed. Only the data for leaf and stem were used for analysis because the seed part of the crops had not completely matured. Based on our field observations and earlier studies (Zhao et al., 2006b, 2007a, b), we assumed that the vegetative parts of the

Table 1
Summary of typical cropland types in the Horqin Sandy Land, northeastern China.

Cropland type	Crop species	Cultivation method	Landform type	Irrigation		Fertilizer				Weeding		
				Frequency	Timing	Kind	Amount	Frequency	Timing	Method	Frequency	Timing
Nonirrigated lowland	Maize	Continuous	Lowland	Not practiced		N	About 600 kg ha^{-1}	Once a year	Late May–June	Hoe	Once or twice a year	May–June
						P	About 250 kg ha^{-1}	Once a year	April–early May			
Irrigated flatland	Maize	Continuous	Flat sandy land	About five times a year	Not fixed (arbitrarily practiced in the growing season)	N	About 600 kg ha^{-1}	Once a year	Late May–June	Hoe	Once or twice a year	May–June
						P	About 250 kg ha^{-1}	Once a year	April–early May			
Nonirrigated dunes	Beans and others (e.g., millet, sorghum)	Rotational	Sand dune	Not practiced		P	About 100 kg ha^{-1}	Once a year	Late May–early June	Hoe	Once or twice a year	July

N, nitrogen; P, phosphorus.

crops (leaf and stem) had matured at the time of the survey and that the proportion of the biomass of mature vegetative and seed parts would not differ between different cultivation histories or degradation stages in croplands. Therefore, examining the changes in the vegetative parts over time using data collected in mid-August is a feasible way to demonstrate when crop biomass decreases.

2.4. Statistical analysis

Vegetation data for each site (using pooled data from the six quadrats) were subjected to detrended correspondence analysis (DCA; Hill and Gauch, 1980) to examine the floristic composition. DCA provides the ordering of sampling sites along environmental gradients represented by the axes of variability in species composition. A site score on an axis is a weighted combination of the abundances of the species that occur in the site; thus the dissimilarity in site scores represents the dissimilarity in species composition. Plant cover data for each species that appeared in more than one quadrat was used in this analysis. Regression tree analysis (Breiman et al., 1984) was then performed using DCA scores representing the variations in floristic composition, soil data, and aboveground biomass of each crop as the response variables. The predictor variables were the cropland types and cultivation histories.

Regression tree analysis is a nonparametric multivariate technique that predicts or explains the variation in a continuous response variable from a set of predictor variables, which can be categorical and/or numeric, by repeatedly splitting the data into more homogeneous groups. Regression tree analysis is a relatively new statistical method and has some advantages over more conventional methods, such as easy graphical presentation of complex results involving multiple interactions (De'ath and Fabricius, 2000; Tittonell et al., 2008). Regression tree models are represented by the root node (the full and undivided dataset) at the top and subsequent binomial splits of the data into the most homogeneous possible groups (branches); splits are made at the one value from all possible values in any of the predictor variables that offers the greatest reduction in deviance (a statistical measure similar to variance) of the two branches. Each side of a split thus represents a subset of the data most closely associated with a certain condition in the predictor variable upon which the split was based; for example, above and below a particular value. This condition is shown at each split node, and the value of the response variable at the terminal node can then be represented as a series of if–then conditions. Model selection in regression tree analysis is performed by pruning branches that fail to provide any further useful information, and several methods exist by which to achieve this pruning (e.g., based on deviance reduction or by using cross-validation). Terminal nodes show the predicted value of the response variable and number of data values remaining in the branch. For smaller datasets such as ours, the best method of selecting the best model is to estimate errors in trees of different sizes by *v*-fold cross-validation (Breiman et al., 1984). We selected the best regression tree model through 10-fold cross-validation and the 1-SE rule (Breiman et al., 1984). All statistical analyses were performed with R software, version 2.8.1 (R Development Core Team, 2008).

3. Results

3.1. Soil properties

Valid regression tree models were constructed for SOC, TN, TP, C:N ratio, EC, and particle size (coarse sand, fine sand, and very fine sand), whereas the variations in silt and clay content were not explained by cropland type or cultivation history. Only cropland type contributed to the tree model of SOC, TN, TP, and particle-size distribution of coarse sand, fine sand, and very fine sand, that is, for SOC, TN, and TP, nonirrigated dunes < other types; for coarse sand content, nonirrigated lowland < other types; for fine sand content, nonirrigated dunes > other types; and for very fine sand content, nonirrigated lowland > other types (Table 2). The C:N ratio and EC were affected by both predictor variables (Fig. 3). The C:N ratio was divided into sites cultivated for 0 or 1 year and sites cultivated for longer periods (node values: 0- and 1-year sites > other sites). The node for 0- and 1-year sites was then subdivided into nonirrigated lowland and other cropland types (node values: nonirrigated lowland > others), and the node for sites cultivated for longer than 0 or 1 year was subdivided into nonirrigated dunes and other cropland types (node values: others > nonirrigated dunes). EC was divided into the site cultivated for 0 years and sites cultivated for longer periods (node values: 0-year sites > other sites), and both nodes were then subdivided into nonirrigated lowland and other cropland types (node values: nonirrigated lowland > others). In addition, a difference in the EC of nonirrigated lowland between sites cultivated for 1 year and those cultivated for longer periods was detected in the model (node values: 1-year sites > other sites).

3.2. Crop growth

Regression tree models explaining crop growth were constructed for two kinds of crop species: maize and mung beans (Fig. 4). The regression tree model for maize showed that the biomass of both nonirrigated lowland and irrigated flatland was

Table 2

Soil properties according to cultivation history on each typical cropland type in the Horqin Sandy Land, northeastern China.

Cropland type		Nonirrigated lowland						Irrigated flatland						Nonirrigated dunes					
Cultivation history (year)		0	1	5	10	20	Ave	0	1	5	10	20	Ave	0	1	5	10	20	Ave
SOC (g kg^{-1})		8.84	8.61	6.66	5.29	5.67	7.01	9.42	5.04	4.73	4.51	5.57	5.85	4.11	2.83	2.77	1.53	2.95	2.84
TN (g kg^{-1})		0.43	0.46	0.44	0.38	0.39	0.42	0.55	0.31	0.34	0.31	0.39	0.38	0.25	0.21	0.21	0.14	0.25	0.21
TP (g kg^{-1})		0.30	0.35	0.45	0.33	0.48	0.38	0.47	0.36	0.38	0.37	0.44	0.40	0.24	0.23	0.22	0.18	0.28	0.23
C:N ratio		21	19	15	14	15	16	17	16	14	15	14	15	17	14	13	11	11	13
EC (μS cm^{-1})		95.3	89.4	56.2	43.8	31.5	63.2	51.7	13.9	27.9	10.8	55.5	32.0	71.4	16.1	19.7	14.9	19.1	28.3
Particle-size distribution (%)	Coarse sand (>0.25 mm)	12.0	4.9	19.6	8.5	6.3	10.2	9.3	14.0	16.0	28.0	13.1	16.1	13.6	31.0	17.3	20.1	14.9	19.4
	Fine sand (0.25–0.1 mm)	39.0	47.7	43.9	35.6	36.7	40.6	41.2	50.5	49.5	36.9	45.2	44.7	58.1	44.1	54.1	56.4	47.0	51.9
	Very fine sand (0.1–0.05 mm)	32.3	32.2	25.2	42.0	41.7	34.7	26.2	19.5	18.7	22.7	21.4	21.7	15.3	15.0	17.7	16.2	25.0	17.8
	Silt (0.05–0.002 mm)	11.1	9.3	7.5	9.5	10.4	9.6	17.9	11.8	11.6	8.6	15.8	13.1	8.0	5.9	6.5	3.5	8.6	6.5
	Clay (<0.002 mm)	4.8	5.7	4.1	4.0	4.8	4.7	4.8	4.4	4.4	4.0	4.4	4.4	4.5	4.5	4.8	4.3	4.9	4.6

Descriptions of cropland types are given in Table 1. SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; EC, electrical conductivity.

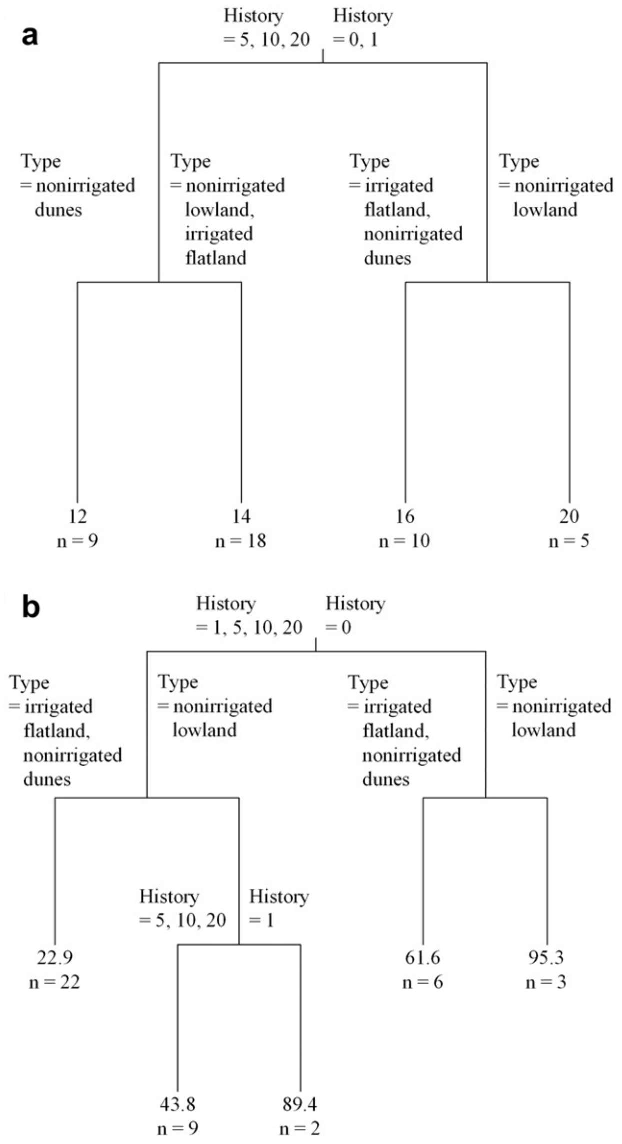

Fig. 3. Regression tree models for (a) C:N ratio and (b) electrical conductivity (EC). Types represent typical cropland types, which are described in Table 1. Histories represent periods of cultivation (year). Numbers at terminal nodes are average values of the response variable in each terminal node, and *n* is the number of sites contributing to the value for each node. The unit of EC is μS cm^{-1}.

lower with cultivation for 10 or 20 years than with cultivation for 1 or 5 years, and the biomass of nonirrigated lowland was lower than that of irrigated flatland at 10 or 20 years after cultivation began. The observed biomass of mung beans showed the following order: 1-year site > 5-year site > 10- or 20-year sites.

3.3. Weed community

We created an ordination plot of the DCA for floristic composition (Fig. 5). The first axis expressed mainly the variations in floristic composition among grasslands (i.e., sites cultivated for 0 years). The second axis showed the variations in floristic composition among croplands, whereas grassland sites on sand dunes (i.e., nonirrigated dune sites cultivated for 0 years) were plotted as contributing to both axes. This result indicated that species composition differed widely between grasslands and croplands, even in the same landform type. A regression tree model using the score of the first axis as

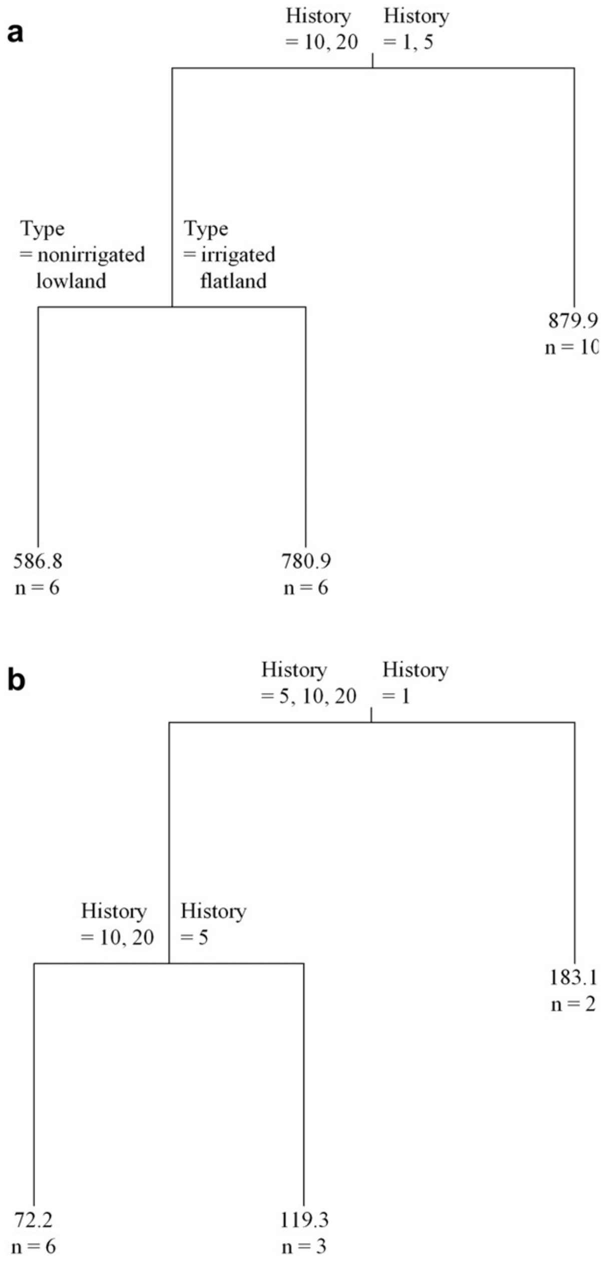

Fig. 4. Regression tree models for (a) maize biomass and (b) mung bean biomass. In the model for maize biomass, types represent typical cropland types, which are described in Table 1. Histories represent periods of cultivation (year). Numbers at terminal nodes are average values of the response variable in each terminal node, and *n* is the number of sites contributing to the value for each node. The unit of biomass is g m^{-2}.

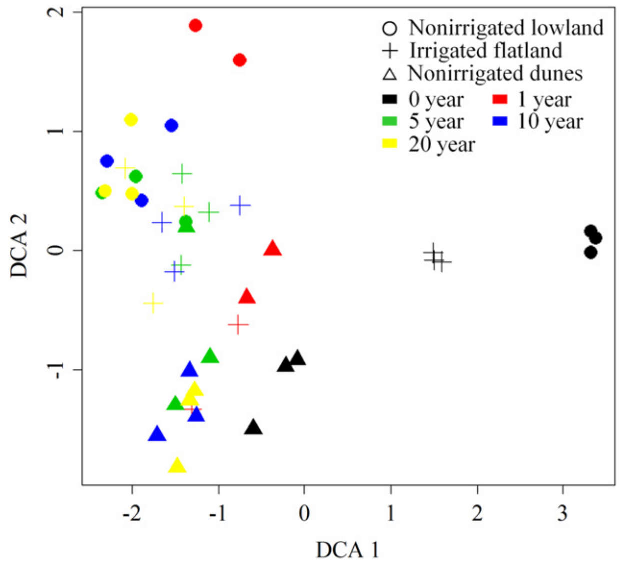

Fig. 5. Ordination plot of detrended correspondence analysis (DCA) showing the distribution of 42 sampling sites. Symbols indicate typical cropland types, which are described in Table 1, and periods of cultivation are indicated by different colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the response variable (Fig. 6a) showed clear differences in species composition between the three types of grassland. Perennial species growing on wet ground (e.g., *Halerpestes ruthenica* and *Glaux maritima*) were characteristically observed on lowland; steppe species, such as *Chloris virgata* and *Artemisia sieversiana*, were relatively common on flat sandy land; and shrub species, such as *Artemisia halodendron* and *Caragana microphylla*, which grow in sandy or degraded land, were particularly observed in sand dunes. The regression tree model also showed that the similarity in species composition between the grasslands and croplands was less at 5 years after the start of cultivation; the degree of dissimilarity (i.e., floristic change) was in the order of nonirrigated lowland > irrigated flatland > nonirrigated dunes. The regression tree model using the score of the second axis revealed that different weed communities were established in each cropland type and that their species composition changed with the cultivation history (Fig. 6b). In nonirrigated lowland, although species indicative of wet conditions (e.g., *Amaranthus retroflexus* and *Equisetum ramosissimum*) were observed at all periods, steppe species, such as *Digitaria ciliaris* and *Setaria viridis*, became increasingly abundant with longer cultivation history. In nonirrigated dunes, plants growing in drier conditions, such as *Tribulus terrestris*, were observed; *Agriophyllum squarrosum*, which is an indicator species of shifting sand dunes, was present 10 and 20 years after cultivation began. Although the weed community in irrigated flatland contained some of the species observed in nonirrigated lowland and nonirrigated dunes, species characteristically found in nonirrigated lowland, such as *A. retroflexus* and *E. ramosissimum*, appeared with increasing frequency in irrigated flatland with increasing cultivation history.

4. Discussion

4.1. Soil properties

There were valid differences in soil condition between the typical cropland types. Although the dominant soil types for all sites were very fine sand and fine sand (Table 2), which is in agreement with the results of Su et al. (2004b), the regression tree model clearly showed that the very fine sand content was highest in nonirrigated lowland while the fine sand content was highest in nonirrigated dunes. Given the differences in SOC, TN, TP, and EC among the cropland types (see the description in Section 3.1 and Fig. 3), the overall soil condition was in the order nonirrigated lowland > irrigated flatland > nonirrigated dunes. Zhao et al. (2007a) reported that croplands derived from lowland contain more soil nutrients and have higher soil moisture levels and resistance to wind erosion than those from sandy grasslands.

For maize, although the C:N ratio of nonirrigated lowland was higher than that of irrigated flatland for up to 1 year after the start

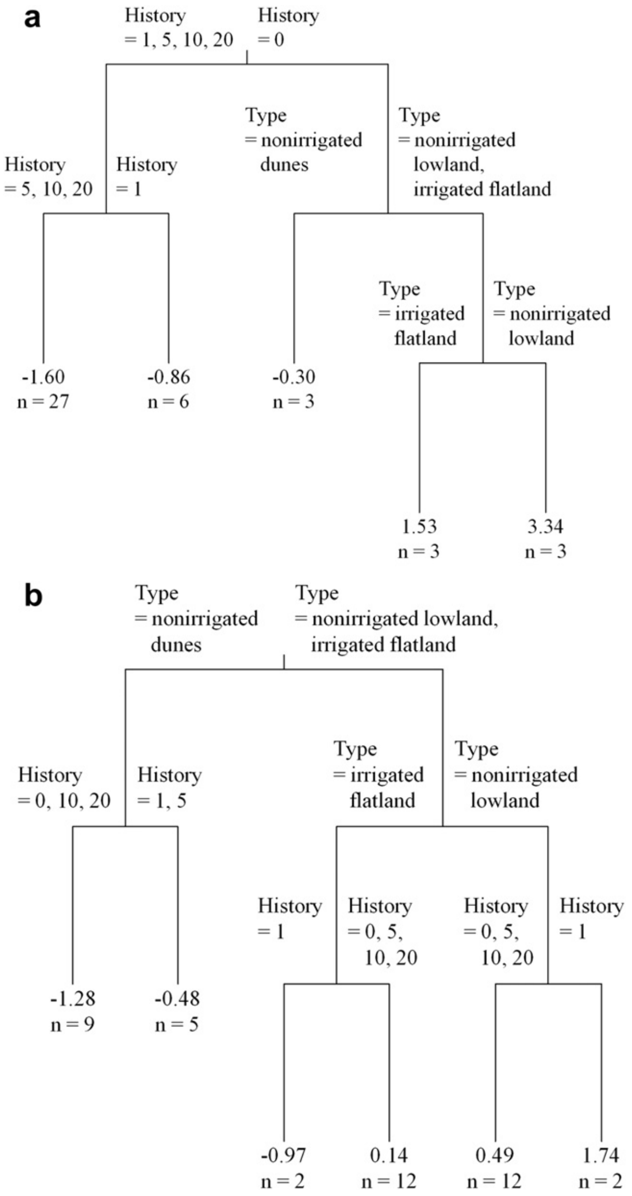

Fig. 6. Regression tree models for (a) the score of DCA axis 1 and (b) the score of DCA axis 2. Types represent typical cropland types, which are described in Table 1. Histories represent periods of cultivation (year). Numbers at terminal nodes are average values of the response variable in each terminal node, and *n* is the number of sites contributing to the value for each node.

of cultivation, the two types of cropland had reached the same level by 5 years after cultivation began (Fig. 3a). The decrease in the C:N ratio of the nonirrigated lowland was, therefore, higher than that of the irrigated flatland. In addition, the EC of the nonirrigated lowland decreased continuously after cultivation started, whereas the EC of the irrigated flatland did not show an obvious change (Fig. 3b). These differences are likely a result of the effect of the irrigation used in irrigated flatland. Irrigation significantly improves soil moisture (Zhao et al., 2007a), and increasing soil moisture leads to an increasing threshold of friction velocity and resistance to wind erosion (Marticorena et al., 1997). Our results thus indicate that the effects of irrigation against wind erosion prevail over the initial natural state of the area.

Meanwhile, the temporal decrease in the C:N ratio observed in all cropland types indicated that SOC decreased compared with the level of nitrogen, which was added as a fertilizer or by legumes. This is in agreement with the points made by Su and Zhao (2002) and Su et al. (2004a). In addition, the decrease in the C:N ratio started between 1 and 5 years after cultivation began. According to Davidson and Ackerman (1993), who reviewed numerous studies of SOC losses associated with cultivation, a majority of the losses occurred within 5 years of the start of cultivation. Our result is thus in agreement with their findings.

4.2. Crop growth

Our results showed that the biomass of both maize and mung beans notably decreased with increasing cultivation history (Fig. 4). Although the biomass of maize in the nonirrigated lowland and irrigated flatland remained at similar levels until 5 years after the start of cultivation, by 10 years after the start of cultivation, maize biomass in the nonirrigated lowland was lower than that in the irrigated flatland. The rate of biomass decrease, therefore, in the nonirrigated lowland was higher than that in the irrigated flatland, probably because of the effect of irrigation, as noted above. Because the lowland originally had higher productivity than the flat sandy land (Okuro, 1997), our results demonstrate that irrigation has a stronger influence on crop productivity (as well as on soil condition) than initial natural state. For mung beans, the regression tree model showed that biomass decreased earlier and more continuously (between 1- and 5-year-cultivated lands and between 5- and 10-year-cultivated lands) than with maize and the rate of decrease was greater than with maize. This notable reduction was likely due to the topographic traits of the sand dunes. Sand dunes are characterized by shifting sands, high temperatures, and low availability of water and nutrients (Ranwell, 1972) and hence are susceptible to wind erosion. Although changes in crop growth occur in soils with properties altered by wind erosion, crops are also influenced directly by harsh winds; seedlings suffer from abrasion and burial during storms and then often die because of reduced photosynthesis, the weight of the sand deposits, and high daytime soil temperatures (Sterk and Haigis, 1998). The crop biomass in nonirrigated dunes thus markedly decreased with increasing cultivation history (Fig. 4b). In short, changes in crop growth are strongly affected by both irrigation practice and erodibility of landform type; as a result, the rate of decrease in crop productivity was in the following order: nonirrigated dunes > nonirrigated lowland > irrigated flatland.

4.3. Weed community

We detected a marked change in species composition in response to cultivation, especially on the lowland (Figs. 5 and 6a). Our results suggest that plant species growing naturally on the lowland are the most intolerant of cultivation among the three landform types and are, to a great extent, replaced by cropland weed species. Our findings may have been influenced by the change in the soil water regime after the start of cultivation as this change was greatest in the nonirrigated lowland; that is, the lowland originally had more soil nutrients and higher water availability but was cultivated without irrigation.

Changes in weed communities with increasing cultivation history were detected in all cropland types (Figs. 5 and 6b). The vegetation patterns corresponded to the soil water content in semi-arid regions (Castelli et al., 2000; Lammerts et al., 2001; Stromberg et al., 1996). Liu et al. (2007) observed psammophytes, such as *A. squarrosum* and *A. halodendron,* on erosion-prone sand dunes of our study region; they also observed limnocryptophyte-meadow species, such as *E. ramosissimum*, and steppe species, such as *C. virgata*, on the more nutrient- and water-rich grasslands. In agreement with the deterioration in soil and crop conditions, the weed communities in nonirrigated lowland and nonirrigated dunes evolved into the types of communities that are established in drier or more degraded conditions. Water is a main limiting factor for people's livelihood in desertified regions (Qi and Luo, 2006); thus plant species associated with a higher soil moisture regime are generally considered to be indicators of better land condition. However, the direction of floristic change in the irrigated flatland was opposite to the direction in nonirrigated lowland and nonirrigated dunes; in the former the abundance of species preferring wetter conditions increased. This result was probably due to the effect of irrigation. Yearly irrigation would provide enough water for weed communities that grow under wet conditions to become established. The observed floristic change appeared to be favorable, but soil and crop conditions in the irrigated flatland actually deteriorated. Our results indicate that the weed community in irrigated flatland cannot be used as an indicator in land evaluations.

4.4. Future cropland management

Our study demonstrates the effectiveness of irrigation for moderating the degradation of soil and crop properties in croplands. The use of irrigation in nonirrigated croplands would be a practical countermeasure to cropland degradation; farmers can level moderately undulating land with a tractor, thereby increasing land area where irrigation is possible. Leveling undulating land would also decrease the erodibility of sand dunes. However, one adverse effect of irrigation is regional groundwater loss. Little consideration has been given to water resources in the current desertification assessment in this region (Zhao et al., 2010), but exhaustive water use over a large area may lead to a serious problem in the future. Further studies on regional water balance are needed.

Although irrigated croplands were less degraded than nonirrigated croplands, the result that degradation trends in crop and soil properties were found in all types of cropland indicates that continuous cropping will not be a sustainable way to use the land in this area. Because continuous cropping is related to economic conditions, it is a technique that cannot be easily changed. Adopting rotation between croplands and grasslands (i.e., periodic fallowing) could, however, contribute to arresting the degradation trends. In addition, a regular input of manure could be effective for improving soil conditions, considering the decrease of SOC relative to TN and TP that are added to croplands under the current land-use system.

The floristic change in the irrigated flatland was seemingly counter to the general trend toward degradation. This suggests that evaluating land condition using plant species can be effective with nonirrigated lowland and nonirrigated dunes but is not suitable with irrigated flatland. Moreover, this adverse change may occur in croplands on other landform types when land is leveled and then irrigated.

5. Conclusion

The present study examined and elucidated the characteristics of cropland degradation under the local land-use system in the Horqin Sandy Land with reference to soil properties, crop growth, and weed communities. We hypothesized that the trends of changes in the three conditions with time differed among the croplands in this area and were affected by the local land-use system. Our hypothesis was supported by our results: The trends of change in each condition did not necessarily occur in parallel and differed statistically among the typical cropland types, especially influenced by irrigation practice and landform type. This study indicates that studying the three indicators (soil properties, crop growth, and weed communities) and their relationship under local land-use systems can provide scientific evidence on which to base local management practices or recommendations for change.

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References

Andrén, O., Zhao, X.Y., Liu, X.M., 1994. Climate and litter decomposition in Naiman, inner-Mongolia, China. Ambio 23, 222–224.

Bowman, R.A., Reeder, J.D., Lober, R.W., 1990. Changes in soil properties in a central plains rangeland soil after 3, 20, and 60 years of cultivation. Soil Sci. 150, 851–857.

Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.J., 1984. Classification and Regression Trees. Wadsworth International Group, Belmont, CA.

Buhler, D.D., 1992. Population-dynamics and control of annual weeds in corn (*Zea mays*) as influenced by tillage systems. Weed Sci. 40, 241–248.

Castelli, R.M., Chambers, J.C., Tausch, R.J., 2000. Soil-plant relations along a soil-water gradient in great basin riparian meadows. Wetlands 20, 251–266.

Celik, I., 2005. Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. Soil Till. Res. 83, 270–277.

Corbeels, M., Shiferaw, A., Haile, M., 2000. Farmers' knowledge of soil fertility and local management strategies in Tigray, Ethiopia. Managing Africa's Soils 10 ii + 23.

Davidson, E.A., Ackerman, I.L., 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20, 161–193.

De'ath, G., Fabricius, K.E., 2000. Classification and regression trees: a powerful yet simple technique for ecological data analysis. Ecology 81, 3178–3192.

de la Fuente, E.B., Suárez, S.A., Ghersa, C.M., León, R.J., 1999. Soybean weed communities: relationships with cultural history and crop yield. Agron. J. 91, 234–241.

Desbiez, A., Matthews, R., Tripathi, B., Ellis-Jones, J., 2004. Perceptions and assessment of soil fertility by farmers in the mid-hills of Nepal. Agric. Ecosyst. Environ. 103, 191–206.

Du Preez, C.C., Du Toit, M.E., 1995. Effect of cultivation on the nitrogen fertility of selected agro-ecosystems in South Africa. Fertil. Res. 42, 27–32.

Hajabbasi, M.A., Jalalian, A., Karimzadeh, H.R., 1997. Deforestation effects on soil physical and chemical properties, Lordegan, Iran. Plant Soil 190, 301–308.

Hill, M.O., Gauch, H.G., 1980. Detrended correspondence analysis: an improved ordination technique. Vegetation 42, 47–58.

Hu, M.C., 1991. A primary research about the quantitative classification indexes of desertification-prone land in the Horqin sandy land. J. Desert Res. 11, 22–29 (in Chinese with English abstract).

ISSCAS, 1978. Physical and Chemical Analysis Methods of Soils. Institute of Soil Sciences, Chinese Academy of Sciences, Shanghai Science Technology Press, Shanghai, pp. 7–59 (in Chinese).

Lammerts, E.J., Maas, C., Grootjans, A.P., 2001. Groundwater variables and vegetation in dune slacks. Ecol. Eng. 17, 33–47.

Li, F.R., Zhao, L.Y., Zhang, H., Zhang, T.H., Shirato, Y., 2004. Wind erosion and airborne dust deposition in farmland during spring in the Horqin sandy land of eastern inner Mongolia, China. Soil Till. Res. 75, 121–130.

Li, S.G., Harazono, Y., Zhao, H.L., He, Z.Y., Chang, X.L., Zhao, X.Y., Zhang, T.H., Oikawa, T., 2002. Micrometeorological changes following establishment of artificially established artemisia vegetation on desertified sandy land in the Horqin sandy land, China and their implication on regional environmental change. J. Arid. Environ. 52, 101–119.

Liu, Z.M., Li, X.L., Yan, Q.L., Wu, J.G., 2007. Species richness and vegetation pattern in interdune lowlands of an active dune field in inner Mongolia, China. Biol. Conserv. 140, 29–39.

Lobe, I., Amelung, W., Du Preez, C.C., 2001. Losses of carbon and nitrogen with prolonged arable cropping from sandy soils of the South African Highveld. Eur. J. Soil Sci. 52, 93–101.

Mango, N.A.R., 1999. Integrated soil fertility management in Siaya District, Kenya. Managing Africa's Soils 7 ii + 28.

Marticorena, B., Bergametti, G., Gillette, D., Belnap, J., 1997. Factors controlling threshold friction velocity in semiarid and arid areas of the United States. J. Geophys. Res.-Atmos. 102, 23277–23287.

Murage, E.W., Karanja, N.K., Smithson, P.C., Woomer, P.L., 2000. Diagnostic indicators of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands. Agric. Ecosyst. Environ. 79, 1–8.

Nelson, D., Sommers, L., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., et al. (Eds.), Methods of Soil Analysis. Part 2, second ed. Agronomy, Madison, WI, pp. 539–577.

Okuro, T., 1997. Studies on the Influence of Grazing on the Land and Vegetation Degradation and Restoration Process in Grassland Regions in Northeast China, Ph.D. dissertation. The University of Tokyo, Tokyo (in Japanese with English summary).

Qi, S.Z., Luo, F., 2006. Hydrological indicators of desertification in the Heihe River Basin of arid northwest China. Ambio 35, 319–321.

R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Ranwell, D.S., 1972. Ecology of Salt Marshes and Sand Dunes. Chapman and Hall, London.

Reeves, D.W., 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Till. Res. 43, 131–167.

Saggar, S., Yeates, G.W., Shepherd, T.G., 2001. Cultivation effects on soil biological properties, microfauna and organic matter dynamics in Eutric Gleysol and Gleyic Luvisol soils in New Zealand. Soil Till. Res. 58, 55–68.

Smith, C.S., McDonald, G.T., 1998. Assessing the sustainability of agriculture at the planning stage. J. Environ. Manage. 52, 15–37.

Smyth, A., Dumanski, J., 1993. FESLM: An International Framework for Evaluating Sustainable Land Management. In: World Soil Resources Report, vol. 73. Food and Agriculture Organization, Rome.

Sterk, G., Haigis, J., 1998. Farmers' knowledge of wind erosion processes and control methods in Niger. Land Degrad. Dev. 9, 107–114.

Stromberg, J.C., Tiller, R., Richter, B., 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecol. Appl. 6, 113–131.

Su, Y.Z., Zhao, H.L., 2002. Characteristics of soil degradation as affected by long-term land use and management systems in a semi-arid sandy soil in north China. Ann. Arid Zone 41, 109–118.

Su, Y.Z., Zhao, H.L., Zhang, T.H., Zhao, X.Y., 2004a. Soil properties following cultivation and non-grazing of a semi-arid sandy grassland in northern China. Soil Till. Res. 75, 27–36.

Su, Y.Z., Zhao, H.L., Zhao, W.Z., Zhang, T.H., 2004b. Fractal features of soil particle size distribution and the implication for indicating desertification. Geoderma 122, 43–49.

Tittonell, P., Shepherd, K.D., Vanlauwe, B., Giller, K.E., 2008. Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya – an application of classification and regression tree analysis. Agric. Ecosyst. Environ. 123, 137–150.

Unger, P.W., 1997. Management-induced aggregation and organic carbon concentrations in the surface layer of a Torrertic Paleustoll. Soil Till. Res. 42, 185–208.

Ventura, W., Watanabe, I., 1978. Growth inhibition due to continuous cropping of dryland rice and other crops. Soil Sci. Plant Nutr. 24, 375–389.

Wu, R.G., Tiessen, H., 2002. Effect of land use on soil degradation in alpine grassland soil, China. Soil Sci. Soc. Am. J. 66, 1648–1655.

Yang, X., Rost, K.T., Lehmkuhl, F., Zhenda, Z., Dodson, J., 2004. The evolution of dry lands in northern China and in the Republic of Mongolia since the Last Glacial Maximum. Quat. Int. 118/119, 69–85.

Yang, X., Scuderi, L.A., 2010. Hydrological and climatic changes in deserts of China since the late Pleistocene. Quat. Res. 73, 1–9.

Yang, X., Zhu, B., Wang, X., Li, C., Zhou, Z., Chen, J., Wang, X., Yin, J., Lu, Y., 2008. Late Quaternary environmental changes and organic carbon density in the Hunshandake sandy land, eastern inner Mongolia, China. Glob. Planet. Change 61, 70–78.

Zhao, H.L., Yi, X.Y., Zhou, R.L., Zhao, X.Y., Zhang, T.H., Drake, S., 2006a. Wind erosion and sand accumulation effects on soil properties in Horqin Sandy Farmland, inner Mongolia. Catena 65, 71–79.

Zhao, H.L., Zhou, R.L., Zhang, T.H., Zhao, X.Y., 2006b. Effects of desertification on soil and crop growth properties in Horqin sandy cropland of inner Mongolia, north China. Soil Till. Res. 87, 175–185.

Zhao, H.L., Cui, J.Y., Zhou, R.L., Zhang, T.H., Zhao, X.Y., Drake, S., 2007a. Soil properties, crop productivity and irrigation effects on five croplands of inner Mongolia. Soil Till. Res. 93, 346–355.

Zhao, H.L., Zhou, R.L., Drake, S., 2007b. Effects of aeolian deposition on soil properties and crop growth in sandy soils of northern China. Geoderma 142, 342–348.

Zhao, W.Z., Xiao, H.L., Liu, Z.M., Li, J., 2005. Soil degradation and restoration as affected by land use change in the semiarid Bashang area, northern China. Catena 59, 173–186.

Zhao, X.Y., Luo, Y.Y., Wang, S.K., Huang, W.D., Lian, J., 2010. Is desertification reversion sustainable in Northern China? – a case study in Naiman County, part of a typical agro-pastoral transitional zone in inner-Mongolia, China. Glob. Environ. Res. 14, 63–70.

Zuo, X.A., Zhao, H.L., Zhao, X.Y., Zhang, T.H., Guo, Y.R., Wang, S.K., Drake, S., 2008. Spatial pattern and heterogeneity of soil properties in sand dunes under grazing and restoration in Horqin sandy land, northern China. Soil Till. Res. 99, 202–212.