Catena 87 (2011) 268–275

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Effects of soil erosion on long-term soil productivity in the black soil region of northeastern China

Xingwu Duan [a], Yun Xie [b,*], Tinghai Ou [b,c], Hongmei Lu [b]

[a] Asian International Rivers Center, Yunnan University, Kunming 650223, PR China
[b] State Key Laboratory of Earth Surface Processes and Resource Ecology, School of Geography, Beijing Normal University, Beijing 10087, PR China
[c] Regional Climate group, Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden

ARTICLE INFO

Article history:
Received 9 December 2009
Received in revised form 17 June 2011
Accepted 20 June 2011

Keywords:
Soil erosion
Soil productivity
Productivity index
Black soil

ABSTRACT

China's northeastern Black Soil Region, one of the country's most important crop production areas, has been seriously affected by soil erosion. This study evaluated the effects of soil erosion on the long-term productivity of this region. We used a modified productivity index (MPI) model (MPI is a number between 0 and 1, with 1 indicating highest productivity) to assess the current effects of soil erosion on soil productivity, as well as to predict long-term change in productivity. Samples from 21 black soil profiles yielded varying MPI values, although most MPI values were indicative of moderate productivity. Organic matter content and available water capacity impact MPI values in the region, whereas soil clay content and pH were less important. Overall, organic matter content and available water capacity of soil profiles decreased consistently as depth of erosion increased. Modeling indicated that MPI in the region will decrease by 0.0052 for each centimeter of topsoil eroded; this rate represents 1% of the current average MPI for the study area. The model predicts a 9.6% productivity reduction over 100 years and a 48.3% reduction over 500 years.

1. Introduction

Soil productivity is the capacity of soil to produce a particular plant or sequence of plants under a specified management system; sustainable soil productivity is the basis for food security. Erosion reduces soil productivity through soil loss and altered physical, chemical, and biological properties (Lal, 2001; Lobo et al., 2005). Large-scale reduction in soil productivity can pose a direct threat to food security (Lal, 2001; Stocking, 2003).

The northeast (NE) black soil region of China is an important grain production area. In 2004, the region produced 82.12 million tons of grain, constituted 17.5% of China's total yield. Regional corn and soybean yields were 44.87 million tons (34% of China's total corn yield) and 10.4 million tons (47% of China's total soybean yield), respectively. However, this region has suffered from serious soil erosion over the last 100 years (Liu, 2003; Yan and Tang, 2005; Yu et al., 1992). Yu et al. (1992) note that approximately 38% of cultivated land in the NE black soil region has been affected by erosion. More specifically, more than 39,000 ha of farmland have been destroyed by the approximately 25,000 large gullies in the region (Li et al., 2006). The thickness of the black soil (humus horizon) layer in the region has decreased significantly, from 60–70 cm to 20–30 cm (Liu, 2003; Yan and Tang, 2005). Accordingly, an assessment of the long-term changes in soil productivity due to erosion is critical to effective policy-making and sustainable agricultural production in this region.

Many methods have been developed to quantify the relationship between the soil properties affected by soil erosion and plant growth (Olson et al., 1994). Simulation modeling is particularly useful for determining long-term effects and also offers unlimited management strategies (NSE, 1981). The productivity index (PI) model (Neill, 1979; Pierce et al., 1983) is relatively simple and requires only a limited number of variables, which makes it particularly useful for places such as China, where data can be limited. PI assumes that the properties of soil layers within the rooting zone are major factors for crop growth and yields and is used to assess the intrinsic or irreplaceable aspects of soil productivity (Larson et al., 1983; Pierce et al., 1983; Runge et al., 1986). Other factors, such as climate, management, and genetic plant potential are assumed to be constant and are not currently included in the model (Gantzer and McCarty, 1987; Pierce et al., 1983). Sufficiency values, ranging from 0 to 1, are defined to quantify the effects of soil properties on soil productivity and the PI value is calculated by summing the product of the sufficiency values for each soil layer to a depth of 100 cm (Larson et al., 1983; Pierce et al., 1983). The PI value represents the relative soil productivity determined by the soil properties by depth; a higher PI value (closer to 1) indicates higher soil productivity. Long-term soil erosion affects both the individual soil factors and the depth, and thus the final PI value.

The original PI model, developed in the corn belt region of the USA, has been widely used to assess soil productivity (Gale et al., 1991; Gantzer and McCarty, 1987; Kiniry et al., 1983; Thompson et al., 1992; Udawatta and Henderson, 2003; Yang et al., 2003) and the long-term

* Corresponding author. Tel.: +86 10 58807391.
E-mail address: xieyun@bnu.edu.cn (Y. Xie).

0341-8162/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2011.06.012

effects of soil erosion on soil productivity (Larson et al., 1983; Lobo et al., 2005; Pierce et al., 1983, 1984; Rijsberman and Wolman, 1985; Schumacher et al., 1994). Data from field surveys, experimental plots, and testing in China's NE black soil region has been used to modify the PI model (Duan et al., 2009) for use in this area. The modified PI (MPI) results correlate more closely to actual corn yields in this region ($R^2=0.76$) than do the PI model results ($R^2=0.54$) (Duan et al., 2009).

In this study, after further validation of the MPI model, we use MPI to assess soil productivity in China's NE black soil region. We also use the MPI model to predict the effects of soil erosion on long-term soil productivity under current climate conditions, agriculture management systems, and soil loss rates.

2. Materials and methods

2.1. Study area

NE China (total area 124 million ha) includes Heilongjiang, Jilin, and Liaoning provinces, as well as part of the Inner-Mongolia autonomous region. Three major north–south mountain ranges—the ChangBai, Xiaoxing'anling, and Daxing'anling mountains—divide the region into three areas, the SanJiang plain, the SunNen plain, and the HouLunBeiEr plateau. The NE region's climate varies from temperate humid in the east to semi-humid monsoon in the west while the average annual precipitation ranges from 400 mm in the northwest to 800 mm in the southeast. The annual mean temperature ranges from −7 to +11 °C, with January average temperatures dropping below −20 °C and July temperatures exceeding 18 °C. In accordance with the Genetic Soil Classification of China (GSCC) (NSSO, 1998; Shi et al., 2006), primary soil types include Dark brown earths, Bleached baijiang soils, Chernozem soils, Meadow soils, and Black soils (Fig. 1). Meadow soils are distributed primarily in the SanJiang and SunNen plains and Chernozem soils occur primarily on the HouLunBeiEr plateau.

Black soils, which are also known as Isohumisols in Chinese Soil Taxonomy (CST) or Mollisols in US Soil Taxonomy (ST) (Gong et al., 1999; Shi et al., 2006), occur mainly in the transition zones between the Xiaoxing'anling and Daxing'anling mountains and the SunNen plain—the NE black soil region (lat 43°N–50°N, long 126°E–128°E). The Chinese soil database (NSSO, 1995) lists 23 black soil series in this region, belonging to three subtypes: Black soils (Haploborolls in ST), Meadow black soils (Haploborolls in ST) and Albic black soils (Argiborolls in ST). The NE black soil region covers approximately 9.4 million ha, has an average altitude of less than 180 m above mean sea level, and is characterized by gentle grades (ranging from 0 to 5%) and long slopes (extend for lengths of 500–2000 m, the maximum lengths even up to 4000 m). The rolling topography has resulted in serious water erosion: 77.5% of the total cropland in this region currently suffers from soil loss (Liu et al., 2008). Primary crops are corn, soybeans, and wheat and most of the cropland in this area was established for agriculture after 1900 (Zhang et al., 2006a).

2.2. MPI model

The original PI model estimates soil productivity by characterization of the soil rooting environment, and consideration of three soil properties, available water-holding capacity (AWC), bulk density

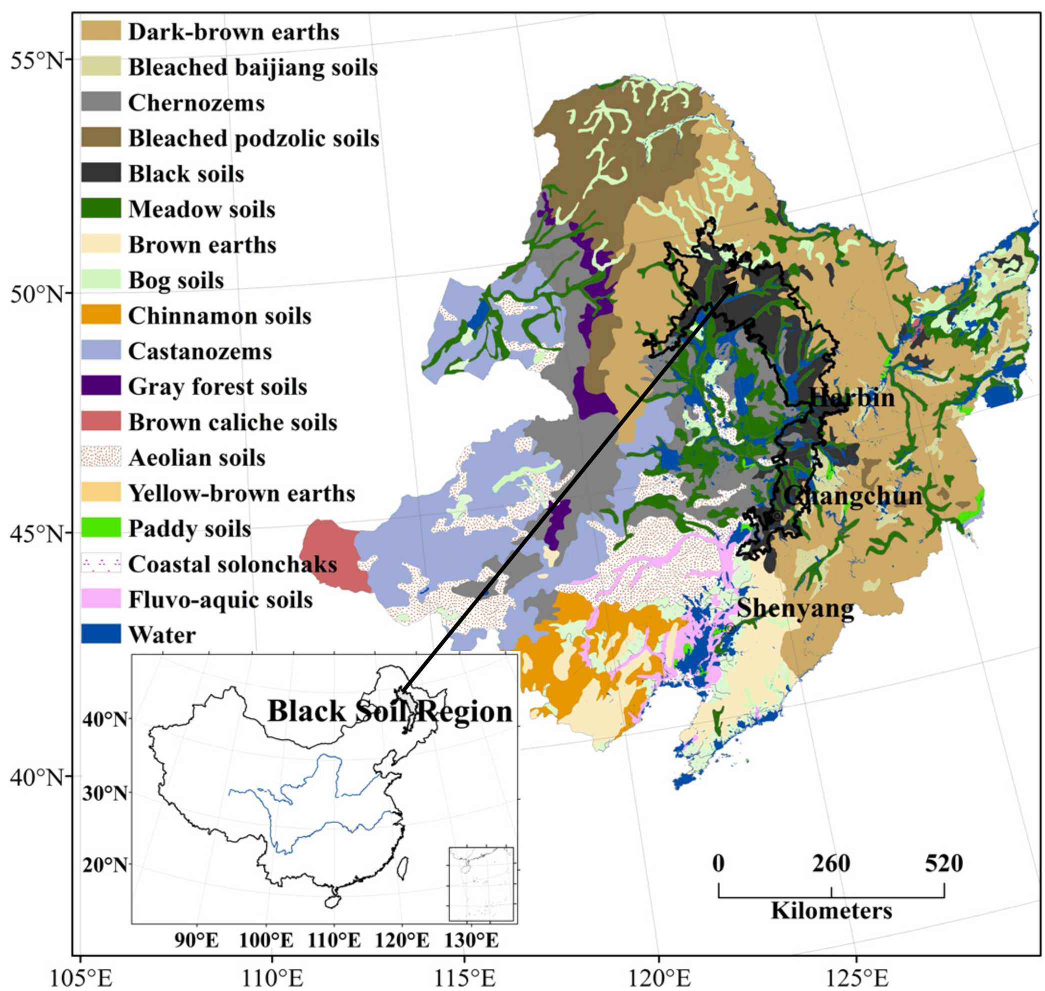

Fig. 1. Study area—China's northeast black soil region.

(BD), and pH (Gantzer and McCarty, 1987). PI is a dimensionless productivity index ranging from 0 to 1 (1 indicating higher productivity). The major features of black soil are higher organic matter (OM) and clay content (NSSO, 1998). OM content plays a crucial role for crop production in the NE black soil region (Han et al., 2001; Wan and Li, 2002) and the chemical fertilizer currently used in this region has not been able to compensate for OM losses (Lin et al., 1994; Xu et al., 2006).

Duan et al. (2009) recommend that both OM and clay content be taken into account for soil productivity assessment and BD should be omitted, the correlation between BD and AWC is higher than the correlation between OM and AWC (Duan et al., 2009). Pierce et al. (1983) suggested 100 cm as a suitable soil thickness for the growth of corn, and calculated the PI using the upper 100 cm of soil (divided into 10 layers of 10 cm each); however, if a limiting layer was present in the first 100 cm soil, the soil depth was based on the limiting layer. Our MPI model, which focuses on assessing potential soil productivity, follows this approach: the total MPI value is the sum of the MPI values of each layer and is based on each layer's physical and chemical properties. Other factors affecting crop yield, such as climate, management, and plant differences, are assumed to be constant. Thus, in accordance with Duan et al. (2009), the primary equation for the MPI model is as follows:

$$MPI = \sum_{i=1}^{n} (A_i \times D_i \times O_i \times CL_i \times WF_i) \tag{1}$$

where i is the order number of the soil layers, and n is the total number of soil layers for the rooting depth. A_i is the sufficiency of AWC (cm^3/cm^3) at the i^{th} soil layer, and is calculated using:

$$A_i = \begin{cases} 0 \ldots\ldots AWC_i \le 0.03 \\ 5 \times AWC_i \ldots\ldots 0.03 < AWC_i \le 0.2 \\ 1 \ldots\ldots AWC_i > 0.2 \end{cases} \tag{2}$$

D_i is the sufficiency of pH at the i^{th} soil layer and is estimated using:

$$D_i = \begin{cases} 0 \ldots\ldots pH_i \le 2.9 \\ -1.31 + 0.446 * pH_i \ldots\ldots 2.9 < pH_i \le 5.0 \\ 0.12 + 0.16 * pH_i \ldots\ldots 5.0 < pH_i \le 5.5 \\ 1 \ldots\ldots 5.5 < pH_i \le 6.5 \\ 2.086 - 0.167 * pH_i \ldots\ldots 6.5 < pH_i \le 8.0 \\ 0.75 \ldots\ldots pH_i > 8.0 \end{cases} \tag{3}$$

O_i is the sufficiency of OM (%)at the i^{th} soil layer:

$$O_i = \begin{cases} \frac{OM_i}{4} \ldots\ldots 0\% \le OM_i < 4\% \\ 1 \ldots\ldots 4\% \le OM_i \end{cases} \tag{4}$$

CL_i is the sufficiency of clay (particle size <0.002 mm) content (%) at the i^{th} soil layer, such that:

$$CL_i = \begin{cases} 1 \ldots\ldots 20\% \le clay_i \le 40\% \\ \frac{clay_i}{20} \ldots\ldots 0 < clay_i < 20\% \\ \frac{100 - clay_i}{60} \ldots\ldots 40\% < clay_i < 100\% \\ 0 \ldots\ldots clay_i = 0.or.clay_i = 100\% \end{cases} \tag{5}$$

WF_i is the weight of the i^{th} layer, which is determined based on the utilization of soil moisture by crops in different layers under ideal conditions in accordance with Pierce et al. (1983) as follows:

$$WF = 0.35 - 0.152\, lg\left(depth + \sqrt{depth^2 + 6.45}\right) \tag{6}$$

where $depth$ indicates the soil depth within the profile. Integration is performed on the results of Eq. (6) after the weight of the i^{th} layer is obtained by normalizing the total value to 1.0.

2.3. Model validation

To validate the performance of the MPI model, we investigated 15 blocks of farmland in 2008 at the Heshan farm (49°00′–49°01′N; 125°16′–125°20′E), located in the northern part of the study area. These land blocks are located in a small basin with similar landforms (down slope tillage, from up slope to lower slope), similar slope (about 4%), and similar fertilization and management systems (mechanical tillage). The major crop types are soybeans and wheat, with one crop harvested per year. The common crop rotation is three years of soybean and one year of wheat or other crop. Accurate crop yields were measured and recorded in the farm's office from 1980. One profile was sampled from the center of each block, with disturbed and undisturbed soil samples collected from the surface to 200 mm below the parent material. In total, 86 disturbed and 258 undisturbed samples were collected from the 15 blocks of farmland. All samples were sealed and transported to the laboratory for analysis.

2.4. Assessment methods

Stocking (2003) suggested a conceptual framework for an “erosion–yield–time” model to assess the long-term changes in soil productivity due to erosion. We used a quantitative method in this study that was based on this conceptual model. As shown in Fig. 2, the assessment steps include the following:

(1) Evaluate the relative productive potential for black soils using the MPI model;
(2) Assess the vulnerability of soils due to erosion based on the MPI;
(3) Estimate the current soil loss rate;
(4) Predict the long-term soil productivity reduction based on the MPI, the vulnerability of soils due to erosion, and current estimated soil loss rate.

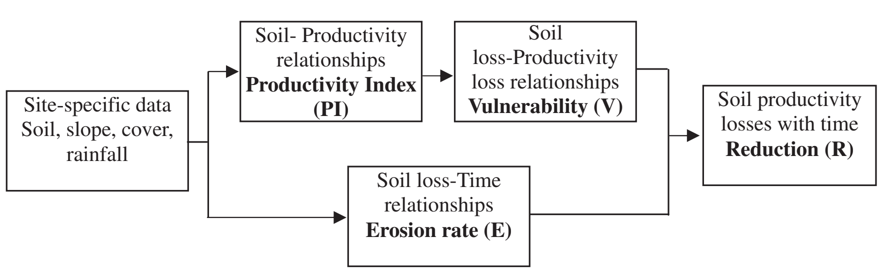

Fig. 2. Framework for assessing effects of soil erosion on soil productivity.

2.5. Field survey

We conducted a field survey of typical profiles for the 23 black soil series from June to September 2007, using GPS and topographic maps to locate the surveyed soil profiles. At each site we recorded data about the surrounding environment, including location, topography, slope, land-use types, and vegetation types. We sampled the soil profiles following soil survey standards as outlined by Liu (1996) and Wang and Zhang (1983), and used soil color charts to determine the soil genetic horizons (RGCRG, 1995). For each layer we collected one disturbed soil sample (2 kg of uniformly mixed soil sampled between the top and the bottom of the genetic horizon) and three undisturbed samples (55 mm diameter, 50 mm height, sampled in the middle of the genetic horizon). Samples were collected in one sublayer when the genetic horizon thicknesses were less than 30 cm; if the genetic horizon was between 30 cm and 60 cm, we divided it into two sublayers. Three sublayers were defined if the genetic horizon was greater than 60 cm. We used the undisturbed samples to analyze the BD and the disturbed soil samples to analyze other soil physicochemical properties (Dane and Topp, 2002; Liu, 1996). We collected cultivation and crop data, including crop type, management model, and crop yields of the land block where soil profile was located.

Finally, we selected a total of 21 series with the same land use (cropland), crop (primarily corn), and cultivation type (machine cultivation and artificial fertilization) to be analyzed for this study (Table 1) and collected 103 disturbed soil samples and 309 undisturbed soil samples from these profiles. Based on NSSO (1995), the selected 21 black soil series are representative of the primary soil conditions in 91% of the black soil area.

Particle size distribution, pH, OM, and AWC of all soil samples (including samples collected from Heshan farm) were determined in the laboratory using normal standards (Dane and Topp, 2002; Liu, 1996).

2.6. Indicators of soil vulnerability to erosion and soil productivity reduction rate

As soil eroded, the productivity calculation function (Eq. (1)) moved down the profile, unless some limiting layer occurred in the first 100 centimeters or until a limiting layer was encountered (Pierce et al., 1983). As a result, soils with unfavorable characteristics in the subsoil or the parent material undergo serious reductions in PI due to erosion (Larson et al., 1983).The productivity index model assumes that the PI values changes linearly with soil depth removal (Pierce et al., 1984; Runge et al., 1986). The soil's vulnerability to erosion, V (cm^{-1}), is defined as the rate of soil productivity index change with soil eroded depth and represents the change in MPI after 1 cm of top soil is removed. Following Runge et al. (1986) and Pierce et al. (1984):

$$V = \frac{\Delta MPI_d}{\Delta d} \tag{7}$$

where ΔMPI_d is the variation in MPI and d is the thickness of the eroded soil in cm. After the first layer (0–10 cm) is eroded, the second layer (10–20 cm) becomes the new top layer. Considering the effects of continuously mixing topsoil with subsoil during cultivation, we assumed that the MPI of the top layer (0–10 cm) after erosion was equal to the average MPI of the top layer (0–10 cm) and the second layer (10–20 cm) before erosion.

The soil productivity reduction rate, R (%), was defined as:

$$R = \frac{\Delta MPI}{MPI_0} \times 100\% = \frac{-V \times E \times t}{MPI_0} \times 100\% \tag{8}$$

where MPI_0 is the current soil productivity index, V is the vulnerability to soil erosion, E is the current soil loss rate (cm/a), and t is the time in years. E is calculated using a simple erosion rate estimation established by Liu et al. (2008):

$$E = 0.7379 \times \theta \tag{9}$$

where 0.7379 is the regression coefficient, θ is the slope of cropland in degrees, and E is expressed in mm/a. Liu et al. (2008) derived the slope distribution from Shuttle Radar Topography Mission data with a horizontal resolution of 90 m×90 m in the study area. We weighted each slope area, calculated the soil loss for different slopes using Eq. (9), and determined the average erosion rate to be 0.0921 cm/a. Land slopes may change as erosion depth increases, which will impact the rate of

Table 1
Description of 21 selected black soil series.

Series recording ID[a]	Profiles code	Area[b] (km^2)	Longitude (°E)	Latitude (°N)	Topsoil depth/profile depth (cm)	Texture	Parent material	Soil subtypes (GSCC/ST)
20276	1	66	124.03	43.26	24/120	Clay loam	Eolian (loess deposit)	Black Soil/Pachic Udic Haplobarolls
20278	2	71	124.05	43.25	22/120	Clay loam to loamy clay	Eolian (loess deposit)	
20282	3	3991	125.74	44.51	70/150	Loamy clay	Eolian (loess deposit)	
20284	4	1702	124.83	43.55	59/150	Clay loam to loamy clay	Eolian (loess deposit)	
20286	5	1177	125.21	43.90	18/130	Loamy clay	Eolian (loess deposit)	
20288	6	158	126.51	44.82	49/140	Clay loam	Eolian (loess deposit)	
20294	7	191	123.82	48.12	39/130	Loamy clay or clay	Alluvial (diluvium)	
20296	8	189	126.22	47.19	30/120	Loamy clay	Alluvial (diluvium)	
20300	9	15128	127.50	46.84	40/110	Loamy clay	Eolian (loess deposit)	
20302	10	75	126.26	47.34	47/110	Loamy clay	Eolian (loess deposit)	
20304	11	12998	127.07	46.44	60/160	Clay loam to loamy clay	Eolian (loess deposit)	
20306	12	631	125.43	48.60	30/120	Loamy clay or clay	Eolian (loess deposit)	
20312	13	169	124.32	43.16	40/120	Clay loam to loamy clay	Eolian (loess deposit)	Meadow Black Soils/ Pachic Udic Haplobarolls
20314	14	17	125.76	44.38	55/180	Loamy clay	Eolian (loess deposit)	
20316	15	421	125.74	45.43	40/90	Sand clay loam to loamy clay	Alluvial (fluvial)	
20318	16	2688	126.38	46.82	80/150	Loamy clay	Eolian (loess deposit)	
20320	17	1199	125.97	45.40	30/110	Loamy clay	Eolian (loess deposit)	
20322	18	2755	126.60	45.37	90/160	Loamy clay	Eolian (loess deposit)	
20324	19	205	126.80	45.01	50/120	Clay loam or clay	Eolian (loess deposit)	Albic Black Soils/Pachic Udic Argibarolls
20326	20	409	127.46	46.43	44/150	Clay loam	Eolian (loess deposit)	
20328	21	2129	127.15	46.22	55/150	Loamy clay	Eolian (loess deposit)	

[a] ID number is the first two digits of the volume number and the last three digits of the page number. For example, 20318 indicates the location of soil profile—page 318 of NSSO (1995).
[b] Data were obtained from National Soil Survey Office (NSSO) (1995).

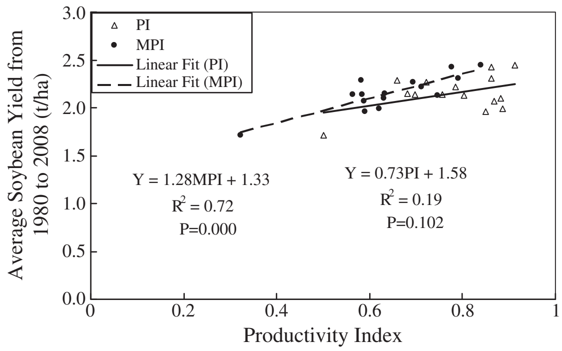

Fig. 3. Linear regression analyses between average soybean yield and soil productivity index using original PI and MPI models.

Eq. (8). Due to the difficulty in simulating this process, we have focused on the long-term effects of sheet erosion on soil productivity under current erosion rates. Forth more, gully erosion also plays an important role in the NE black soil region, but due to in short of observation data, this paper only focused on sheet erosion, gully erosion and its effects on soil productivity were not considered.

3. Results and discussions

3.1. Validation of MPI

To compare the two models (original PI and MPI), we calculated both values for the 15 profiles from the Heshan farm. We performed linear regression analyses between perennial average soybean yields (from 1980 to 2008) and productivity indices (Fig. 3). The original PI model accounted for approximately 19% of the variations of perennial soybean yields (significant at 0.103 level). In contrast, the MPI model accounted for approximately 72% of the variations of perennial soybean yields (significant at 0.0001 level), validating the effectiveness of the MPI in assessing soil productivity in the study area.

3.2. MPI values of black soil series samples

Much of the black soil cropland in the study area was established in the 1950s, at which time the OM in these soils ranged from 6% to 15% (Xiong and Li, 1987). In our study, we found OM ranging from 1.9% to 5.99% for the 103 collected samples (Table 2). OM decreased significantly with increasing soil depth (Fig. 4). The average OM of the surface layer was 3.72% (Table 3), which was significantly lower than the reported OM in the 1950s (Xiong and Li, 1987). Because the current fertilization system seldom compensates for the loss of OM (Lin et al., 1994; Xu et al., 2006), the degradation of OM was significant. An OM content less than 4% was not ideal for crop growth (Alvarez et al., 2002; Howard and Howard, 1990; Janzen et al., 1992) and results in a poor MPI (Duan et al., 2009). Thus, OM is an important soil productivity impact factor in the study area.

Average pH increases with increasing soil depth in the first 40 cm of depth and maintains a constant value (about 6.75) below 40 cm (Fig. 4); this configuration may be a result of the effects of tillage and the use of chemical fertilizers (Guo et al., 2010). The pH of most samples ranges between 5 and 8, which was suitable for most crop growth (Gale et al., 1991; Pierce et al., 1983). Thus, pH is not a stress factor in the MPI. Average AWC decreases with increasing soil depth (Fig. 4), and approximately 77% of the samples have an AWC less than 0.2 m^3/m^3, which was defined as the critical level for crop production in the PI (Gantzer and McCarty, 1987; Pierce et al., 1983). Consequently, AWC is considered a stress factor in the study area. The average clay content of the 103 soil samples was approximately 35% (Table 2) and increased with increasing soil depth (Fig. 4) ranging from 20% to 40% in more than 90% of the samples. As this range was sufficient for crop growth in the MPI model (Duan et al., 2009), clay content is not a stress factor for soil productivity in the study area. In

Table 2
Physicochemical properties, MPI, V, and R of surveyed profiles.

Profiles code	Soil subtypes (GSCC)	Soil physicochemical properties (surface layer)				MPI[a]	V[b] (cm^{-1})	R[c] in one year (%)
		OM (%)	pH	AWC (cm^3/cm^3)	Clay (%)			
1	Black soil	2.46	5.38	0.25	31.88	0.37	−0.0062	0.16
2		2.08	5.37	0.47	28.62	0.39	−0.0056	0.13
3		3.93	7.74	0.13	35.10	0.71	−0.0051	0.07
4		2.10	5.78	0.19	37.58	0.48	−0.0029	0.06
5		4.38	6.24	0.17	32.73	0.49	−0.009	0.17
6		3.22	5.89	0.30	37.12	0.68	−0.0047	0.06
7		5.04	6.53	0.05	49.48	0.21	−0.0025	0.11
8		3.45	5.83	0.28	44.60	0.50	−0.0067	0.12
9		4.91	5.57	0.13	35.91	0.47	−0.0035	0.07
10		3.79	5.65	0.08	42.75	0.30	−0.0034	0.10
11		4.60	6.49	0.13	31.29	0.58	−0.0044	0.07
12		5.34	5.87	0.15	46.91	0.47	−0.0053	0.10
Average of black soils subtypes		3.78	6.03	1.94	37.83	0.47	−0.0056	0.10
13	Meadow black soils	3.10	5.05	0.28	30.30	0.43	−0.0068	0.15
14		3.68	6.91	0.14	36.61	0.46	−0.0029	0.06
15		2.10	6.34	0.32	25.03	0.46	−0.0034	0.07
16		5.02	5.14	0.20	38.35	0.85	−0.0071	0.08
17		1.90	6.78	0.19	36.31	0.36	−0.003	0.08
18		5.99	8.02	0.31	16.00	0.75	−0.0026	0.03
Average of meadow black soils subtypes		3.63	6.37	0.24	30.43	0.55	−0.0043	0.08
19	Albic black soils	3.18	5.56	0.17	33.52	0.58	−0.0056	0.09
20		3.50	5.51	0.21	28.91	0.53	−0.0093	0.16
21		4.48	7.18	0.20	33.21	0.85	−0.0092	0.10
Average of Albic black soils subtypes		3.72	6.08	0.19	31.88	0.65	−0.0081	0.11
Total soil series	Min	1.9	5.05	0.05	16	0.85	−0.0093	0.032
	Max	5.99	8.02	0.47	49.48	0.21	−0.0025	0.169
	Average	3.72	6.13	0.21	34.86	0.52	−0.0052	0.097
	Std. Deviation	1.19	0.82	0.09	7.50	0.169	0.0022	0.03875

[a] Soil productivity index.
[b] Soil vulnerability to erosion—rate of MPI change with the soil eroded thickness.
[c] Percentage decrease in MPI due to one year soil loss at current rate.

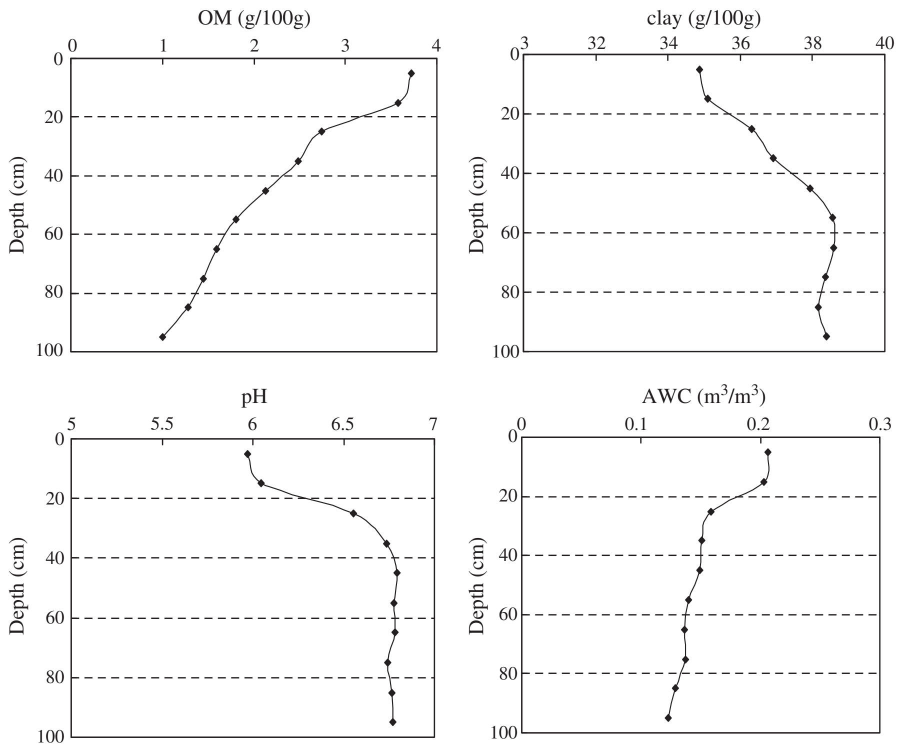

Fig. 4. Average change in soil characteristics versus soil depth.

summary, OM and AWC are shown to be MPI stress factors in the study area, while clay content and pH are not.

Less than 5% of the black soil series exhibit an MPI associated with low productivity (MPI<0.4); approximately 70% had medium productivity (MPI=0.4–0.7); and about 25% had high productivity (MPI >0.7).

Table 3
Group I soil characteristics.

Profiles code	Depth (cm)	Genetic horizons	BD (g/cm^3)	Clay (g/100 g)	pH	OM (g/100 g)	AWC (m^3/m^3)
1	0–24	A	1.28	31.88	5.38	2.46	0.25
	24–40	B	1.37	37.37	7.16	0.12	0.12
	40–70	C	1.38	36.83	7.26	0.74	0.13
	70–100	C	1.57	26.17	7.3	0.69	0.07
2	0–22	A	1.11	28.62	5.37	2.08	0.47
	22–45	B	1.34	31.51	6.45	1.45	0.23
	45–80	C	1.30	24.90	7.25	0.64	0.24
	80–110	C	1.42	21.99	7.08	0.17	0.18
5	0–18	A	1.39	32.73	6.24	4.38	0.17
	18–51	B	1.54	37.43	6.87	1.29	0.08
	51–80	C	1.41	30.95	7.05	0.64	0.08
	80–110	C	1.49	33.24	6.44	0.86	0.09
8	0–18	A	1.08	44.60	5.83	3.45	0.28
	18–30	A	1.33	37.43	5.79	3.32	0.09
	30–50	B	1.32	34.67	6.35	1.55	0.09
	50–70	C	1.39	41.15	6.26	1.68	0.05
	70–100	C	1.43	36.21	6.12	0.74	0.08
13	0–19	A	1.19	30.30	5.05	3.10	0.28
	19–40	A	1.50	35.52	6.51	1.59	0.07
	40–54	B	1.34	36.76	6.79	1.19	0.12
	54–83	C	1.37	40.79	6.65	0.53	0.13
	80–110	C	1.43	32.19	6.86	0.70	0.15
20	0–25	A	1.24	25.03	6.34	2.10	0.32
	25–40	A	1.35	28.88	7.9	2.36	0.18
	40–70	B	1.24	29.46	7.9	1.50	0.23
	70–90	B	1.24	29.14	7.46	1.75	0.23
	90–120	C	1.26	26.95	7.44	0.70	0.23
	120–150	C	1.27	26.49	7.36	0.33	0.23

The four black soil series with the highest productivity typically had higher OM content and AWC than the other series. Series with the lowest productivity included those with very low OM content and/or high clay contents and low AWC. For example, soil profile 17, which has an MPI of 0.36, is a meadow black soil which has undergone extensive management and long-term cultivation, leading to nutrient loss and low OM content.

3.3. Vulnerability of soil productivity due to soil erosion

As soil depth increased, OM and AWC typically decreased, whereas pH and clay content increased (Fig. 4). MPI deceased as eroded soil depth increased, although the reduction trends vary among the different soil series (Fig. 5). Of the 21 black soil series evaluated in this study, 6 have an obvious critical point for this trend (Fig. 5a); we classified these series as group I soils. The MPI of these soils decreased dramatically as depth of erosion increased until the erosion depth reached the critical point (about 40 cm). Below this critical point, the rate of MPI decreased was very low (or negligible) as shown in Fig. 5a. The average V for group I soils was $-0.007\ cm^{-1}$. In these soils, the “A” genetic horizon (Table 3) has a relatively high productivity, but was very thin (18 to 45 cm). Below this horizon lie less productive subsurface horizons (lower OM and AWC, higher BD) that typically have significantly lower MPI than that of the surface soil (Fig. 5a). Group I represents degraded black soils that have suffered from long-term erosion and were characterized by a thin layer of remaining topsoil. These soils are vulnerable to erosion and need protection.

The remaining 15 black soil series have been divided into three groups (II, III, IV) based on their *V* value (Fig. 5b, c, d). Group II (Fig. 5b) represents the best black soil in the study area, having a very high soil productivity (average MPI > 0.83) and the highest average *V* ($-0.008\ cm^{-1}$). Group III (Fig. 5c) has medium *V* ($-0.005\ cm^{-1}$) and MPI values (0.46 to 0.71, average 0.60), while Group IV (Fig. 5d) has the lowest average *V* ($-0.003\ cm^{-1}$) and MPI values (0.21 to 0.75, average 0.43). These findings indicate that higher average MPI values are associated with higher *V* values (Fig. 4). The parent material of

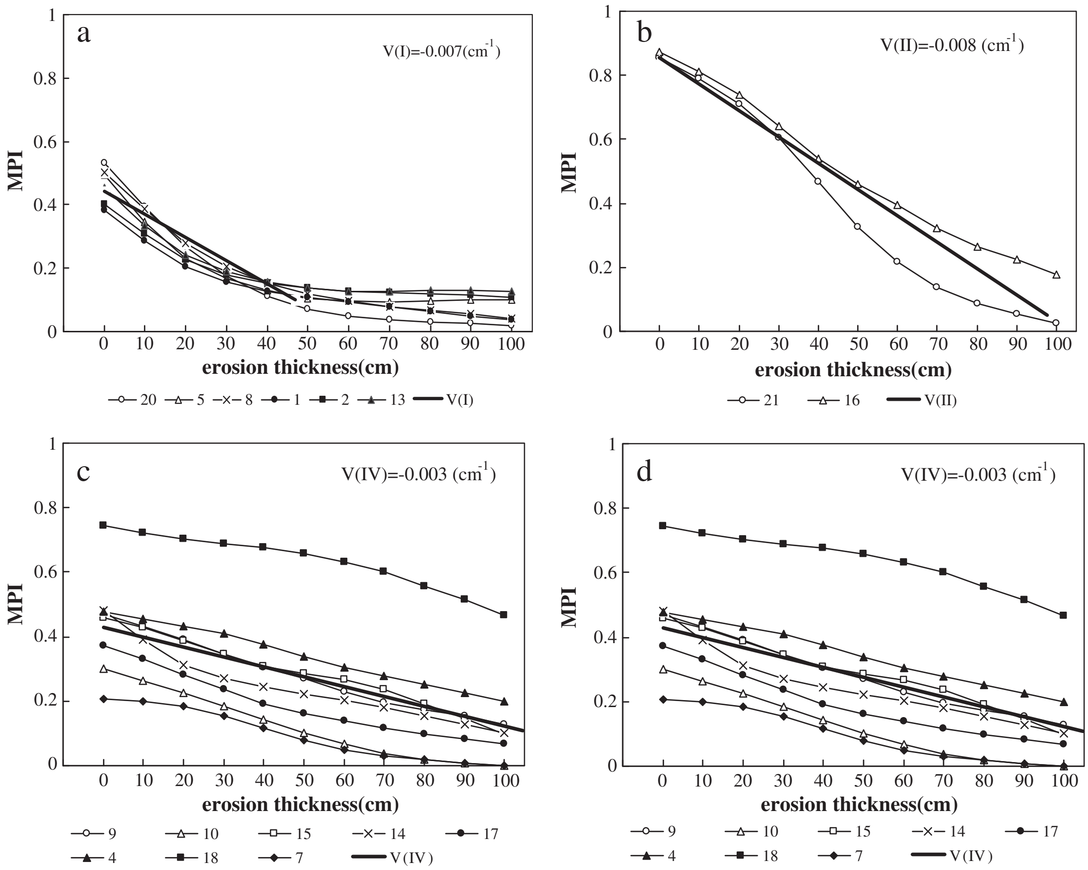

Fig. 5. MPI versus soil loss.

most black soils is yellow clay, which has low productivity due to low OM content, high clay content, and low AWC. Once the higher productivity soil is eroded, the remaining soil has a very low MPI; thus, there is a direct correlation between *V* and the MPI value.

The average V for the 21 black soil series was $-0.0052\ \mathrm{cm}^{-1}$ (Table 2), indicating that the MPI will decrease by 0.0052 (or by about 1% of the current average MPI value) after 1 cm of soil has eroded. Wang et al. (2009) conducted a desurfacing experiment in the study area and showed that the average reduction of soybean yield was 14.9% per 10 cm of soil eroded. Zhang et al. (2006b) observed that the reduction of soybean yield was 19.7% per 10 cm of soil eroded with the same method in the NE black soil region. Our result (average reduction of soil productivity of 10% per 10 cm of soil eroded) was lower than both of the studies. This difference may result in part from different soil properties. The top soil in the Wang et al. (2009) study was 40 cm and in the Zhang et al. (2006b) study was 30 cm, whereas, our study area included the entire region with topsoil thicknesses that varied from 18 cm to 90 cm. Additionally, the study method may have a significant influence on the result. Bakker et al. (2004) compared studies describing the relationship between erosion and productivity and found that results were significantly different with different study methods.

3.4. Long-term soil productivity reduction under the current soil erosion rate

The rate of MPI reduction over one year indicates an annual soil productivity decrease of 0.1% as a result of the current soil loss rate of 0.0921 cm/a. There were no significant differences in the R value among the three soil subtypes.

Long-term of reduction in soil productivity using current soil erosion rates were predicted over 20, 50, 100, 300, and 500 years (Table 4). After 500 years, approximately 48% of the current black soil productivity is projected to be lost due to soil erosion.

As erosion time increased, more soils will be subject to a higher rate of productivity reduction (Table 5). The R values are less than 5% for all soils in the study area after 20 years of erosion and for most of black soils after 50 years erosion. However, almost all black soil will lose more than 5% of soil productivity after 100 years of erosion, and about 88% of soil will lose more than 25% of soil productivity after

Table 4
Projected rates of soil productivity reduction.

Years	Predicted R (%)	
	Range	Average
20	0.64–3.37	1.93
50	1.61–8.43	4.83
100	3.21–16.85	9.67
300	9.64–50.56	29
500	16.07–84.26	48.34

Table 5
Percent of area under long-term erosion.

Projected year	% of Soils within range			
	R value range (%)			
	<5	5–25	25–50	>50
20	100			
50	94	6		
100	6	94		
300		88	9	3
500		6	88	6

500 years. The results clearly demonstrate that the reduction in soil productivity due to long-term erosion in the research area is very serious and may pose a direct threat to the food security of China.

4. Conclusions

We validated an MPI simulation model and used it to evaluate the long-term effect of soil erosion on potential soil productivity in China's NE black soil region. More than half of the investigated soil series exhibited moderate productivity levels. OM and AWC were found to be major stress factors in the MPI model; both of these decreased significantly with increasing depth of soil erosion, leading to a decreased in MPI with depth. Findings indicate that current productivity of the black soils will decrease by approximately 1% for each 1 cm of topsoil that erodes. Consequently, long-term soil erosion may seriously threaten the future food production in the NE black soil region. Effective soil and water conservation measures should be implemented immediately to control soil erosion in this region.

MPI was useful in evaluating the potential soil productivity and was significantly correlated to soybean yield in NE black soil region. However, the simulation result may be influenced by the selection of model parameters and the demarcation of sufficiency values. More control experiments and observation should be done to account for specific soil prosperities and the response of crops to these factors, thus to improve the model performance.

Using a simulation model to assess the effects of soil erosion on potential soil productivity at a regional scale, such as we did in this study, may yield slightly different results than experimental observations. Each of the methods has its advantages and disadvantages, but the model simulation method is easier to operate and lower cost results than small-scale experimental observations.

This study assessed the intrinsic aspects of soil productivity that are not easily replaced under current agriculture management systems and sheet erosion rates. Other factors such as technological developments, increases in agricultural investment, and gully erosion may also have an effect on soil productivity, changing the erosion rates over time. These processes are very complicated and need further study.

Acknowledgements

This work was supported by the National Natural Science Foundation Project of China (grant number: 40671111) and the Science (Engineering) Research Project of Yunnan University (grant number: 2010YB017).

References

Alvarez, R., Alvarez, C.R., Steinbach, H.S., 2002. Association between soil organic matter and wheat yields in humid Pampa of Argentina. Commun. Soil Sci. Plant Anal. 33 (5–6), 749–756.

Bakker, M.M., Govers, G., Rounsevell, M.D.A., 2004. The crop productivity–erosion relationship: an analysis based on experimental work. Catena 57 (1), 55–76.

Dane, J.H., Topp, G.C. (Eds.), 2002. Methods of Soil Analysis: Part 4. Soil Science Society of America Press, Physical Methods, USA.

Duan, X.W., Xie, Y., Feng, Y.J., Yin, S.Q., 2009. Study on the method of soil productivity assessment in black soil region of Northeast China. Agric. Sci. China 8 (4), 472–481.

Gale, M.R., Grigal, D.F., Harding, R.B., 1991. Soil productivity index: predictions of site quality for white spruce plantations. Soil Sci. Soc. Am. J. 55 (6), 1701–1708.

Gantzer, C.J., McCarty, T.R., 1987. Predicting corn yield on a claypan soil using a productivity index. Trans. ASABE 30 (5), 1347–1352.

Gong, Z.T., Chen, Z.C., Shi, X.Z., 1999. Chinese Soil Taxonomy. Science Press, Beijing, pp. 648–662 (in Chinese).

Guo, J.H., Liu, X.J., Zhang, Y., Shen, J.L., Han, W.X., Zhang, W.F., Christie, P., Goulding, K.W.T., Vitousek, P.M., Zhang, F.S., 2010. Significant acidification in major Chinese croplands. Science 327 (5968), 1008–1010.

Han, X.Z., Wang, S.Y., Song, C.Y., Liu, X.B., Meng, K., 2001. Study on the efficacy of organic matter in black soil. Syst. Sci. Compr. Stud. Agric. 17 (4), 256–259 (in Chinese).

Howard, P.J.A., Howard, D.M., 1990. Use of organic carbon and loss-on-ignition to estimated soil organic matter different soil types and horizons. Biol. Fertil. Soils 9 (4), 306–310.

Janzen, H.H., Lamey, F.J., Olson, B.M., 1992. Soil quality factors of problem soils in Alberta. Proc. Alberta Soil Sci. Workshop, 35, pp. 17–28.

Kiniry, L.N., Scrivner, C.L., Keener, M.E., 1983. A soil productivity index based upon predicted water depletion and root growth. Res. Bull, 1051. Univ. of Missouri. Coll. Agr., Food Agr. Exp. Sta.

Lal, R., 2001. Soil degradation by erosion. Land Degrad. Dev. 12 (6), 519–539.

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

Li, F.P., Li, J.Y., Xu, Z.X., 2006. The status quo of black soil degradation and water and soil loss in Northeast China. Res. Soil Water Conserv. 13 (3), 50–54 (in Chinese).

Lin, B., Lin, J.X., Li, J.K., 1994. The changes of crop yield and soil fertility with long-term fertilizer application. Plant Nutr. Fertilizing Sci. 1, 6–18 (in Chinese).

Liu, G.S., 1996. Soil Physics and Chemistry Analysis and Description of Soil Profiles. China Standard Press, Beijing. (in Chinese).

Liu, B.Y., 2003. Approach to issues of soil deterioration and sustainable utilization of typical Chernozem Region. Soil Water Conserv. China 12, 28–29 (in Chinese).

Liu, B.Y., Yan, B.X., Shen, B., Wang, Z.Q., Wei, X., 2008. Current status and comprehensive control strategies of soil erosion for cultivated land in the Northeastern black soil area of China. Sci. Soil Water Conserv. 6 (1), 1–8 (in Chinese).

Lobo, D., Lozano, Z., Delgado, F., 2005. Water erosion risk assessment and impact on productivity of a Venezuela soil. Catena 64 (2–3), 297–306.

National Soil Erosion-Soil Productivity Research Planning Committee (NSE), 1981. Soil erosion effects on soil productivity: a research perspective. J. Soil Water Conserv. 36 (2), 82–90.

National Soil Survey Office (NSSO), 1995. Chinese Soil Genus Records, Vol.2. China Agriculture Press, Beijing (in Chinese).

National Soil Survey Office (NSSO), 1998. Soils of China. China Agriculture Press, Beijing, pp. 318–336 (in Chinese).

Neill, L.L., 1979. An evaluation of soil productivity based on root growth and water depletion. M.S. thesis. Univ. Mo., Columbia.

Olson, K.R., Lal, R., Norton, L.D., 1994. Evaluation of methods to study soil erosion-productivity relationships. J. Soil Water Conserv. 49 (6), 586–590.

Pierce, F.J., Larson, W.E., Dowdy, R.H., Graham, W.A.P., 1983. Productivity of soil: assessing of long-term changes due to erosion. J. Soil and Water Conserv. 38 (1), 39–44.

Pierce, F.J., Dowdy, R.H., Larson, W.E., Graham, W.A.P., 1984. Soil productivity in the corn belt: an assessment of erosion's long-term effects. J. Soil Water Conserv. 39 (2), 131–136.

Research group and cooperative research group on Chinese soil taxonomy (RGCRG, 1995. Index on Chinese soil taxonomy (2nd version). Chinese Agriculture Science and Technology Press, Beijing, pp. 1–218 (in Chinese).

Rijsberman, F.R., Wolman, M.G., 1985. Effect of erosion on soil productivity: an international comparison. J. Soil Water Conserv. 40 (4), 349–354.

Runge, C.F., Larson, W.E., Roloff, G., 1986. Using productivity measures to target conservation programs: a comparative analysis. J. Soil Water Conserv. 41 (1), 45–49.

Schumacher, T.E., Lindstrom, M.J., Mokma, D.L., Nelson, W.W., 1994. Corn yield: erosion relationships of representative loess and till soils in the North Central United States. J. Soil Water Conserv. 49 (1), 77–81.

Shi, X.Z., Yu, D.S., Warner, E.D., Sun, W.X., Petersen, G.W., Gong, Z.T., Lin, H., 2006. Cross-reference system for translating between genetic soil classification of China and soil taxonomy. Soil Sci. Soc. Am. J. 70, 78–83.

Stocking, M.A., 2003. Tropical soils and food security: the next 50 years. Sci. 302 (5649), 1356–1359.

Thompson, A.L., Gantzer, C.J., Hammer, R.D., 1992. Productivity of claypan soil under rain-fed and irrigated conditions. J. Soil Water Conserv. 47 (5), 405–410.

Udawatta, R.P., Henderson, G.S., 2003. Root distribution relationships to soil properties in Missouri oak stands: a productivity index approach. Soil Sci. Soc. Am. J. 67 (6), 1869–1878.

Wan, W., Li, X.B., 2002. Study on the marginal productivity of cultivated land with change of soul organic matter of China. Scientia Geographica Sinica 22, 24–28 (in Chinese).

Wang, G.L., Zhang, G.Z., 1983. Soil knowledge and general detailed of soil survey technology. Water and Electric Power Press, Beijing. (in Chinese).

Wang, Z.Q., Liu, B.Y., Wang, X.Y., Gao, X.F., Liu, G., 2009. Erosion effect on the productivity of black soil in Northeast China. Sci China Ser. D: Earth Sci. 52 (7), 1005–1021.

Xiong, Y., Li, Q.K., 1987. Soil of China. Science Press, Beijing, pp. 648–662 (in Chinese).

Xu, M.G., Liang, G.Q., Zhang, D.F., 2006. Soil fertility evolution in China. Chinese Agricultural Science and Technology Press, Beijing, pp. 301–329 (in Chinese).

Yan, B.X., Tang, J., 2005. Study on black soil erosion rate and the transformation of soil quality influenced by erosion. Geogr. Res. 24 (4), 499–506 (in Chinese).

Yang, J., Hammer, R.D., Thompson, R.D., Blanchar, R.W., 2003. Predicting soybean yield in dry and wet year using a soil productivity index. Plant Soil 250 (2), 175–182.

Yu, D., Shen, B., Xie, J., 1992. Damages caused by soil and water erosion and their controlling approaches in Northeast China. Bull. Soil Water Conserv. 12 (2), 25–34 (in Chinese).

Zhang, S.W., Zhang, Y.Z., Li, Y., Chang, L.P., 2006a. Analyses in Temporal and Spatial Characteristics of Land Use and Land Cover in the Northeast China. Science Press, Beijing, pp. 42–48 (in Chinese).

Zhang, X.Y., Liu, X.B., Sui, Y.Y., Zhang, S., Liu, H., Herbert, S.J., 2006b. Effects of artificial topsoil removal on soybean dry matter accumulation and yield in Chinese Mollisols. Soybean Sci. 25 (2), 123–126 (in Chinese).