Influence of Long-Term Fertilization on Crop Production and Soil Quality of a Recent Alluvial Soil

Jing Li, Fadong Li,* Qiang Liu, Yan Zhang, Guangshuai Zhao, and Zhu Ouyang

ABSTRACT

The Yellow River Delta (YRD) has been formed during the last 150 yr and is the youngest land in China. Identifying the current soil quality, the impact of long-term fertilization on crop production, and how to improve crop production in this region are of great concern to scientists and the government. The objectives of this research were to analyze the trends of wheat (*Triticum aestivum* L.) and corn (*Zea mays* L.) production and fertilizer application using data covering a period of about 25 yr, determine the current soil quality and compare the changes of that with soils collected in the second national soil census, and discuss the impact of long-term fertilization on crop production and soil quality in the YRD. Records indicated that crop production increased 2.1-fold from 1984 to 2008, with an approximate 3.5-fold increase in fertilizer application. A fuzzy comprehensive assessment of soil quality indicated an improvement during this same time period, but the average soil quality was still low relative to national standards, particularly due to low N availability. Although fertilization strategies appeared to have been successful in this region, declines in fertilizer use efficiency and the currently poor soil quality indicate a need for improved management strategies. Effective technology and education programs are required to improve fertilizer application practices and the management of soil quality, which would increase crop production.

The Yellow River is the second longest river in China and the world's second largest river in terms of sediment discharge to the sea (Yang et al., 2012a). The YRD is a typical ecotone of the Yellow River and Bohai Bay (Huang et al., 2012) and consists of sedimentary sand that is carried by the river and deposited to form new land. The geographic location of sediment accumulation forming the YRD has shifted several times due to the complicated imbrication pattern of the lower river channel (Wang et al., 2006). The modern YRD, formed since 1855 due to erosion and settling along the old channel, hosts the delta's natural wetlands and is subject to environmental pollution due to extensive oil and gas exploitation, as well as agricultural and industrial development in this region (Wang et al., 2009). The watershed of the YRD is the widest and youngest wetland in the warm temperate zone of China (Chen et al., 2012). It is one of China's major grain and cotton (*Gossypium* spp.) producing areas (Li et al., 2007). In 1989, the YRD ranked eighth as a national agricultural development zone and was one of the top 10 key agriculture comprehensive development zones in the country (State Council of China, 1993). Based on the advantages of abundant natural resources and a developed industrial foundation, the central government of China formally implemented a development plan for constructing a high-efficiency eco-economic zone for the YRD in 2009 (National Development and Reform Commission, 2009).

Kenli County is a representative county located at the YRD. Local farmers began using fertilizer in 1952; the total amount reached 87,400 kg in 1960 and quickly increased to 498,400 kg in 1970 (Cui et al., 2006). Previous surveys have shown that organic fertilizer was predominant in the study area from 1950 to 1965 (National Bureau of Statistics, 1984–2008). The main forms of fertilizer included human and animal feces, wet compost green manure, and crop straw. The application rate of organic fertilizer was 30,000 to 37,500 kg ha^{-1}. During this time, the available chemical fertilizers included phosphates, $(NH_4)_2SO_4$, NH_4NO_3, and urea. After the 1970s, the amount and variety of fertilizer used on farmlands steadily increased. In the late 1980s, however, with the development of agricultural mechanization, the use of farmyard manure declined each year, while the number of available chemical fertilizers multiplied. At present, most farmlands receive only chemical fertilizer, except for some crop straw that is plowed under (People's Government of Kenli County, 1984–2008). Meaningful estimates of the contribution of inorganic fertilizer to crop yield can and have been made worldwide. One study was conducted in the Morrow Plots (Illinois) that evaluated the effects of fertility treatments on various crops and rotations since 1876. It was reported that fertilizer inputs are responsible for between 30 and 50% of crop yield increases since the 1960s (Tilman et al., 2002). When fertilizer is used in excess, however, the soil quality will be imbalanced.

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Abbreviations: OM, organic matter; YRD, the Yellow River Delta.

Soil quality is a serious concern because the soil provides several vital functions, such as supporting food and fiber production by plants, influencing air quality through interaction with the atmosphere, and serving as a medium for storage and purification of water (Karaca et al., 2011). A number of quantitative studies have been conducted regarding soil quality assessment; these have focused on soil structure (Celik et al., 2010), soil moisture (Song et al., 2010), soil C and N (Kaur et al., 2008), soil enzymology (Karaca et al., 2011), and others. Changes in soil quality caused by imbalanced fertilizer use, acidification, salinity, alkalinity, and a decline in soil organic matter may take several years to become apparent (Chen et al., 2012). Long-term case studies are useful for studying changes in soil properties and processes, providing information regarding the long-term sustainability of agricultural systems, and helping to formulate future strategies to maintain soil health (Swarup et al., 1998). So far, the studies of crop production and soil quality of newborn lands are limited. Two important questions are: how are crop production and soil quality of newborn lands affected after long-term fertilization, and what are the best fertilization practices for local farmers?

One of several methods that have been used to assess soil quality is fuzzy comprehensive assessment, which is based on fuzzy logic (Wang, 2002). Fuzzy set theory, introduced by Zadeh (1965), reduces inconsistency and data complexity and is useful for assessing, interpreting, and classifying soil quality (Adebowale et al., 2008). It is useful for solving problems associated with fuzzy boundaries and monitoring errors of assessment results (Shen et al., 2005). For example, fuzzy evaluation methods are being used to comprehensively evaluate the contributions of various pollutants according to pre-established, weighted membership functions. Thus, sensitivity is enhanced relative to other indices that have been used to evaluate soil quality (Li et al., 2009).

The YRD was selected as a study site to investigate the influence of long-term fertilization on crop production and soil quality of a newborn land. The objectives of this study were to: (i) analyze trends in crop production from 1984 to 2008; (ii) identify trends in fertilizer application from 1984 to 2008; (iii) determine the current soil quality and compare it with soils collected in 1982; and (iv) investigate the impact of long-term fertilization on crop production and soil quality in the YRD in China.

STUDY AREA AND METHODOLOGY

Study Area

The YRD (117°31′–119°18′ E, 36°55′–38°16′ N) is located on the southern coast of the Bohai Bay and the western coast of Laizhou Bay (Fig. 1). It is a typical, fan-shaped delta with a higher altitude in the west and a lower riverbed in the east. As an agricultural area with a long history, Kenli County (118°14′–119°12′ E, 37°23′–37°49′ N) was selected as the study area. It is a mid-river province of the YRD, located near the mouth of the Yellow River. The total area is approximately 2204 km^2. Its elevation is between 13 and <1 m. It belongs to the warm-temperate, subhumid, continental monsoon climate zone, with an annual mean temperature of 11.9°C; average maximum and minimum temperatures are 26°C in July and −4°C in January. The mean annual precipitation in the study area is 590 mm, mostly occurring from July to September (data source: Resource and Environmental Science Data Center, Chinese Academy of Sciences).

Data Sources

Data on soil quality indicators, crop yield, and fertilizer application in the study area were collected for a period covering about 25 yr (1984–2008), either from statistical yearbooks (Statistics Bureau of Shandong Province, 1984–2008; National Bureau of Statistics, 1984–2008; People's Government of Kenli County, 1984–2008) and the second national soil census in 1982 or derived in the laboratory.

Soil Sampling and Experiment

Surface soil samples (n = 1800, 0–20 cm) were collected at locations distributed throughout the entire mainland area in 2008 (Fig. 1), with a relatively uniform distribution (1.1 by 1.1 km). The sampling sites were representative of the various soil types, soil quality, and terrain distribution within the region.

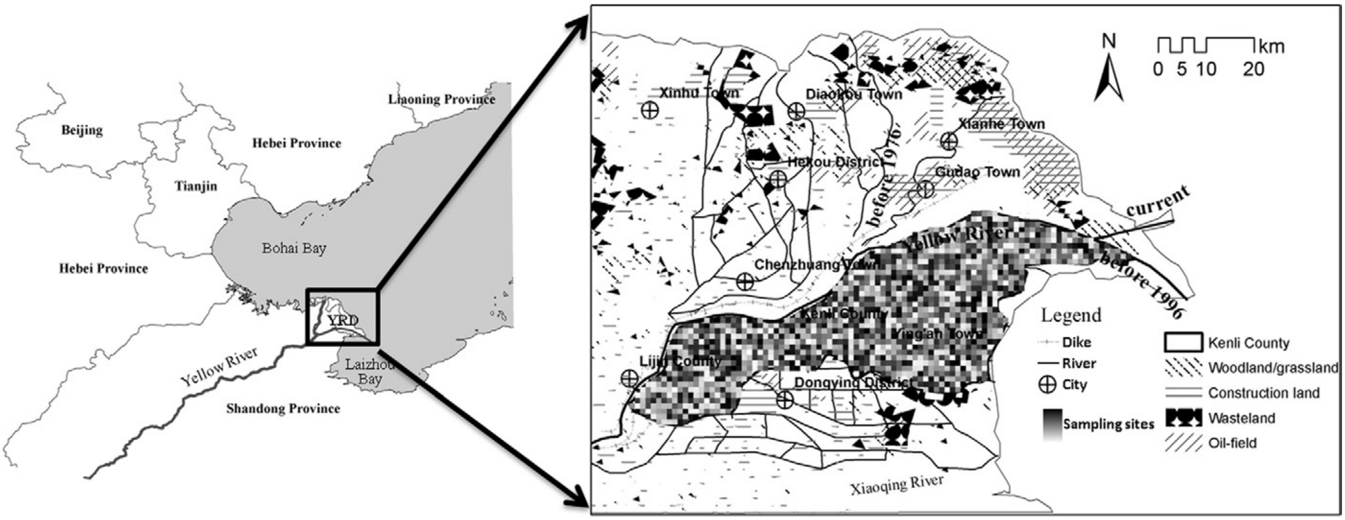

Fig. 1. Location of the study area in the Yellow River Delta (YRD) (data source: Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences).

Organic matter (OM), pH, total N, available N, available P, and available K were determined. Soil pH was measured in a 1:2.5 soil/water suspension by a potentiometric glass electrode (Hou et al., 2012). The oxidation method with $K_2Cr_2O_7$–H_2SO_4 was used to determine OM (National Centre for Agricultural Technology Extension, 2005). In brief, approximately 0.5 g of soil was sieved through a 0.149-mm sieve and digested with 10 mL of 1 mol L^{-1} $K_2Cr_2O_7$ and 10 mL of concentrated H_2SO_4 at 180°C for 5 min, followed by titration of the digests with $FeSO_4$. The Kjeldahl digestion procedure was used to quantify total N, and available N was determined by steam distillation with 1.2 mol L^{-1} NaOH after Kjeldahl digestion of the acid hydrolysate (Gallaher et al, 1976). The Mo–Sb colorimetric method of Olsen et al. (1954) was used to determine available P. The method measures phosphate extracted from soil using 0.5 mol L^{-1} $NaHCO_3$ (pH 8.5) under controlled conditions (1:100 soil/solution, end-over end extraction at 10 rpm, 23°C). The flame photometric method was used to measure available K in the extract (National Centre for Agricultural Technology Extension, 2006). The method measures K extracted from soil using 1 mol L^{-1} CH_3COONH_4 (pH 7) under controlled conditions (1:10 soil/solution, oscillation for 30 min, then filtered and determined by flame photometer).

The SPSS 12.0 for Windows was used for statistical analysis (Shen et al., 2005; Wang et al., 2011). Frequency distributions of the levels of OM, total N, available N, available P, and available K were conducted, and Spearman's correlation analysis was used to analyze the relationship between crop production and fertilizer application.

Fuzzy Comprehensive Assessment

The fuzzy comprehensive assessment was conducted according to previously described methods (Shen et al., 2005; Adebowale et al., 2008; Li et al., 2009). Briefly, assessment parameters were selected that were representative, rational, and accurate to form an assessment factor set *U*, which was based on the actual local soil characteristics:

$$U=\{u_1, u_2, \ldots, u_n\} \qquad [1]$$

where *n* is the number of selected assessment parameters (*n* = 5 in the current assessment). The assessment criteria set *V* was established from the National Soil Nutrient Classification of China (National Soil Survey Office, 2002):

$$V=\{v_1, v_2, \ldots, v_m\} \qquad [2]$$

where *m* is the number of assessment criteria categories (*m* = 5 in the current assessment).

Table 1. The national standard classification for soil nutrient content and the corresponding classification of data in 1982.

Level	Description	Organic matter	Total N	Available N	Available P	Available K
		—— g kg^{-1} ——		——— mg kg^{-1} ———		
I	very good	>30	>1.5	>120	>20	>150
II	good	20–30	1–1.5	90–120	10–20	100–150
III	normal	10–20	0.75–1	60–90	5–10	50–100†
IV	poor	6–10†	0.5–0.75†	30–60†	3–5†	30–50
V	very poor	<6	<0.5	<30	<3	<30

† Corresponding classification of data in the study area in 1982.

The next step was to formulate the membership function, which represents the degree to which the specified concentration belongs to the fuzzy set. The membership degree of assessment parameters at each level can be described quantitatively by a set of formulae of membership functions:

$$w_i(x)=\begin{cases} x/v_i & x \geq v_i \\ 1+\dfrac{v_1-x}{v_1-v_2} & v_2<x<v_i \\ 2+\dfrac{v_2-x}{v_2-v_3} & v_3<x<v_2 \\ 3+\dfrac{v_3-x}{v_3-v_4} & v_4<x<v_3 \\ 4+\dfrac{v_4-x}{v_4-v_5} & v_5<x<v_4 \end{cases} \qquad [3]$$

where *x* is the actual monitoring data (raw metals value) of any assessment parameter, and $w_i(x)$ is the membership degree of assessment parameter (*x*) for Classification Grades I, II, III, IV, or V, with values of 1, 2, 3, 4, and 5, respectively. The higher the number, the lower the soil quality. The membership function yields matrix $\mathbf{W}(x)$, which was calculated by substituting the monitoring data of each assessment parameter and the national standards into the membership functions:

$$\mathbf{W}(x)=[w_1(x), w_2(x), \ldots, w_n(x)] \qquad [4]$$

$$\bar{W}=\sum_{i=1}^{n}\frac{w_1(x)}{n} \qquad [5]$$

The parameter $\mathbf{W}(x)$ includes not only the difference between each element, but also the criterion. Thus, the value of the $\bar{W}$ can be calculated (Eq. [5]) and expresses the comprehensive classification of the assessment parameters on the scale of Grades I to V (see Table 1).

RESULTS AND DISCUSSION

Status of Soil Quality of the Yellow River Delta in 1982

Two national soil surveys conducted in the 1950s and 1980s in China provided a countrywide assessment of soil quality. Most modern research studies still refer to data derived in the 1980s (Yang et al., 2012b; Zhang et al., 2012). After more than 30 yr of development, current assessments and trends in soil quality are of great concern to the government.

The second census data from 1982 showed that the mean OM content in Kenli County was 8.4 g kg^{-1}. According to the classification of soil nutrient contents (Table 1), this soil belongs to Grade IV (i.e., poor). The mean concentration of total N was 0.5 g kg^{-1}, available N was 44.6 mg kg^{-1}, and available P was 3.3 mg kg^{-1} (all Grade IV; Table 1). The available K content was 79.2 mg kg^{-1}, indicative of Grade III.

Fuzzy comprehensive assessment, based on fuzzy logic, was used to assess and classify soil quality in 1982. The membership function and matrix formation **W**(x) was calculated as an average of the grades of all parameters:

$$\mathbf{W}(x) = \left[w_{\mathrm{OM}}(x), w_{\mathrm{TN}}(x), w_{\mathrm{AN}}(x), w_{\mathrm{AP}}(x), w_{\mathrm{AK}}(x)\right] = (3.40, 3.96, 3.51, 3.85, 2.46)$$

$$\bar{W} = \sum_{i=1}^{n} \frac{w_1(x)}{n} = 3.43$$

where TN is total N, AN is available N, AP is available P, and AK is available K. Thus, the value of $\bar{W}$ was 3.43. This comprehensive classification belongs to Grade IV, indicating that the soil quality of the YRD in 1982 was poor.

The soil C/N ratio has been used to assess the degree of decomposition of OM (Gong et al., 2008). Soil microbial activity is considered vigorous when the C/N value of the topsoil (0–20 cm) is in the range from 8 to 15 (Ma, 2010). Lower C/N values suggest that organic C has been removed as a result OM decomposition. The average C/N of soils in the 1982 survey was 9.74, which was lower than the average value of dry land in China. The C/N ratio in the plow layer of farmlands in China (0–20 cm) varied from 10.7 in the south to 9.2 in the east and northwest, with an average value of 9.9 (Xu et al., 2006). The differences among the regions were significant ($P < 0.05$). Overall, the C/N value of the measured soils indicated high microbial activity (Lu and Chen, 2003). However, the average N/P ratio in the soil of the YRD was 30.62, indicating that P was deficient. Kenli's natural soil conditions are characteristic of a vast land with a sparse population, which comprised little fertilized farmland in the 1980s. The characteristic tillage pattern resulted in a reduction in the inputs of fresh OM each year.

Trends in Crop Production from 1984 to 2008

Data collected from 1984 to 2008 provided estimates of the yields of winter wheat and summer corn, which were the major food crops in the study area. The production of both crops increased during the period from 1984 to 2008. The wheat yield per hectare (kg ha^{-1}) increased by about 89% and the corn yield (kg ha^{-1}) increased 99% during this period. The average annual growth rates of wheat and corn yields were 4.7 and 5.0%, respectively (Fig. 2). Abnormal values appeared in the years 1997 and 2000, when corn production dropped significantly. Drought was the critical factor (Zou and Liu, 2013). Precipitation was 499 mm in 1997 and 356 mm in 2000, respectively, both lower than the mean annual precipitation in the study area of 590 mm, and evaporation reached 2000 mm in the same year. Due to reduced rainfall, runoff of the Yellow River decreased; effective irrigation was not possible, which led to reduced crop production (Lin et al., 2012). In the 1980s, the average yield of wheat was 3251 kg ha^{-1} and corn was 3818 kg ha^{-1}, which increased to 5357 and 5343 kg ha^{-1}, respectively, in the 1990s. Since 2000, wheat yields have averaged 5925 kg ha^{-1} and corn yields have averaged 5490 kg ha^{-1}.

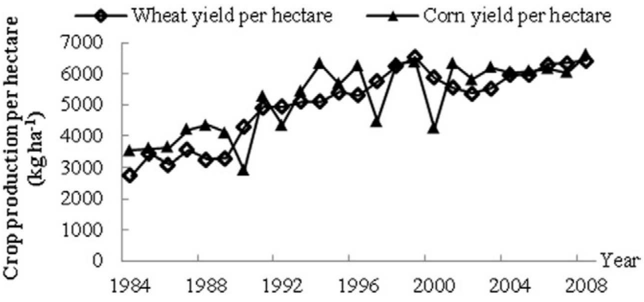

Fig. 2. Trends in crop production from 1984 to 2008 in Kenli County.

There are large differences in the productivity of cultivated land in the Yellow River irrigation areas (Statistics Bureau of Shandong Province, 1984–2008; National Bureau of Statistics, 1984–2008). For example, in 2007, the average crop yield was 6100 kg ha^{-1} in Shandong Province and reached up to 8095 kg ha^{-1} in Wen County. Also, crop yields in Kenli County are low compared with adjacent agro-ecological communities, which have similar climate and landforms.

After several years of continuous growth, the food production growth rate slowed due to the influence of external factors (Yang, 2011). For example, agricultural infrastructure and grain sowing acreage were shown to be the key factors resulting in decreased food production, contributing 41.9 and 24.6% of the variability in grain production in China, respectively (Fan, 2011). Also, the influence of extreme weather and climate events can't be ignored. Thus, food production fluctuates with production capacity in China, and in Kenli County as well.

Trends in Fertilizer Application from 1984 to 2008

Total fertilizer and N fertilizer application increased tremendously from 1984 to 2008 (Fig. 3). Total fertilizer application was minimal in 1985 (184.5 kg ha^{-1}) and increased approximately 3.5-fold to reach a maximum in 2004 (640.5 kg ha^{-1}). Fertilizer application in 1993 was anomalous, with the application of N fertilizer, phosphate fertilizer, potash fertilizer, and compound fertilizer increasing sharply at the same time. The price of fertilizer, government guidance, and market promotion impacted fertilizer rates in Kenli County (Cui et al., 2006). The average fertilizer application during the period from 1984 to 2008 was 436.5 kg ha^{-1}. In general, the fertilizer application rate increased during this period at an average annual growth rate of 8.8%.

The proportions of different fertilizers that were applied were stable. As shown in Fig. 3, N fertilizer was most commonly applied, accounting for about 60% of the total fertilizer applications, followed by phosphate fertilizer and compound

Table 2. Spearman rho correlation analysis between crop production and fertilizer application for 25 yr.

	Correlation coefficient			
Crop	N fertilizer	P fertilizer	K fertilizer	Compound fertilizer
Wheat (P = 0.001)	0.763**	0.841**	0.852**	0.691**
Corn (P = 0.001)	0.709**	0.647**	0.675**	0.680**

** Correlation is significant at the 0.01 level (two-tailed).

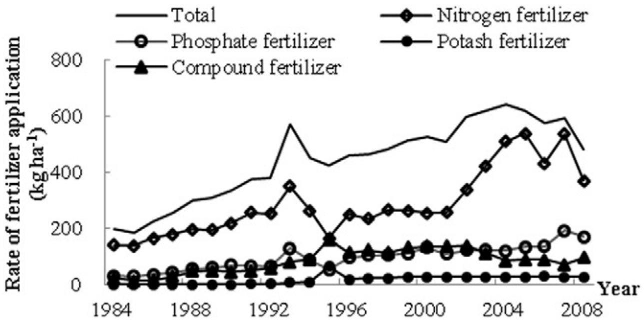

Fig. 3. Trends in fertilizer application from 1984 to 2008 in Kenli County.

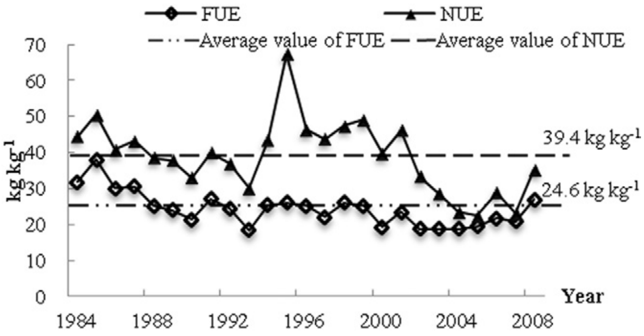

Fig. 4. Trends in fertilizer use efficiency (FUE = grain yield per unit fertilizer applied, kg kg^{-1}) and N use efficiency (NUE = grain yields per unit N applied, kg kg^{-1} N) from 1984 to 2008 in Kenli County.

fertilizer, together accounting for about 36.5%. Potash fertilizer application was relatively low at just 3.5%. Application of each fertilizer was positively correlated with wheat and corn production from 1984 to 2008 ($P < 0.01$; Table 2).

China's fertilizer consumption, especially N fertilizer, has increased during the last 25 yr. Total grain production increased by about 51% during this period. In China, fertilizer use efficiency (FUE = grain yield per unit fertilizer applied, kg kg^{-1}) decreased by about 52%, from 32 kg kg^{-1} in 1984 to 15 kg kg^{-1} in 2005 (Fig. 4). Similarly, N use efficiency (NUE = grain yields per unit N applied, kg kg^{-1} N), decreased by about 24%, from 43 kg kg^{-1} in 1984 to 32 kg kg^{-1} N fertilizer in 2005 (Wang et al., 2011). In Kenli County, the FUE ranged from 18.5 to 38.0 kg kg^{-1} from 1984 to 2008 and averaged 24.6 kg kg^{-1}, which was higher than the national average of 20.2 kg kg^{-1} during this period (Wang et al., 2011). The peak value of NUE was 67.3 kg kg^{-1} N, with increased grain yields and decreased N fertilizer applied in 1995 (Zou and Liu, 2013), while the lowest NUE was 22.4 kg kg^{-1} N in 2005. The average value is 39.4 kg kg^{-1} N, which is lower than the current global average estimate of 44 kg kg^{-1} N (Dobermann, 2007).

Current Soil Quality of the Yellow River Delta

The statistical characteristics of soil quality indicators and their classifications are listed in Table 3. Soil quality varied greatly in different parts of the study region, e.g., available K ranged from 23.0 to 1656.0 mg kg^{-1}. The coefficient of variation of quality indexes ranged from 38 to 110%. The average values of OM, total N, available N, available P, and available K were 10.8 mg kg^{-1}, 0.7 g kg^{-1}, 60.0 mg kg^{-1}, 11.2 mg kg^{-1}, and 159.0 mg kg^{-1}, respectively.

Frequency analysis describes the distribution tendency of soil quality indicators (Fig. 5). The values of total N, available N, available P, and available K presented a relatively even distribution; however, the value of OM concentrated in the range from 10.0 to 20.0 mg kg^{-1}. Table 3 classifies the frequency distribution of soil quality in Kenli according to the parameters and levels listed in Table 1. Approximately half of the soils exhibited poor soil OM content (<10 g kg^{-1}); among these, 34.7% were graded poor (6–10 g kg^{-1}) and 13.2% had very poor soil OM content (0–6 g kg^{-1}). Available N was most deficient in the soil samples relative to soil standards. Only 12.2% of samples scored normal or better (>60 mg kg^{-1}). About half of the soil samples were in the poor range (30–60 mg kg^{-1}), and 38.5% of the samples were very poor in available N content (<30 mg kg^{-1}). The available P content of the soils was relatively higher, with 11.3% of samples scoring very good (20 mg kg^{-1}), 17.5% scoring good (10–20 mg kg^{-1}), and 28.6% scoring normal (5–10 mg kg^{-1}). The available K content of soils in Kenli County was also relatively high, with 37.5% of samples belonging to Grade I (very good, >150 mg kg^{-1}), 27.6% belonging to Grade II (good, 100–150 mg kg^{-1}), and only 0.1% belonging to Grade V (very poor, <30 mg kg^{-1}).

According to the calculated averages and classification of soil nutrients in 2008, OM quality was Grade III, available N was Grade IV, available P was Grade II, and available K was Grade I. The concentrations of OM and available N were poor, but the concentrations of available P and available K were relatively high. Given these data, the membership function and matrix formation $\mathbf{W}(x)$ was calculated based on the fuzzy comprehensive assessment:

$$\mathbf{W}(x)= \left[w_{\mathrm{OM}}(x), w_{\mathrm{TN}}(x), w_{\mathrm{AN}}(x), w_{\mathrm{AP}}(x), w_{\mathrm{AK}}(x)\right] = (2.92,\ 3.36,\ 3,\ 1.88,\ 0.94)$$

$$\bar{W} = \sum_{i=1}^{n} \frac{w_1(x)}{n} = 2.42$$

Table 3. Descriptive statistics and classifications of soil quality indicators in Kenli County in 2008.

Parameter	Min.	Max.	Mean	SE	CV	Classification I	II	III	IV	V
						%				
Organic matter, g kg^{-1}	0.6	28.4	10.8	0.4	37.8	–	1.0	51.1	34.7	13.2
Total N, g kg^{-1}	0.1	9.8	0.7	0.8	95.8	–	–	0.4	0.7	98.9
Available N, mg kg^{-1}	0.1	119	60.0	18.8	49.9	–	1.0	11.2	49.4	38.5
Available P, mg kg^{-1}	0.1	97.7	11.2	10.1	110.1	11.3	17.5	28.6	18.4	24.2
Available K, mg kg^{-1}	23	1656	159.0	105.1	71.0	37.5	27.6	30.8	4.0	0.1

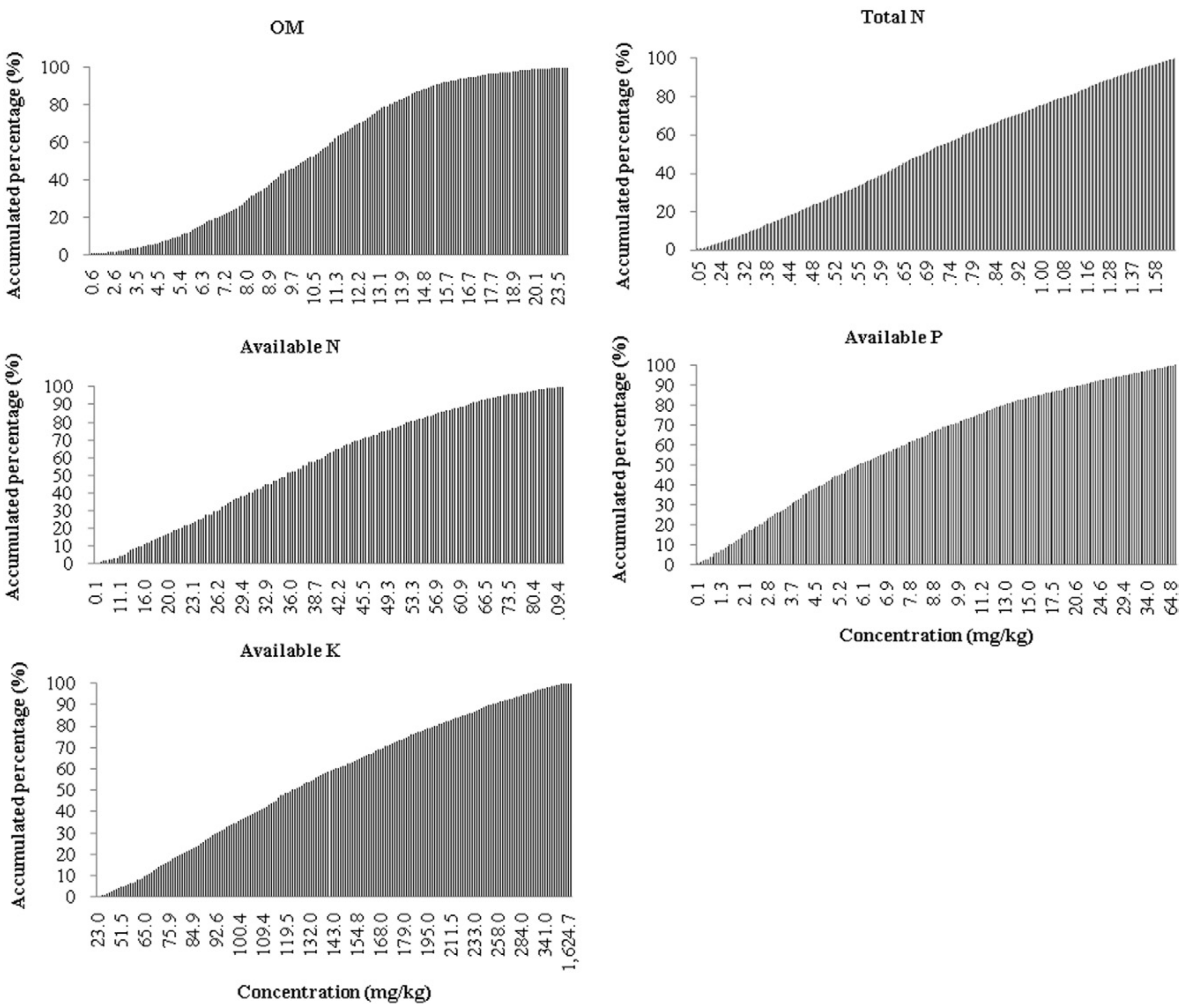

Fig. 5. Frequency analysis of soil quality indicators in Kenli County.

Thus, the value of $\overline{W}$ for YRD soils in 2008 was 2.42, which is lower (i.e., better) than the value in 1982 (3.43). On the whole, the comprehensive classification belongs to Grade III, indicating that soil quality in the YRD in 2008 was in the medium range. Additionally, soil quality in Kenli County in 2008 appeared to have improved during the period 1984 to 2008, with available P content increasing more than other parameters (i.e., more than threefold: from 3.3 to 11.2 mg kg^{-1}). In comparison, the average OM content increased 2.4 g kg^{-1} (from 8.4 to 10.8 g kg^{-1}), available K increased 79.8 mg kg^{-1} (doubled since 1984), total N increased 0.2 mg kg^{-1}, and available N increased 15.4 mg kg^{-1} (Table 4).

With the introduction of chemical fertilizers, the application of organic fertilizers to cropland in Kenli County decreased from 1982 to 2008 but the OM content of the soil increased. This increase can be explained by the increased popularity of mechanical harvesting and the return of straw. Currently, most winter wheat is harvested by machine and the wheat stubble residue in the field (0–20 cm) probably enhanced the soil OM content. Similarly, based on a social survey, more than 95% of straw, almost 16,500 kg ha^{-1}, was returned directly to the fields in the study area.

Increases in total N and available N in Kenli County were probably due to the accumulation of various N fertilizers, including urea, NH_4HCO_3, $NH_4H_2PO_4$, compound fertilizer, and others. Compared with the second census of soil quality (1982), the available P content increased 7.9 mg kg^{-1}. Based on the critically deficient phosphate status in 1982, a local

Table 4. Comparison of soil quality indicators in 2008 and in 1982 in Kenli County.

Statistic	Organic matter	Total N	Available N	Available P	Available K
	g kg^{-1}		mg kg^{-1}		
Mean content in 1984	8.4	0.5	44.6	3.3	79.2
Mean content in 2008	10.8	0.7	60.0	11.2	159.0
Change	+2.4	+0.2	+15.4	+7.9	+79.8
Rate of increase, %	28.6	40.0	34.5	239.4	100.8

technician of the Agriculture Bureau recommended that farmers supplement the land with more phosphate fertilizer.

The second soil census data also indicated that available K was relatively abundant compared with other soil quality indicators, so farmers did not apply potash fertilizer. In the early 1990s, a spot check experiment demonstrated that available K was decreasing to a deficient level. In combination with the Project of Potassium Supplement initiated by Shandong Province, the local agriculture bureau led farmers to apply chemical potash, thus increasing the available K content and soil quality.

CONCLUSIONS

Based on the data analysis of crop yield (winter wheat and summer corn), fertilizer use, and soil quality from 1984 to 2008, the main conclusions of this study are:

1. Crop production increased from 6270.0 to 13021.5 kg ha^{-1} during the study period, with average annual growth rates of the wheat and corn yields of 4.7 and 5.0%, respectively. Abnormal reductions in corn production in 1997 and 2000 were the result of drought.
2. Total fertilizer application increased from 184.5 to 640.5 kg ha^{-1} during the study period, with fluctuations, and an average annual growth rate of 8.8%.
3. The soil quality indicators varied largely in the study area. Compared with the soil quality standard, the classification values of the fuzzy comprehensive assessment of soil quality increased from 3.43 (poor level) in 1982 to 2.42 (normal level) in 2008, with a big improvement in OM, available P, and available K contents.
4. Although fertilizer application increased approximately 3.5-fold and crop production increased 2.1-fold from 1984 to 2008, the current status of soil quality is not optimistic given declines in fertilizer use efficiency. The use of fertilizer following the principle of adaptation to local conditions is critical to ensure increases in crop yield and soil quality in the YRD.

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