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Spatio-temporal variations of soil nutrients influenced by an altered land tenure system in China

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ABSTRACT

Initiated during the late 1970s in China, the Household Responsibility System (HRS) has brought a profound change to the rural economy. The shift from a collective farming system to individually-owned family farms has changed land management practices, affecting both soil quality and agro-environmental sustainability. The purpose of this study was to investigate spatio-temporal variability of soil nutrients influenced by the altered land tenure system, and to evaluate the potential for site-specific management. Using geostatistics and GIS, we characterized the spatial variability of soil nutrients in paddy rice fields in the Hangzhou–Jiaxing–Huzhou watershed, China, following 20 years of altered land management policy. Soil samples, collected in 1982 and 2001, were analyzed for soil organic matter (SOM), total nitrogen (TN), available phosphorus (AP), and available potassium (AK). The spatial variability of each of these soil properties decreased from 1982 to 2001, verifying that the extrinsic factors of the altered land management practices had a weakening effect on the intrinsic factors of soil formation properties. Spatial correlation ranges for SOM, TN, and AP in 2001 all decreased from 1982 with the exception of AK. Temporal geographic maps revealed significant changes in soil nutrient concentrations in the form of increases in SOM, TN, and AP and a sharp decline of AK during the period 1982–2001. This result gave an indication of the imbalance among N, P, and K fertilizers applied in the study area. The results of the comprehensive assessment for current soil nutrients could also, inversely, present challenges for future site-specific management policy on agriculture.
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1. Introduction

Initiated in the late 1970s in China, the Household Responsibility System (HRS) has transformed China's rural economy (Lin, 1987). Farmland was allocated to each farmer household on the basis of family size. The farmers were then given the authority to manage the contracted land, including all decisions regarding production. This policy shift from a collective farming system to individually-owned family farms has altered farmland nutrient patterns.

The Hangzhou–Jiaxing–Huzhou (HJH) watershed in Zhejiang Province is the key rice production area in southeast China, with a multiple cropping index of 2. Due to the direct relationship between soil nutrients and crop yield/quality, over-fertilization by land owners was perceived as one of the major factors contributing to the declining water quality. The second general soil survey in China was carried out in the region in 1982. Before 1982, all farmland in this area was uniformly managed by the local government, which allotted equal amounts of fertilizers to each village. In 1982, the HRS land management was implemented in this area, which gave farmers the authority to manage their contracted land. Since farmlands were managed by individual family farms, fertilizer rates and management methods for different farmlands varied greatly due to lack of scientific guidance (Qian, 2001). In the year 2000, for example, the highest and lowest annual gross amount of various fertilizer applications was 24.3×10^6 kg and 5.6×10^6 kg, which were applied in Jiaxing and Deqing counties, respectively. Moreover, in the case of annual mean fertilization, Pinghu, Haiyan and Yuhang ranked highest with the quantities of 748.6 kg ha^{-1}, 711.7 kg ha^{-1}, and 599.6 kg ha^{-1}, respectively. Deqing had the lowest annual mean fertilization amount of 288.7 kg ha^{-1}. The annual mean N fertilizer application of different counties in the HJH watershed in 2000 was between 179.5 kg ha^{-1} and 550.4 kg ha^{-1}. For 1996–2000, the annual mean fertilization in this area shows an excessive N application for the first 3 years and then a decrease when compared to the mean N fertilization in Zhejiang Province. The highest N fertilization was 773 kg ha^{-1}, occurring in Pinghu in 1996. However, K fertilization in the HJH watershed was lower during 1996–2000 when compared to that in Zhejiang Province. Understanding the spatio-temporal variability of soil nutrients induced by the altered land tenure system is essential for agricultural policy to create site-specific management practices that will promote agro-environmental sustainability.

Soil nutrients are important factors in evaluating soil quality, an essential component in developing sustainable land management and

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Fig. 1. Sketch map of the study area, HJH watershed.

sustaining the global biosphere (Nael et al., 2004). Over-fertilization may contribute to agricultural non-point source pollution which may degrade water quality, induce deficiency of other elements and interfere with soil metabolic processes (Zaman and Schumann, 2006). Conversely, under-fertilization may restrict crop yield and quality (Zaman and Schumann, 2006). Precision agricultural management, such as variable rate fertilizer application, avoids these problems. This approach, however, requires an understanding of the spatial variations of soil properties within fields.

Geostatistics has been proven to be a useful tool in effectively assessing the variability of soil nutrients (Webster and Oliver, 2001; Corwin et al., 2003; Mueller et al., 2003). Geostatistical methods have been applied to

Table 1
Median values of selected topsoil properties for soils found in the study area (from Batjes, 1997).

FAO unit	pH	OC	CEC	CMK	ESP	BULK	PORES	AWC	GRAV
Ferric acrisol	5.0	0.75	6.4	1.6	1	1.44	46	122	F
Orthic acrisol	4.9	0.78	7.5	1.5	1	1.38	48	113	F
Calcic cambisol	8.1	0.63	20.6	46.3	2	1.45	45	130	F
Eutric gleysol	6.2	1.19	20.4	17.6	2	1.43	46	122	F
Mollic gleysol	6.6	2.20	33.5	26.8	1	1.44	46	127	F
Pellic vertisol	7.2	0.92	45.3	45.8	2	1.59	40	130	F

pH: median soil pH, measured in water.
OC: median organic carbon (%).
CEC: median cation exchange capacity.
CMK: median sum of exchangeable Ca, Mg, and K (cmolc/kg).
ESP: median exchangeable sodium percentage (% of CEC).
BULK: median bulk density (g/cm^3).
PORES: median total porosity (%).
AWC: available water capacity in mm to a depth of 100 cm.
GRAV: median content of fragments less than 2 mm; F = few (0–5%).

analyze soil variability from a spatial resolution of centimeters to a few meters (Webster and Nortcliff, 1984; Cahn et al., 1994; Solie et al., 1999; Wilcke, 2000), as well as regional scales (Yost et al., 1982; Chien et al., 1997; White et al., 1997; Guo et al., 2002; Liu et al., 2006). In addition to spatial analysis, geostatistics can be employed temporally to investigate the changes in the spatial patterns of soil properties over time (Hoskinson et al., 1999; Liu et al., 2004).

Very little research has been conducted on the impact of reformed land tenure systems on the spatial variability of soil nutrients. A study by Collard and Zammit (2006) analyzed the effect of land management on soil carbon components in Queensland, Australia. In addition, a few recent papers have determined agricultural site-specific management zones for variable rate soil amendment application based on soil variability (Inmna et al., 2005; Zaman and Schumann, 2006; Duffera et al., 2007). Such analyses must be incorporated and built upon in order to thoroughly understand the effect of the HRS on the spatial variability of soil nutrients.

Therefore, the objectives of this research were to (1) investigate the spatial variation of soil nutrients in paddy rice fields; (2) evaluate the spatio-temporal variation mechanisms of soil properties; and (3) evaluate

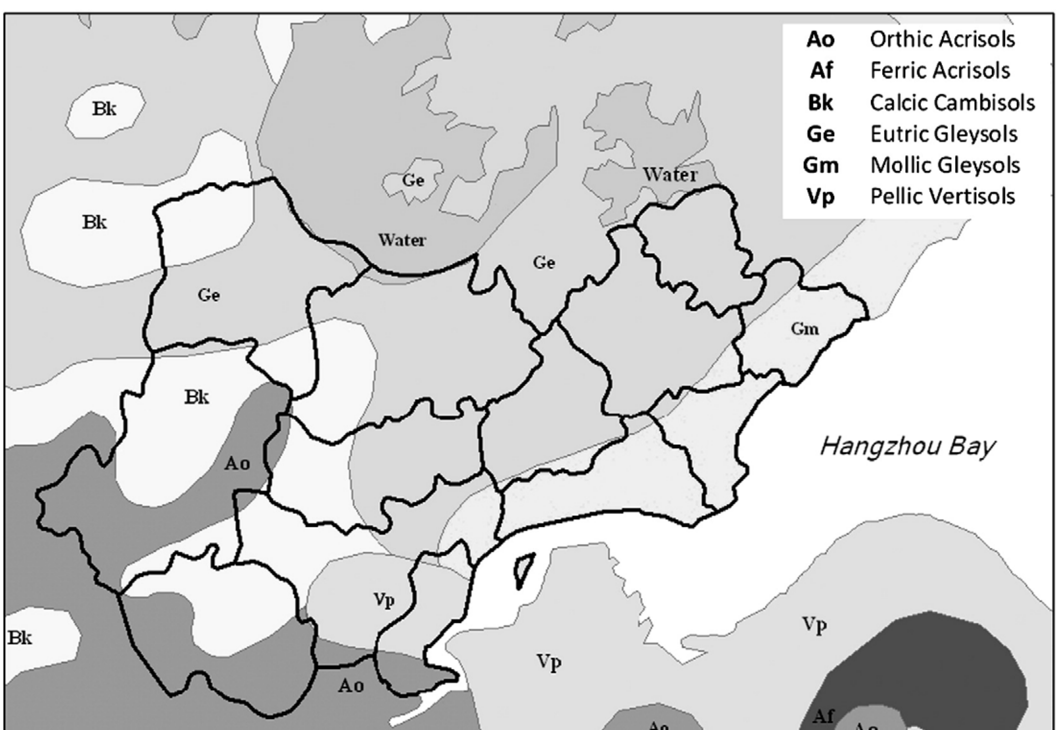

Fig. 2. Map of dominant soils in the HJH watershed.

the soil fertility of the paddy rice fields in the HJH watershed in 2001 and partition the fields into appropriate site-specific management zones. Understanding the effects of an altered land tenure system on spatio-temporal variability of soil properties will enable future agricultural land management policy to better promote long-term agro-environmental sustainability. These future policies can educate farmers on the amount of fertilizer needed for production while also decreasing the potential for agricultural runoff.

2. Materials and methods

2.1. Study area

The HJH watershed, located south of Taihu Lake and north of Zhejiang Province, was selected as the study area (Fig. 1). Latitude and longitude coordinates range from 30.09 to 31.19 N and 119.26 to 121.25 E, respectively. The region includes the counties of Jiaxing, Jiashan, Tongxiang, Haining, Haiyan, Pinghu, Huzhou, Deqing, Anji, Changxing, most of Hangzhou city and parts of Lin'an. The counties vary in area with Anji having the largest area with 1705.99 km^2 and Haiyan the smallest at 539.85 km^2. Typical of regions in Southeast China, the watershed, covering 6390.8 km^2, is densely covered with drainage ditches that form a network waterway. The major soil groups within the HJH, as defined by the Food and Agriculture Organization of the United Nations' (FAO) soil classification (FAO, 1995), are acrisols, cambisols, gleysols, and vertisols. Fig. 2 displays a regional soil map obtained from the FAO (1995) and Table 1 shows their median values for selected topsoil properties. Though acrisols, cambisols, gleysols, and vertisols have some different soil properties, they are all with high water table and Eh and important for rice production (*Oryza satiya*). A paddy soil refers to any type of soil used or potentially usable for growing aquatic rice. The term 'paddy soil' is ambiguously used to signify lowland rice soils (Kyuma, 2004). As stated above, the term 'paddy soil' is related only to land use and not to any strict definition of soil in the pedological sense. Eswaran et al. (2001) listed all

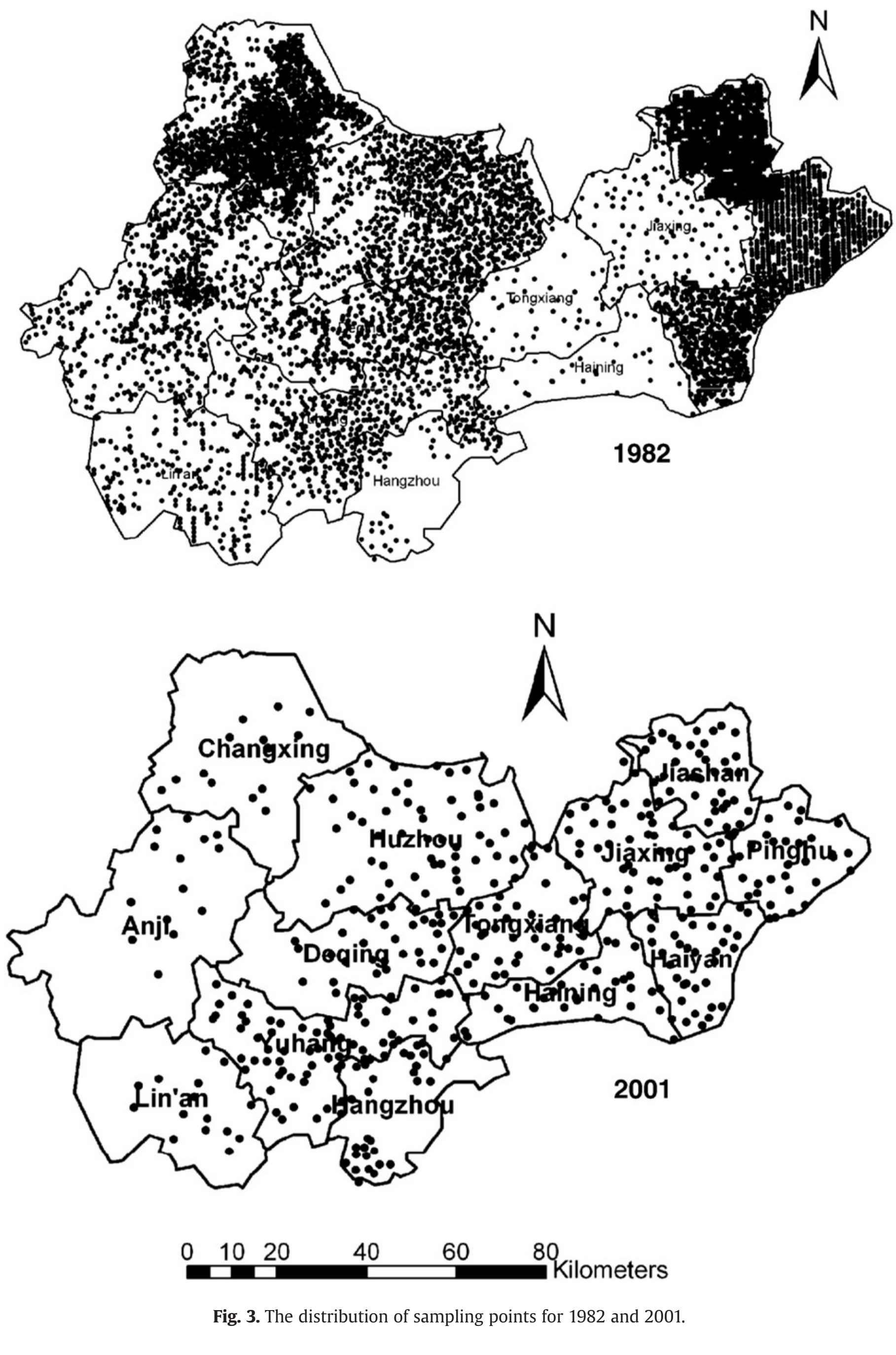

Fig. 3. The distribution of sampling points for 1982 and 2001.

Table 2
Classification of soil nutrients in Zhejiang Province and their separate weights given by Zhejiang soil science experts.

Soil properties	Weight	Classification					
		High		Middle		Low	
		1	2	3	4	5	6
SOM/g kg^{-1}	0.625	>50	40–50	30–40	20–30	20–10	≤10
AP/mg kg^{-1}	0.1365	>40	30–40	20–30	20–10	10–5	≤5
AK/mg kg^{-1}	0.2385	>150	100–150	80–100	50–80	30–50	≤30

soil orders in Soil Taxonomy (1999) except gelisols as soils potentially used for paddy rice cultivation. Therefore, for this paper, acrisols, cambisols, gleysols, and vertisols are terms used as “paddy soil” synonymously.

2.2. Soil sampling and missing survey data treatment

Soil samples were collected from the HJH watershed at depths of 0–20 cm in 1982 and 2001. In 1982, 6343 soil samples were taken from various locations within the HJH watershed (excluding data from Tongxiang, Haining, and Hangzhou) and were georeferenced by scanning the sampling location map and digitized with the topographic maps in the same area. In 2001, based on field accessibility and available GPS technology, a georeferenced sampling scheme was used to locate 460 sampling locations in similar locations as the 6343 samples taken in 1982. Selection of the sampling sites in the year 2001 was based on a statistical analysis of the sampling sites of 1982 through an analysis of the uniformity of soil sample distribution and soil types in the area. Due to the lack of database management in 1982, the survey data of Tongxiang, Haining, and Hangzhou were lost.

In order to compare the nutrient change pattern for the entire region, the following criteria was established for the treatment of missing survey data. Because the counties with missing data have similar land use (rice agriculture) and soil properties (eutric and mollic gleysols with high water table and low Eh) as their neighboring counties (Fig. 2 and Table 1), it is reasonable to assume that there is a similarity in patterns of nutrient change between these areas. Although it is understood that this procedure would introduce uncertainty in the results within an acceptable degree, the method allowed us to investigate the spatial variations of the nutrient distribution before and after the altered land tenure systems. In order to minimize this uncertainty, we used the difference between average data of few adjacent counties to estimate the missing data in Tongxiang, Haining, and Hangzhou. For Tongxiang, the difference between the average values of soil organic matter (SOM), total nitrogen (TN), available phosphorus (AP), and available potassium (AK) in Huzhou, Jiaxing, and Deqing in 1982 and 2001 were calculated, and the missing data in 1982 were estimated to determine the absolute values of the soil properties using the following equation:

$$X_m = X_{2001} - D \tag{1}$$

where X_m is the value for missing data in 1982; X_{2001} is the sample data in 2001; D is the difference between the average values of soil nutrients in Huzhou, Jiaxing, and Deqing in 1982 and 2001. Similar methods were followed for Haining and Hangzhou, with data from the adjacent counties of Haiyan and Yuhang used for Haining, and data from the adjacent county of Yuhang used for Hangzhou. In order to make a scientific comparison between the two soil surveys, the 1982 survey was sampled with the same number of samples as the 2001 survey for temporal comparison. Distribution of sampling points is presented in Fig. 3.

2.3. Analytical methods

All soil samples were air-dried and ground to pass a 2-mm sieve for analyzing SOM, TN, AP, and AK. The SOM was determined by the potassium dichromate wet combustion procedure (Agricultural Chemistry Committee of China, 1983). The TN was measured by Kjeldahl method (Agricultural Chemistry Committee of China, 1983). The AP (Olsen-P) was extracted using 0.5 mol L^{-1} $NaHCO_3$ (pH = 8.5) and the P concentration in the extract was determined using the molybdenum-blue method (Agricultural Chemistry Committee of China, 1983). The AK was extracted using 1.0 mol L^{-1} NH_4OAc (pH = 7) and measured using flame emission spectrometry (Agricultural Chemistry Committee of China, 1983).

2.4. Statistical methods

2.4.1. Outliers treatment

Outliers can cause a distortion of data distribution that may violate geostatistical theory (Barnett and Lewis, 1994). In this study, outliers are defined as any data value greater than three standard deviations from the mean ($A \pm 3s$, where A denotes the average value for each soil property and s is the standard deviation). Outliers greater than $A + 3s$ and lower than $A - 3s$ were then replaced with the maximum and minimum values in the new dataset, respectively. The replacement of outliers with maximum and minimum values was needed for kriging analysis, as too many outliers will make the variogram erratic (Armstrong and Boufassa, 1988).

2.4.2. Geostatistics

The main application of geostatistics in soil science is the estimation and mapping of soil attributes in unsampled areas (Goovaerts, 1999). Kriging, a geostatistical technique, is a linear interpolation procedure

Table 3
The statistical values of soil properties.

Soil properties	Year	Mean	Minimum	Maximum	SD[a]	Kurtosis	Skewness	CV[b]/%
SOM[c]/g kg^{-1}	1982	28.67	6	54	8.44	−0.24	−0.079	29.44
	2001	34.04	10.92	61.4	9.16	−0.05	−0.19	26.91
TN[d]/g kg^{-1}	1982	1.67	0.43	2.9	0.44	0.43	−0.29	26.35
	2001	2.01	0.64	3.29	0.50	−0.19	−0.21	24.87
AP[e]/mg kg^{-1}	1982	8.34	3	30	5.13	4.56	2.01	61.51
	2001	11.86	2.01	46.63	10.08	3.58	1.96	85.02
Logarithm of AP	1982	0.86	0.48	1.48	0.22	0.081	0.67	25.58
	2001	0.96	0.30	1.67	0.31	−0.37	0.49	32.02
AK[f]/mg kg^{-1}	1982	88.6	17.84	211	37.18	1.06	1.04	41.96
	2001	73.73	16.27	177.88	30.17	2.005	1.226	40.93
Logarithm of AK	1982	1.91	1.25	2.32	0.18	−0.051	−0.035	9.42
	2001	1.83	1.21	2.25	0.17	0.63	−0.17	9.46

[a] SD, standard deviation.
[b] CV, coefficient of variation.
[c] SOM, soil organic matter.
[d] TN, total nitrogen.
[e] AP, available phosphorus.
[f] AK, available potassium.

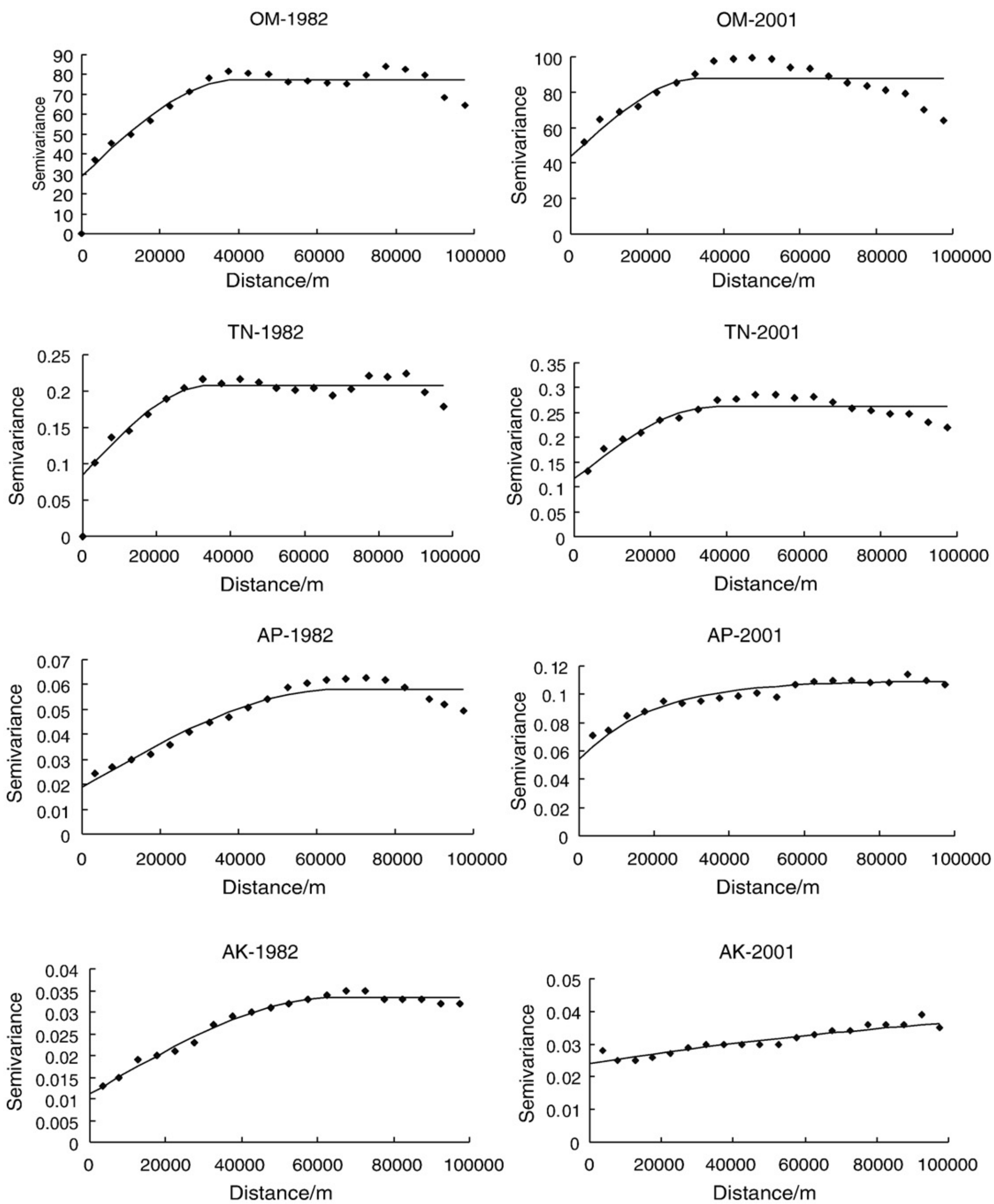

Fig. 4. Experimental semivariograms of soil nutrients in 1982 and 2001 with fitted models.

that provides a best linear unbiased estimator for quantities that vary in space. The procedure provides estimates at unsampled sites. Kriging estimates are calculated as weighted sums of the adjacent sampled concentrations. That is, if data appear to be highly continuous in space, the points closer to those estimated receive higher weights than those farther away (Cressie, 1990).

Table 4
Best-fitted semivariogram models for soil properties and their parameters.

Soil properties	Date	Model	C_0 Nugget	$C+C_0$ Sill	$C_0/C+C_0$ Nugget/Sill	Range/m	r^2
SOM/g kg^{-1}	1982	Spherical	28.9	77.48	37.3	39,600	0.884
	2001	Spherical	43.9	87.81	50	33,600	0.742
TN/g kg^{-1}	1982	Spherical	0.0847	0.207	40.84	37,500	0.894
	2001	Spherical	0.117	0.262	46.2	36,400	0.803
AP/mg kg^{-1}	1982	Spherical	0.0189	0.058	32.58	65,300	0.836
	2001	Exponential	0.054	0.11	49.1	59,700	0.927
AK/mg kg^{-1}	1982	Spherical	0.0111	0.0334	33.23	65,300	0.987
	2001	Linear	0.024	0.048	50	/	0.894

The study employed a geostatistical analysis to determine the spatial patterns of soil nutrients for the 1982 and 2001 datasets. Semivariograms were developed using GS$^+$ version 7.0 (Geostatistics for the Environmental Sciences) to establish the degree of spatial dependency of soil nutrients among data points and to establish the range of spatial dependence for the soil nutrients. Information generated from the semivariogram was used to calculate sample weighing factors for spatial interpolation by a kriging procedure in the Geostatistical Analyst extension in ArcGIS 9.0.

Semivariance, $\gamma(h)$, is computed as half the average squared difference between the components of data pairs (Wang, 1999; Goovaerts, 1999) using the formula:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \tag{2}$$

where $N(h)$ is the number of data pairs separated by a distance h, Z is the measured value for soil property at the spatial position x.

Several standard models are available to fit the experimental semivariogram including spherical, exponential, Gaussian, linear and power models (Wang, 1999). For the analysis in this study, we

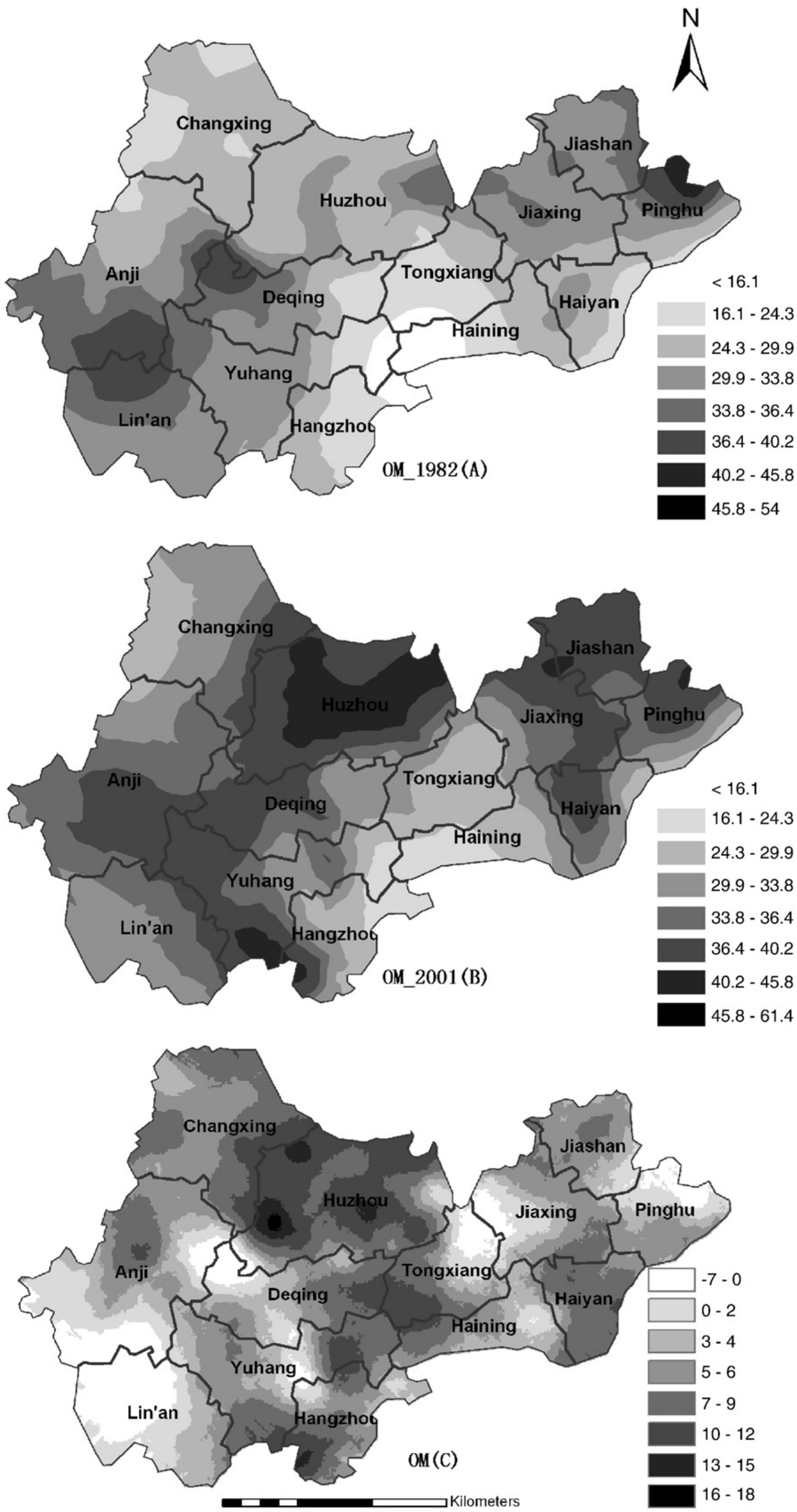

Fig. 5. The spatial distribution maps (produced by ordinary kriging) of SOM, TN, AP and K for 1982 (A), 2001 (B) and the changes of soil nutrients concentration during the period 1982–2001 (C).

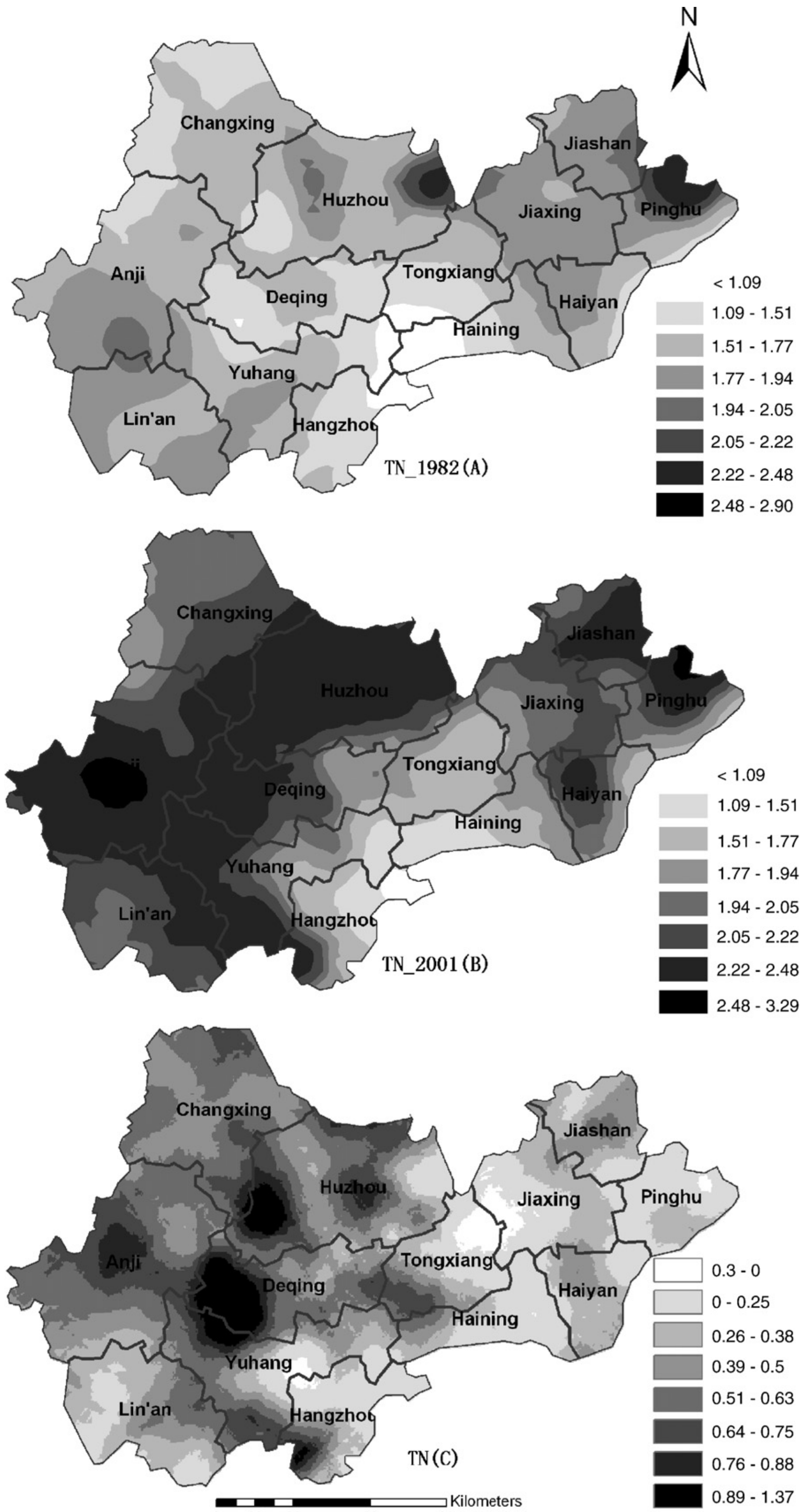

Fig. 5 (*continued*).

used the semivariogram model with the greatest r^2 value for the estimation of semivariogram parameters. As a result, the fitted spherical model, exponential model and linear model were chosen. The models and parameters such as nugget variance (C_0), structural variance (C), and sill (C_0+C) are discussed in more detail in Wang (1999).

Typically, the semivariance increases with increasing lag distances to approach or attain a maximum value or sill (C_0+C) that is equivalent to

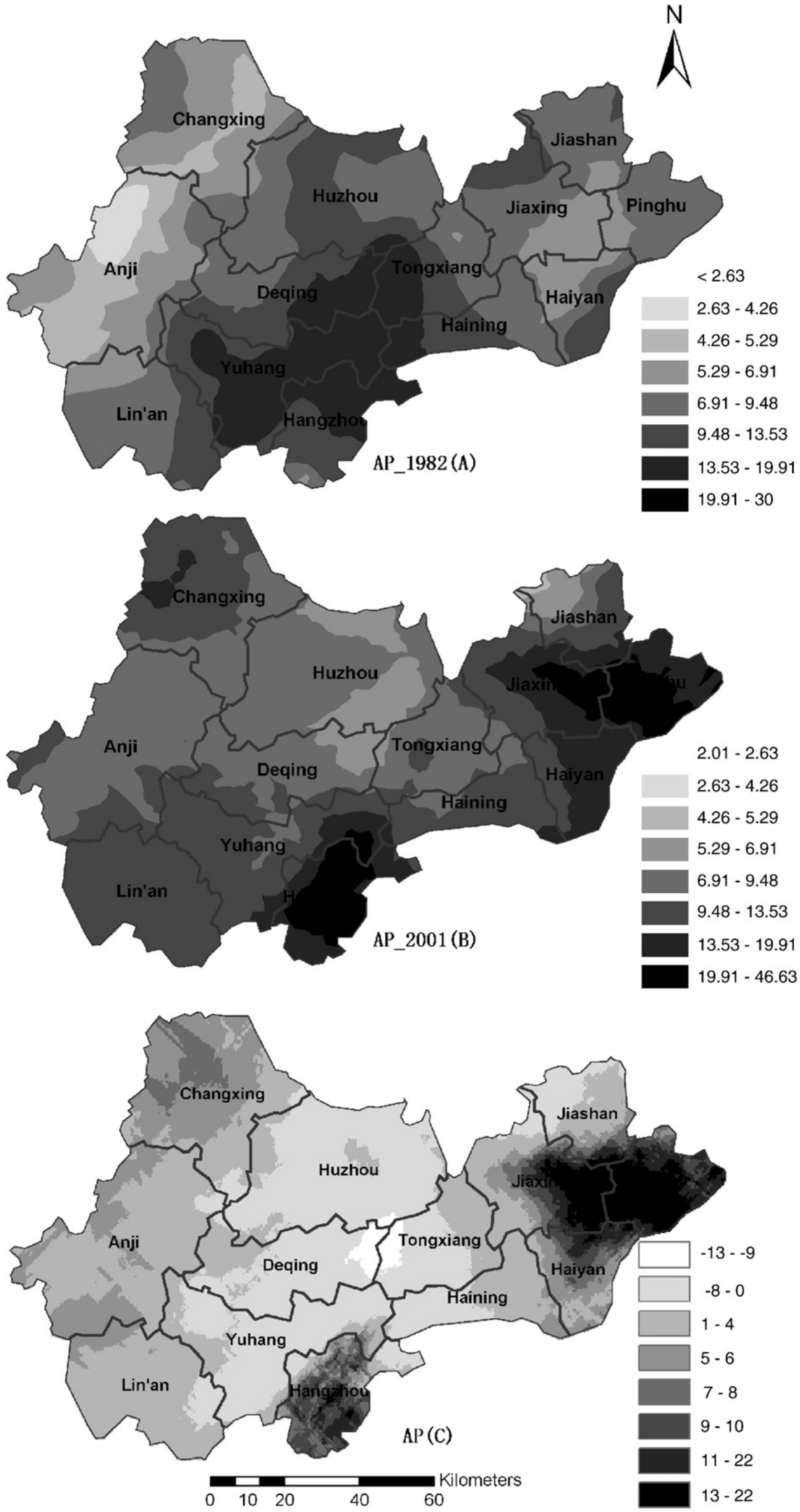

Fig. 5 (*continued*).

the population variance. The nugget/sill ratio can be regarded as a criterion to classify the spatial dependence of soil properties. If the ratio is less than 25%, the variable has strong spatial dependence, between 25% and 75%, the variable has moderate spatial dependence, and greater than 75%, the variable shows only weak spatial dependence (Chien et al., 1997).

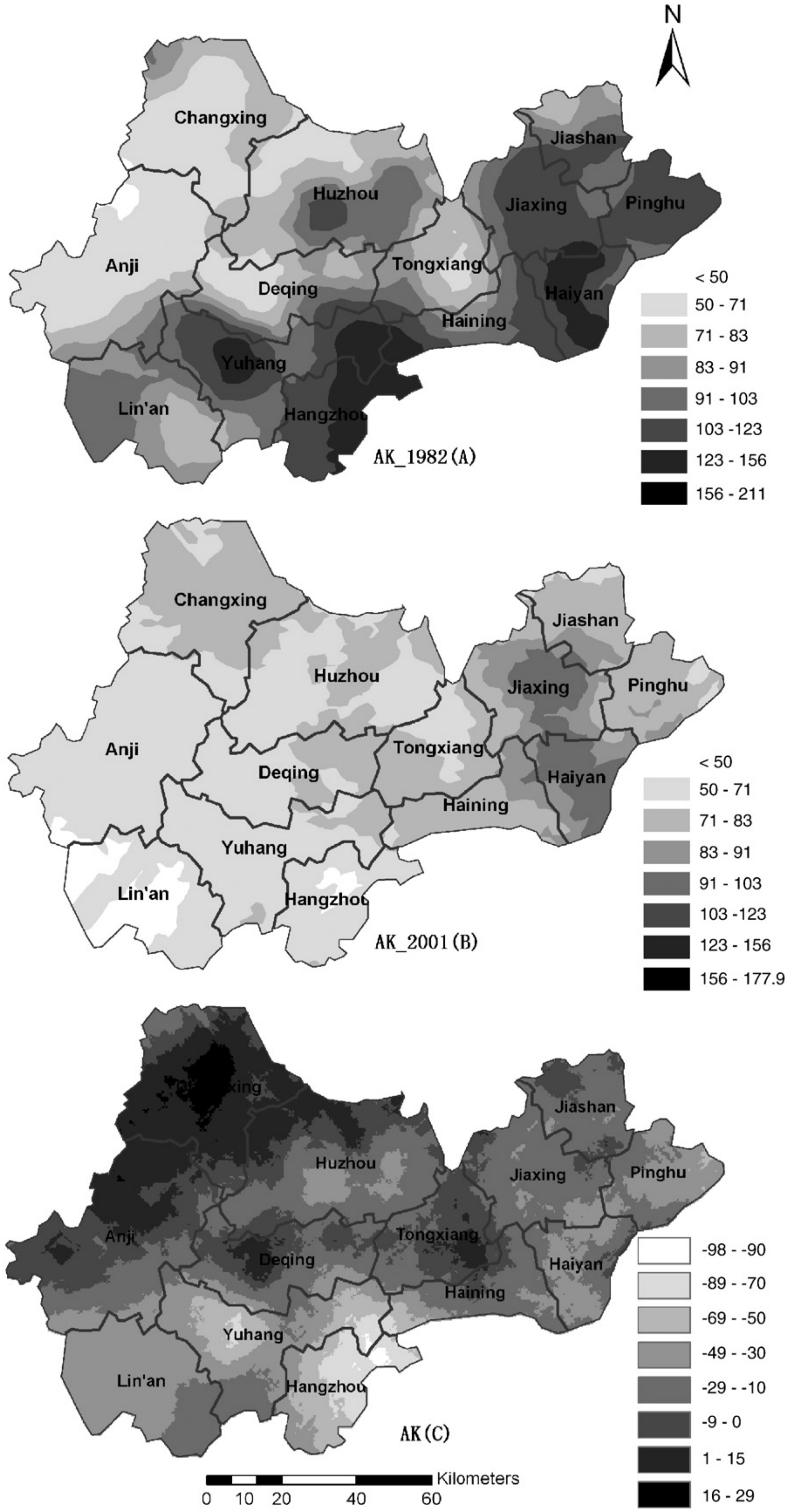

Fig. 5 (*continued*).

2.5. Single factor assessment and comprehensive appraisement

During the project of arable soil survey and evaluation, soil science experts gathered together and established a classification standard for soil nutrients in Zhejiang Province. This classification standard also includes paddy soils. Soil nutrients such as SOM, AP, and AK were considered as the main controlling factors for soil fertility. TN was not considered to be a main controlling factor. The classification criteria and separate weights determined at this meeting are displayed in Table 2. The membership grades of SOM, AP, and AK can be calculated with the following membership functions that were developed by the soil science experts:

$$\begin{aligned} q_{\mathrm{SOM}} &= 1/\left\{1 + 0.1828 \times (X_{\mathrm{SOM}} - 5.0267)^2\right\} \\ q_{\mathrm{AP}} &= 1/\left\{1 + 0.00345 \times (X_{\mathrm{AP}} - 28.0641)^2\right\} \\ q_{\mathrm{AK}} &= 1/\left\{1 + 0.000128 \times (X_{\mathrm{AK}} - 164.5)^2\right\} \end{aligned} \quad (3)$$

where q is the value of single factor assessment and X is the sample value.

The comprehensive index for soil nutrient (IFI) was calculated by the following function:

$$IFI = \sum(q_i \times w_i) \quad (4)$$

where q_i is the membership grade for soil nutrient factor at location i and w_i is the weight. The values for IFI range from 0 to 1. The closer the *IFI* value is to 1, the higher the soil fertility.

Based on the 6 classification criteria in Table 2, we gave the values of 50, 40, 30, 20, and 10 to X_{SOM}, 40, 30, 20, 10, and 5 to X_{AP}, 150, 100, 80, 50, and 30 to X_{AK}, respectively. Their corresponding thresholds of single factor assessment (q) and comprehensive appraisement (IFI) for SOM, AP, and AK were calculated using Eqs. (3) and (4). Also, the q value for each soil property in the 460 locations in 2001 was calculated by Eq. (3) and the corresponding IFI value by Eq. (4). The spatial pattern map of soil comprehensive fertility was delineated using 460 IFI values by kriging interpolation.

3. Results

3.1. Statistical characterization of data

Descriptive statistics including mean, maximum, minimum, standard deviation, kurtosis, skewness and CV for SOM, TN, AP, and AK are given in Table 3. For both datasets of 1982 and 2001, the SOM and TN were normally distributed. AP and AK were not normally distributed and further analyzed upon their logarithmically transformed data. From 1982 to 2001, the mean values of the SOM, TN, and AP increased from 28.67 g kg^{-1} to 34.04 g kg^{-1}, 1.67 g kg^{-1} to 2.01 g kg^{-1}, and 8.34 mg kg^{-1} to 11.86 mg kg^{-1}, respectively. Conversely, the AK sharply declined from 88.6 mg kg^{-1} in 1982 to 73.73 mg kg^{-1} in 2001.

The CV values of measured soil properties ranged from 24.87 for TN in 2001 and 85.02 for AP in 2001, and the variability of soil properties within the study site was classified as medium (15%–75%) except for the AP in 2001, which had a high variability (>75%). The groupings are based on the CV values described by Dahiya et al. (1984). In general, the CV values of SOM, TN, and AK all declined during 1982–2001 (Table 3).

3.2. Geostatistical analysis of spatial variability

Fig. 4 displays the semivariogram and fitted models for each soil property. The attributes of the semivariograms for the 1982 and 2001 data are summarized in Table 4.

In the 1982 dataset, the semivariograms for the SOM, TN, AP, and AK were all well fitted with a spherical model. The semivariograms for SOM and TN for the 2001 dataset were also fitted with a spherical model, while the AP and AK were fitted using an exponential model and a linear model, respectively.

Table 4 shows that the nugget/sill ratios for all soil properties in 1982 and 2001 range from 32.58% to 50% with moderate spatial dependence. The nugget variance for 2001 data all increased which resulted in higher nugget/sill ratios than in 1982. Meanwhile, the spatial correlation range values for SOM, TN, and AP in 2001 all decreased. The spatial correlation distance is undefined for soil AK in 2001 within the active lag distance of 100 km.

Table 5
The membership grades for soil nutrients and their corresponding IFI values.

SOM/g kg^{-1}	AP/mg kg^{-1}	AK/mg kg^{-1}	q_{SOM}	q_{AP}	q_{AK}	IFI
50	40	150	0.9998	0.6705	0.9738	0.95
40	30	100	0.8384	0.9872	0.6525	0.8
30	20	80	0.5712	0.8168	0.5225	0.6
20	10	50	0.3739	0.4704	0.3734	0.4
10	5	30	0.2523	0.3527	0.3016	0.3

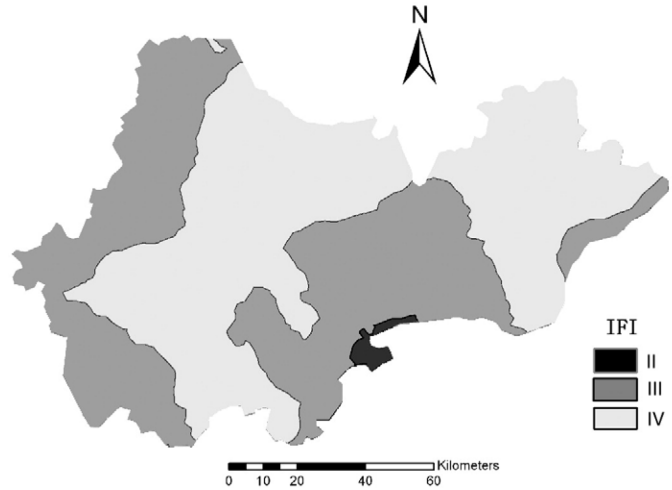

Fig. 6. Classification map for soil fertility in HJH watershed in 2001.

3.3. Temporal changes of spatial patterns over 1982–2001

The spatial patterns of different soil nutrients for 1982 and 2001 and the changes of soil nutrients concentrations during 1982–2001 are presented in Fig. 5. The high and low concentration spatial patterns of SOM and TN in 1982 and 2001 displayed similar patterns. Low SOM concentrations were found in the southeastern area due to the low soil carbon (SC) of pellic vertisols near the Hangzhou Gulf (Fig. 2 and Table 1). Fig. 5 shows higher AP concentrations in 2001 for nearly the entire watershed. There have also been large temporal changes for AK between 1982 and 2001. The AK concentrations in majority of the study area decreased, which agrees with the declining K fertilization in recent years.

3.4. Comprehensive appraisement of soil fertility

The results of the single factor assessment and the corresponding comprehensive index (IFI) for SOM, AP, and AK according to their classification are displayed in Table 5. The thresholds of IFI are 0.95, 0.8, 0.6, 0.4, and 0.3. Therefore, the soil comprehensive fertility can be classified into the following 6 grades: I (IFI>0.95), II (0.8<IFI≤0.95), III (0.6≤IFI<0.8), IV (0.4≤IFI<0.6), V (0.3≤IFI<0.4), and VI (IFI<0.3).

Fig. 6 presents the comprehensive appraisement result of soil fertility based on the IFI classification. The soil fertility in the HJH watershed in 2001 can be classified into three grades: II (0.8–0.95), III (0.6–0.8), and IV (0.4–0.6). The majority of the soils in the study site are of medium fertility (grades III–IV) and a small portion of soils are of rich fertility (grade II), which is distributed southeast of Haining and Hangzhou.

4. Discussion

4.1. Temporal changes of classical statistical results

The summary statistics of soil quality indicators show that land management change has a large influence on soil nutrients. In general, intensive farming systems are known to cause a SOM decline resulting from changes to soil structure caused by tillage, removal of biomass, and increased mineralization and decomposition of exposed soils (Collard and Zammit, 2006). It was reported that the average value of SOM in the black soils of Keshan County, Heilongjiang province, decreased from 120 g kg^{-1} to 70 g kg^{-1} after 10 years of cultivation, to 45 g kg^{-1} after 25 years, and to 37 g kg^{-1} after 50 years (General Soil Survey Office, 1995). However, the contradictory SOM results in the HJH watershed may be due to the continuous high moisture content of the paddy soils, which slows down organic matter decomposition and nitrogen mineralization rate (General Soil Survey Office, 1995). The condition of AP and AK was due to the fertilization level during the past 20 years when excessive AP and insufficient AK were applied to the paddy rice fields. Excessive P fertilization enhances the potential of P runoff as well as P saturation within the soil column (Powlson, 1998; Edwards and Withers, 1998). These results show a negative impact on both agricultural and environmental issues.

4.2. Mechanism of spatial variability

The spatial variability of soil properties may be affected by both intrinsic soil formation factors, such as soil parent materials, and extrinsic soil management factors, such as fertilization. Usually, strong spatial dependence of soil properties can be attributed to intrinsic factors, and weak spatial dependence can be attributed to extrinsic factors (Cambardella et al., 1994). Higher nugget/sill ratios were found in 2001 because the extrinsic soil management factors probably weakened the spatial correlation due to the field management by farmers in China after 1982. It was reasonable to see a larger spatial correlation distance for SOM and TN in 1982 because the concentrations became evenly distributed over a long history of land management. Due to the implementation of the HRS, smaller correlation distances were found in the 2001 soil OM and TN samples, which is consistent with their decreasing CV values (Table 3). Lacking any guidance, farmers believed more fertilizer would generate higher yields, causing an uneven distribution of AP and AK concentrations. Generating information on the fertility status of soils, in conjunction with periodic training on proper fertilization rates, will help farmers to better maintain soil quality and long-term agricultural sustainability.

This result indicates a rational sampling distance for SOM and TN within their spatial correlation ranges. For AP, however, it is important to note that the spatial correlation range was larger than in 1982 despite the higher CV value in 2001. AP and AK are greatly affected by fertilization. Additional AP and AK samples should be added or auxiliary data could be used to improve their estimate accuracy. The understanding of the spatial patterns of soil properties could suggest grouping soils in order to obtain uniform regions of soil properties suitable for different management strategies and soil quality evaluation (Yost et al., 1982). It is notably pointed out that the spatial variance on a small-scale field could be covered on the condition of large scale (Webster, 1985; Isaaks and Srivastava, 1989).

4.3. Temporal changes of spatial patterns

Temporal changes of the spatial patterns of soil nutrients due to an altered land tenure system are apparent in the results. Since soil TN is known to be highly correlated with SOM, it was not surprising that the results of this analysis also revealed the two variables as having similar spatial patterns (Fig. 5). Therefore, with the altered agricultural practices during the past 20 years, the SOM and TN concentrations became evenly distributed throughout the watershed. What is most obvious in the maps is that both SOM and TN concentrations in the southeastern area were higher than before, offering further proof of the effect of extrinsic factors such as the application of both inorganic fertilizer and organic manure on the intrinsic factors relating to soil quality (Zhejiang Soil Survey Office, 1994). The temporal changes of AP and AK were also significant with much higher P concentrations and lower K concentrations in 2001. Soils in paddy rice fields often have higher P availability than upland soils because of long-term flooding. Under the conditions of long-term flooding, the soil redox potential (Eh) value decreases and reduction ability is enhanced. The iron oxide film out of the occluded phosphorus disappears, resulting in higher P availability. It was reported that the K supporting capability of paddy soils originating from alluvial matter and lacustrine matter in China are weak (General Soil Survey Office, 1995). In the paddy rice fields of this study, the status of long-term flooding may cause a lower Eh, which likely resulted in more K removed by crops.

4.4. Implications for precision agriculture

The spatial distribution of soil nutrients over long distances provides new insight into increasing the efficacy of precision agriculture through implementation of grouping soil management in paddy rice fields. However, knowledge of the comprehensive status for soil nutrients is needed before a proper decision is made for soil appraisement and crop adjustment. The comprehensive assessment result for soil fertility (Fig. 6) supplies valuable information for precision agriculture and crop management, as well as increasing the knowledge base needed for agro-environmental management. The current fertility status indicated a need for a variable rate fertilizer application to balance the existing nutrient ratios. Thus farmer training workshops are needed that can provide a technical overview of the appropriate fertilization amount and product.

5. Conclusions

The study clearly showed the spatio-temporal variability of soil nutrients in paddy rice fields induced by the HRS altered land tenure system. Over a long period of HRS land policy, the spatial variability of soil properties was determined not only based on the characteristics of the soil properties but also on the soil management practices of the fields. It was found that a majority of the agricultural areas under the HRS land policy showed an imbalance between P and K, caused by a lack of fertilizer application guidance. The CV values of soil nutrients decreased slightly in 2001 except for AP, which showed that the HRS altered land tenure system minimized soil variation. However, excessive and uneven P fertilization in the HJH watershed resulted in higher CV of AP. Under the long time span of variable extrinsic factors such as fertilization practices, the nugget variance for 2001 data increased, which resulted in higher nugget/sill ratios than that of 1982. The range values of soil nutrients in 2001 decreased. Additional samples should be added or auxiliary data could be used to improve the estimate accuracy for AP and AK.

Altered land tenure system has a distinct effect on soil nutrients. Soil spatio-temporal variations, in turn, can present management challenges to farmers, further affecting the land management policy. The temporal changes of spatial patterns for SOM, TN, AP, and AK during 1982–2001 should be used as indicators for soil management such as proper fertilization. Conducting research over a large area provided the spatial patterns of soil nutrients over long distances which a small-scale study would fail to accomplish. The obtained understanding of soil nutrient variations can help with crop modeling (Pan, 1998), in addition to helping with soil precision management, soil survey and evaluation.

Based on the soil nutrient classification criteria and their separate weights in Zhejiang Province, the comprehensive index for soil nutrients (IFI) was calculated after the single factor assessment for each factor. The entire watershed was classified into three site-specific management zones with dominant medium fertility (grades III–IV) and a small portion of rich fertility (grade II). The comprehensive appraisement of soil fertility gives important implications for site-specific agricultural management.

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