



Climate and soil management factors control spatio-temporal variation of soil nutrients and soil organic matter in the farmland of Jiangxi Province in South China

Bifeng Hu^{1,2} · Modian Xie^{1,2} · Hongyi Li^{1,2}  · Rebin He¹ · Yue Zhou³ · Yefeng Jiang^{1,2,4} · Wenjun Ji⁵ · Jie Peng⁶ · Fang Xia⁷ · Zongzheng Liang⁸ · Wanming Deng¹ · Junjie Wang¹ · Zhou Shi^{5,9}

Received: 14 May 2022 / Accepted: 17 February 2023 / Published online: 3 April 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Purpose This study aims to explore the spatio-temporal variation of soil nutrients as well as soil organic matter (SOM), and clarify the role of environmental and soil management factors in determining soil nutrients and SOM in farmland over Jiangxi Province of Southern China.

Materials and methods Between 2005 and 2012, we collected 16,504 surface soil samples (0–20 cm) from farmland across Jiangxi Province. Based on this soil dataset, we summarized the changes in SOM, alkali-hydrolyzable nitrogen (available N), available phosphorus (P), available potassium (K), pH, and cation exchange capacity. Then, we used the geostatistical method to explore and map the spatio-temporal variability of SOM, and available N, P, and K. Finally, the random forest algorithm was used to identify the main factors controlling the variation of SOM and available N, P, and K.

Results and discussion Our results revealed a clear right-skewed trend for the histogram of available P and K, pH, and cation exchange capacity in farmland soil of Jiangxi Province. From 2005 to 2012, the average concentrations of SOM and available P showed an insignificant decreasing temporal trend in the farmland of Jiangxi Province. The average concentrations of available N and available K showed a significant increasing trend between 2005 and 2012. In general, most of the soil samples had SOM, available N and P content at or above the level of Class 3 (high grade), and available K at or below the level of class 4 (moderate grade). The apparent lack of K fertility was detected. Regarding the spatio-temporal variation pattern, noticeable changes in the concentrations of SOM and available N, P, and K were detected in most of the region in 2012 when compared with 2005.

Conclusion Farmland soils in Jiangxi Province had good fertility, and soil nutrients and SOM in farmland showed strong spatial variability. Overall, the climate (e.g., mean annual precipitation and mean annual temperature) and soil management (e.g., straw return and chemical fertilizer application) had dominant effects on soil nutrients and SOM, while other factors such as relief and soil properties had slight effect. The straw return is a sustainable way to improve soil fertility. Moreover, soil pH has a slight impact on soil nutrients and SOM. Great efforts are needed to prevent farmland soils from further acidification.

Keywords Spatial–temporal trend · Farmland · Random forest · Influencing factors · Soil management

Responsible editor: Caixian Tang

Highlights

- The content of SOM and available P showed insignificant decreasing trend in the farmland soil between 2005 and 2012.
 - The content of available N and K showed significant increasing trend in farmland between 2005 and 2012.
 - Strong spatio-temporal variation was detected for the soil nutrients and SOM.
-

Extended author information available on the last page of the article

1 Introduction

Soil nutrients and soil organic matter (SOM) play a critical role in soil quality, plant growth, and nutrient cycling in the ecosystem, and they are closely correlated with soil productivity (Hu et al. 2021a; Farooq et al. 2021). Crop development mainly depends on the availability of soil nutrients and SOM. Soil nutrients including nitrogen (N), phosphorus (P), and potassium (K) as well as SOM are recognized as the most

critical mineral components for plants and microorganisms (Hu et al. 2021a). In addition, SOM, N, P, and K are closely related to a variety of current environmental issues such as carbon sequestration, carbon neutralization, and eutrophication (Hu et al. 2021b; Huang et al. 2021). Therefore, accurate information related to the spatial–temporal variability and factors determining soil nutrients and SOM in farmland is critical for soil management and agricultural production. However, the farmland ecosystem is usually complex due to varying conditions (e.g., crop types, soil management practices, topography, geomorphology and lithology heterogeneity, climate factors) (Fu et al. 2021; Wu et al. 2021). All of these lead to significant spatial heterogeneity of the soil nutrients and SOM (Yan et al. 2021a, b).

Many researchers have conducted studies to analyze the spatial or spatio-temporal variability of soil nutrients and SOM in various terrestrial ecosystems of different regions around the world (Granger et al. 2021; Zhou et al. 2021). Geostatistical methods have proved to be an effective tool to reveal the spatial variation of soil properties; hence, it has been broadly used to predict spatial distribution of soil properties at various spatial scales (Hu et al. 2019; Sheng et al. 2022). However, the high spatial heterogeneity of soil nutrients and SOM, coupled with the limited observations, leads to tremendous uncertainty in predicting spatial–temporal variation of soil nutrients and SOM, primarily when the study was conducted at a large spatial scale. At the same time, there is growing interest in exploring environmental factors (e.g., climate, relief properties) and anthropogenic activities which determine the variation of soil nutrients and SOM (Souza and Billings 2021). Previous studies have mainly focused on analyzing the role of natural factors such as climate conditions, terrain properties, and lithology for the variation of soil nutrients and SOM. However, few studies have quantified the influence of anthropogenic factors like straw return and chemical fertilizer input on the variation of soil nutrients and SOM in farmland (Farooq et al. 2021; Souza and Billings 2021). Moreover, the correlations between the soil properties and environmental as well as anthropogenic factors are very complex (Peng et al. 2019; Liu et al. 2022); thus, more robust and flexible methods are urgently needed to capture complicated and non-linear relationships between soil properties and their possible controls. Therefore, understanding spatio-temporal variation of soil nutrients as well as SOM, and identifying its potential controls is of great importance and crucial for implementing efficient and reasonable soil management measures to enhance soil fertility and promote agricultural production.

Jiangxi Province has a farmland area of 27,216 km² and produced 21.9 million tons of grain in 2021. Yet, to meet the increasing demand for food, the large amount of chemical fertilizer is applied and the farmland is intensively cultivated to improve food production. Therefore, it is of great

importance to explore the spatio-temporal variation and potential controls of soil nutrients and SOM in the farmland of Jiangxi Province. However, current information on the spatio-temporal variation and possible controls of soil nutrients and SOM is still far from demand.

Therefore, in this study, we aim to explore the spatio-temporal variation of SOM, and available N, P, and K between 2005 and 2012 in farmland throughout Jiangxi Province. In addition, we identified the most important variables (e.g., straw return, chemical fertilizer input, precipitation, temperature, soil properties) which affect the variation of SOM, and available N, P, and K. Finally, specific recommendations were put forward. The results obtained from this study were expected to provide critical information for making scientific and efficient farmland management policies as well as enhancing food production. We hypothesized that (1) the soil nutrients and SOM were largely affected by soil management measures, relief, soil properties, and climatic conditions; (2) the spatial distribution of soil nutrients and SOM is uneven in farmland of Jiangxi Province; (3) substantial spatial–temporal variation of soil nutrient concentration is expected due to the long-term effect of different soil management measures, relief factors, soil properties, and climatic condition; and (4) the machine learning methods could well capture the relationships between the concentrations of soil nutrients and SOM and multiple covariates; hence, it is an excellent tool to identify main factors which determine spatio-temporal of soil nutrients and SOM. This study provides crucial information for understanding the spatio-temporal variations of soil nutrients and SOM in the farmland. In addition, it will allow for the optimization of farmland management strategies and policy decisions.

2 Materials and methods

2.1 Study area

We conducted this study in Jiangxi Province, which is situated in Southern China. The Jiangxi Province is geographically located between 24°29'14"N–30°04'41"N and 113°34'36"E–118°28'58"E (Fig. 1). The total area of farmland in Jiangxi Province is 27,216 km², among which the areas of paddy field, irrigated farmland, and dry farmland are 22,705, 41, and 4470 km², respectively (https://bnr.jiangxi.gov.cn/art/2021/12/29/art_35804_3,810,534.html) (Fig. S1). Jiangxi Province is characterized by a humid subtropical climate, with hot, rainy summers and chilly, dry winters. The mean annual temperature of Jiangxi Province ranges from 16.3 to 19.5 °C, and the annual precipitation varies between 1341 and 1943 mm.

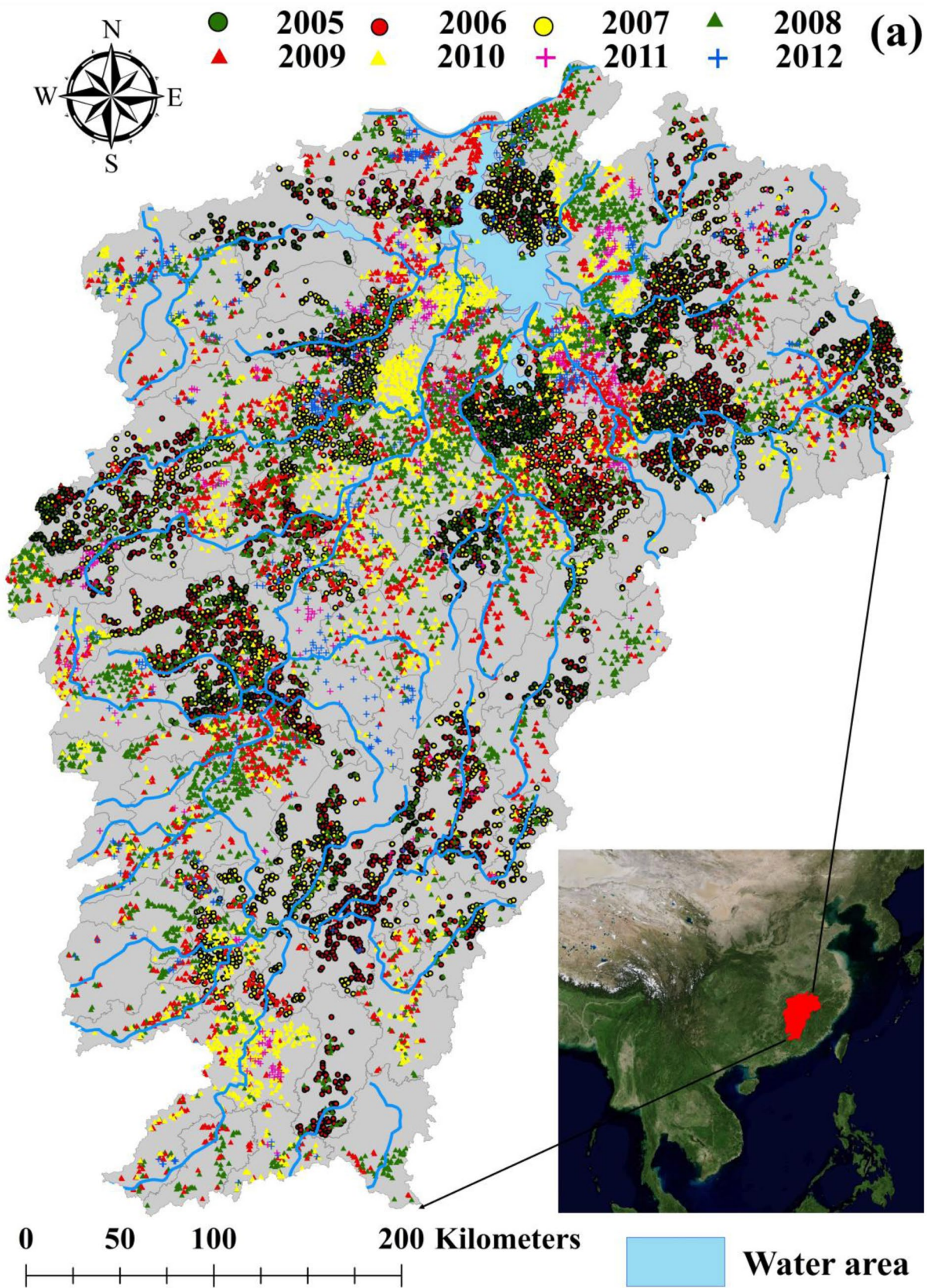


Fig. 1 Map of sampling locations

2.2 Data collection and chemical analysis

An extensive survey was conducted in farmland across Jiangxi Province. A total of 16,504 surface (0–20 cm) soil samples were collected between 2005 and 2012 under the framework of the soil testing and formulated fertilization project which was organized by the Department of the Ministry of Agriculture and Rural Affairs of China. The representative soil samples were randomly collected by an “S” shape pattern on each 0.3–0.5 km² plot. At each plot, five subsamples (with a depth of 20 cm) within a 100-m radius were collected, and thoroughly mixed to obtain a composite sample of around 1 kg after removing the surface litter. The sampling locations were recorded using a portable global positioning system. Then, the tone and large roots were removed. All soil samples were air-dried, crushed using a mortar and a pestle, and then sieved through a 20-mesh nylon screen (1 mm aperture size) to determine the concentration of SOM, and available N, P, and K. The SOM concentration was determined by the dichromate oxidation method of Walkley–Black (Nelson and Sommers 1983). The available N was extracted with KCl and measured by alkaline hydrolysis diffusion method (Spargo and Alley 2008). The available P was extracted using sodium bicarbonate and the concentration was determined by the molybdenum blue method (Bao 2000). The available K was determined by spectrophotometry and flame photometry (Bao 2000; Hu et al. 2021b). Soil pH was analyzed by potentiometer at a soil/water ratio of 1:2.5 referring to the national standard (NY/T 1377–2007) regulated by the Chinese government (Bao 2000). The bulk density was determined using the cutting ring (5 cm diameter and 5 cm height) method (Liu et al. 2021a, b). The cation exchange capacity was measured using the ammonium acetate method (Schollenberger and Simon 1945). The exchangeable calcium and exchangeable magnesium were measured using ammonium acetate extraction-atomic absorption method (Bao 2000). The soil available silicon was measured using the molybdenum blue colorimetric methods (Wang et al. 2021a, b, c).

Other information about soil properties, soil management, and topography was also recorded when conduct soil sampling (Table S1). The raster data of mean annual precipitation, mean annual temperature, and population density with a spatial resolution of 1 km was downloaded from the Resources and Environmental Sciences Data Center, Chinese Academy of Sciences (RESDC 2017). Relief factors, such as slope, aspect, topographic wetness index, topographic position index, and multi-resolution valley bottom flatness, is calculated based on the DEM data issued by the European Space Agency using SAGA GIS (<http://saga-gis.org/>) software. The Topographic wetness index is a physical indicator to measure

the effect of regional topography on runoff flow direction and accumulation. The Topographic position index is a topographic position classification identifying upper, middle, and lower parts of the landscape. The multi-resolution valley bottom flatness is a topographic index designed to identify areas of deposited material at a range of scales, based on the observations that valley bottoms are low and flat relative to their surroundings and that large valley bottoms are flatter than smaller ones. The landform is recorded according to the expert knowledge when sampling. The landowners provide information on the input of N fertilizer, P fertilizer, K fertilizer, and straw return amount.

2.3 Data analysis

The minimum, maximum, mean value, standard deviation, and coefficient of variation (%) of SOM and available N, P, and K in different years were analyzed using the RStudio (R Development Core Team 2013). Hillel (1980) divided the variability into three classes: weak (< 10%), moderate (10–100%), and strong (> 100%) variability, based on the coefficient of variation value. The statistical analysis and correlation test were employed in RStudio (R Development Core Team 2013). The optimized experimental semi-variograms in different years were fitted using GS + 9.0 software (Gamma Design Software, Plainwell, MI, USA). The random forest models were trained using the *caret* package in RStudio (Liaw 2002). All the maps of soil nutrients and SOM in different years were produced using ArcGIS (ESRI Inc., Version 10.7).

2.4 Geostatistical analysis

We used geostatistical method to analyze the spatial variation and map the spatial distribution of soil nutrients and SOM. The experimental semi-variogram was fitted to indicate the spatial dependence of soil nutrients and SOM. The experimental semi-variogram could be expressed as (Webster and Oliver 2007):

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

where $y(h)$ represents the semi-variance with spatial lag of h , $Z(x_i)$ is the value of variable Z at observed site i , and $N(h)$ means the number of pairs of soil samples with distance lag of h . As one of the most widely used geostatistical methods, the ordinary kriging was used to map the spatial distribution of soil nutrients and SOM using ArcGIS 10.7 software (Hu et al. 2020a).

2.5 Random forest

The random forest is a classical and widely used machine learning method developed by Breiman (2001). It builds a large number of decision trees (500 trees were used in this study) and then combines all the tree to generate a random forest. The final prediction results are the averaged value produced by different individual decision tree. The random forest could model the linear or non-linear relationships between the dependent variable (SOM, and available N, P, and K in this study) and independent variables (like soil management factors, climate condition, terrain properties, soil properties in this study) (Hu et al. 2020b; Munnaf and Mouazen 2022). Moreover, it could quantify the importance of independent variables in the constructed model, according to how much worse the prediction would be if the independent variables were randomly permuted (Chen et al. 2019; Jia et al. 2020; Yan et al. 2020). Breiman (2001) provides the detailed principle of the random forest.

In this study, 24 explanatory variables thought to affect SOM, and available N, P, and K were chosen using an extensive literature review and expert knowledge (Table S1). These variables covered the lithology, climate, relief, soil management, and soil properties. The random forest model was constructed to calculate the relative importance of these variables. The covariates used in this study and corresponding sources are listed in Table S1.

In addition, the relative importance of different variables was calculated by the mean increase in prediction error for out-of-the-bag data, which occur as a result of randomly permuting each variable while leaving all others unchanged (% IncMSE) when running the machine learning models (Xie et al. 2021). The formula is as follows:

$$W_i = \frac{g_i}{\sum_{n=1}^m g_i} \quad (2)$$

where W_i was the relative importance of the i th factor, g_i was the value of %IncMSE for the i th factor, and m was the number of covariates.

3 Results

3.1 Descriptive statistics of soil nutrients and SOM

The average concentration of SOM slightly dropped by 3.6% and decreased from 30.9 to 29.8 g/kg in 2012 when compared with 2005 (Table S2). The mean concentration of available N grown by 7.8% and increased from 155.8 mg/kg in 2005 to 167.9 mg/kg in 2012. In terms of available P, the averaged concentration dropped by 16.4% and decreased from 23.8 mg/kg in 2005 to 19.9 mg/kg in 2012. The mean

concentration of available K slightly improved by 5.1% and increased from 86.0 mg/kg in 2005 to 90.6 mg/kg in 2012. The coefficient of variations of SOM and available N, P, and K varied from 30.7 to 74.7% between 2005 and 2012, which indicates moderate variability of soil nutrients and SOM concentration in the farmland of Jiangxi Province (Hillel 1980).

The mean pH value in the farmland of Jiangxi Province varied between 5.1 and 5.3, which belongs to the acidic grade as regulated by the Office of the National Soil Survey in China (1998). The mean concentration of cation exchange capacity changed between 6.0 and 6.4 cmol/kg. As indicated by the standard issued by the Office of the National Soil Survey in China (1998), it illustrates that farmland soil in Jiangxi Province has a weak ability to maintain fertility. In addition, a right-skewed trend was detected for the histogram of SOM and available N, P, and K, pH, and cation exchange capacity (Table S2, Fig. S2). This means the value of the SOM and available N, P, and K, pH, and cation exchange capacity deviate from the normal distribution. It also indicates that the mean values of the SOM and available N, P, and K, pH, and cation exchange capacity tend to higher than corresponding median values due to existing of a few extremely highly values (Fig. S2).

3.2 Temporal trend of soil nutrients and SOM

The boxplot of SOM and available N, P, and K and fitted temporal trends of mean between 2005 and 2012 are presented in Fig. 2. The averaged concentration of SOM and available P showed insignificant temporal trend between 2005 and 2012 ($p=0.93$), whereas the mean concentration of available N ($p<0.05$) and available K ($p<0.01$) presented a significant increasing trend.

3.3 Geostatistical analysis of soil nutrients and SOM

The optimized fitted semi-variogram models for the SOM and available N, P, and K in different years are listed in Table S3. The high R^2 value of most of experimental semi-variogram models indicate that the fitted semi-variogram models could well reveal the spatial variation of soil nutrients and SOM (Table S3). The exponential model gives the best fit for the experimental semi-variogram models of soil nutrients and SOM in most of the years.

The nugget variance (C_0) represents the experimental error and field variation within the minimum sampling interval (Xia et al. 2019; Hu et al. 2022). The sill is commonly considered to be the variogram value where the variogram points or function flatten off at increasing distance (Webster and Oliver 2007; Xia et al. 2021). The nugget to sill ratio ($C_0/(C+C_0)$, %) represents the proportion of spatial variation caused by random factors. When the $C_0/(C+C_0)$ ratio is less than 25%, it means strong spatial dependence. When the

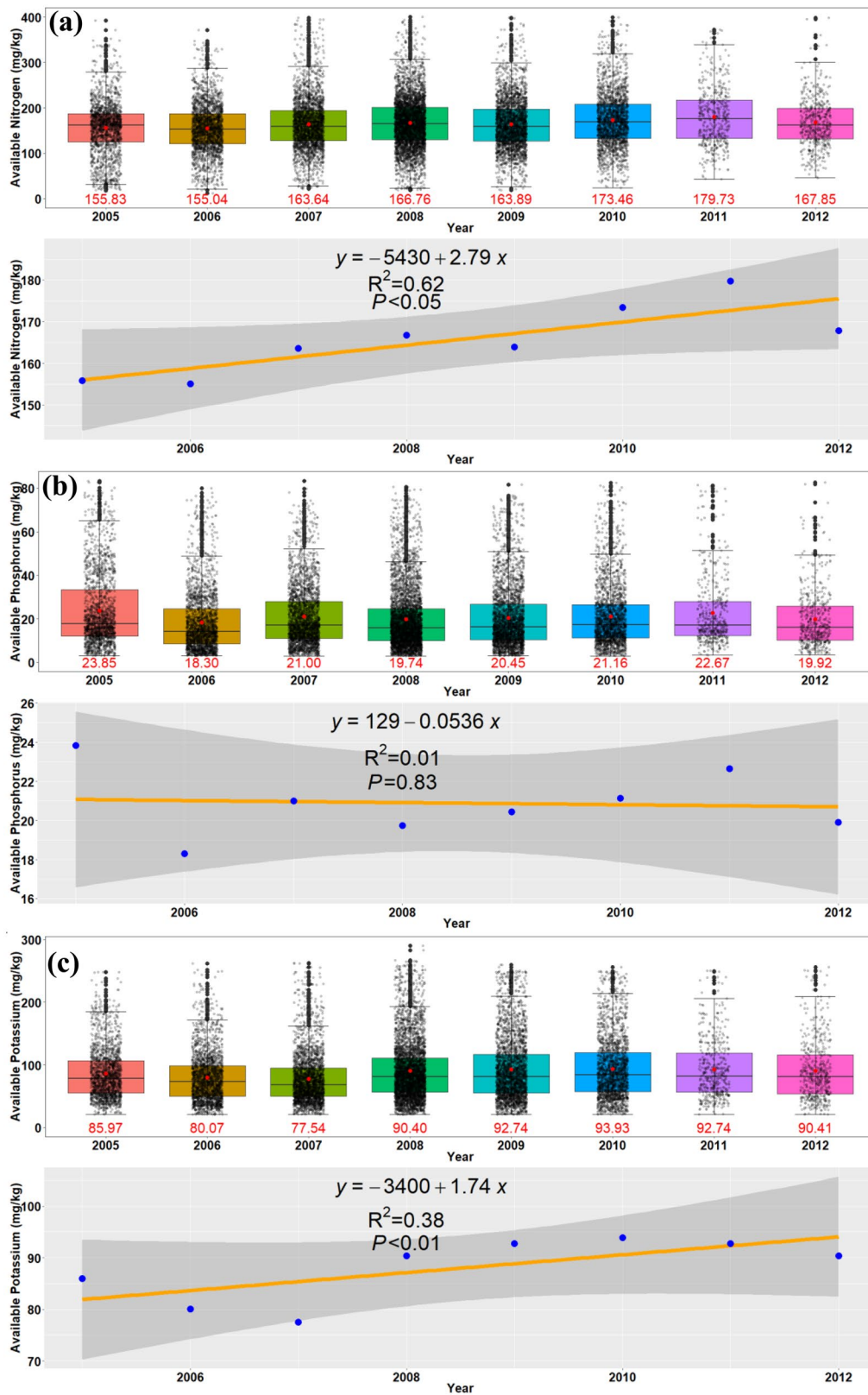


Fig. 2 Temporal trend of soil available nitrogen (a), available phosphorus (b), available potassium (c), soil organic matter (d), pH (e), cation exchange capacity (f) in the farmland of Jiangxi Province. The upper figures are the boxplot of soil properties in each year. The blue point

indicates the mean value of soil properties in each year. The solid orange line indicates the fitted linear temporal trend of each soil property. The grey area means the 95% confidence interval of the fitted temporal trend

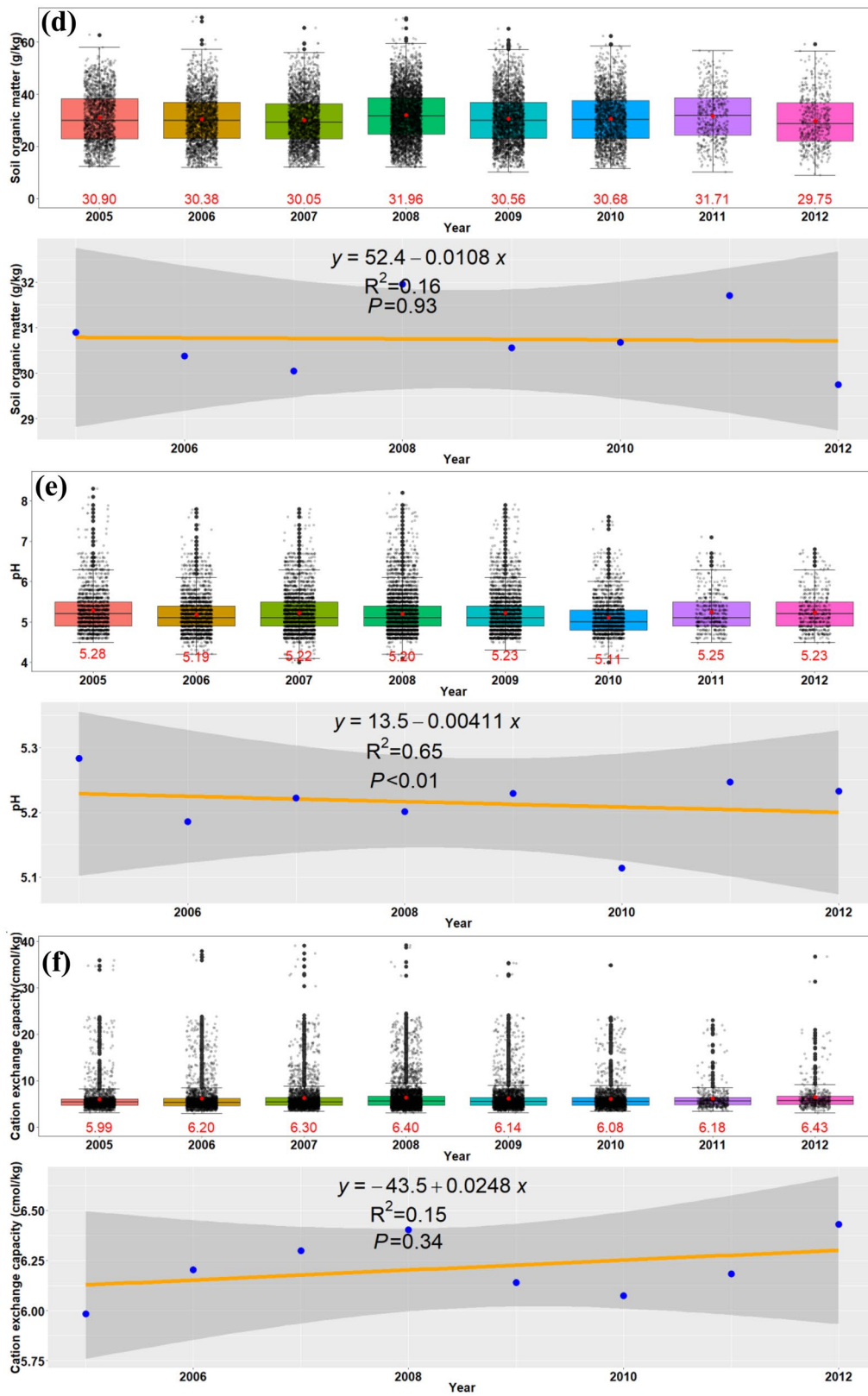


Fig. 2 (continued)

$C_0/(C + C_0)$ ratio is between 25 and 75%, it means moderate spatial dependence. When the $C_0/(C + C_0)$ ratio is larger than 75%, it means weak spatial dependence (Webster and Oliver 2007; Hu et al. 2017). As shown in Table S3, the $C_0/(C + C_0)$ ratio of different soil nutrients and SOM in different years varied between 50.0 and 89.9%. Among which, the $C_0/(C + C_0)$ ratio of available N in 2012 and available P in 2005 and 2012 is the smallest, while the $C_0/(C + C_0)$ ratio of available K in 2008 is the largest. This indicates that the soil nutrients and SOM showed weak to moderate spatial dependency in the farmland of Jiangxi Province.

The spatial range of soil nutrients and SOM in different years changed between 12.8 and 166.2 km. The spatial range of available K in 2011 was the smallest, while the spatial range of SOM in 2012 was the largest. The spatial range of available K showed increasing trend, while the spatial range of SOM, available N, and available P violently fluctuated between 2005 and 2012.

3.4 Spatial–temporal variation of soil nutrients and SOM

3.4.1 Spatial–temporal variation of SOM

Changes were observed for the SOM concentration in different regions between 2005 and 2012 (Fig. 3). The high value of SOM concentration mainly appeared in the central part of Jiangxi Province, while the low value of SOM concentration mainly observed in Northern and Southern regions. As shown in Fig. 3a, the value of SOM clearly decreased from 2005 to 2012 in farmland of the central part of Jiangxi Province, especially in the plain around Poyang Lake, while the SOM concentration in the farmland of the eastern, western, and southeastern parts of Jiangxi Province increased.

3.4.2 Spatial–temporal variation of available nitrogen

The general spatial pattern of available N in farmland of Jiangxi Province keeps stable between 2005 and 2012 (Fig. 4). The high value of available N was mainly detected in the central part of Jiangxi Province, while the low value majorly discretely distributed in western, northern, and southern regions of Jiangxi Province. Great difference was observed for the temporal change of the concentration of available N in different regions. The available N in farmland in the central part of Jiangxi Province decreased. In contrast, the available N in the western and southern region increased between 2005 and 2012 (Fig. 4i).

3.4.3 Spatial–temporal variation of available phosphorus

Between 2005 and 2012, the high concentration of available P in farmland is mainly observed in the central and eastern

parts of Jiangxi Province, while the low value was primarily detected in the Northern part and plain around the Poyang Lake (Fig. 5). In addition, the spatial pattern of available P concentration considerably changed from 2005 to 2012. The available P concentration in farmland in the southern, western, and eastern parts of Jiangxi Province slightly increased. Especially, the available P concentration in farmland in the southeastern part greatly increased, while available P concentration in the farmland of the central region decreased from 2005 to 2012.

3.4.4 Spatial–temporal variation of available potassium

Clearly, change was taken place for the spatial pattern of available K concentration in farmland of Jiangxi Province from 2005 to 2012 (Fig. 6). Concentration of available K in northern part kept at high level while in southern and western and eastern part kept at low level between 2005 and 2012. In addition, the high concentration and low value of available K are crosswise distributed in the central part of Jiangxi Province. In terms of temporal trend, the available K concentration in the central part of Jiangxi Province increased, while available K concentration in most regions of the southern, western, and eastern parts decreased between 2005 and 2012 (Fig. 6i).

3.4.5 General spatial pattern of soil nutrients and SOM during whole the study period

By compiling all the soil samples collected between 2005 and 2012, we produced the maps of different soil nutrients and SOM during whole the study period (Fig. 7). Our results indicate that the high values of SOM are mainly observed in farmland of the central part of Jiangxi Province, while the low values of SOM were mostly detected in northern part throughout the study period (Fig. 7a). In terms of available N, the high values are mainly located in the central part and plains around the Poyang Lake, while the low value is mainly situated in the southern and northern parts of Jiangxi Province (Fig. 7b). Regarding available P, the high values are primarily distributed on the central and southwestern part of Jiangxi Province. In contrast, the low value is primarily observed in the western and eastern part (Fig. 7c). For the available K, the high values are concentrated in the central parts and plains around Poyang Lake and the low values are concentrated in the eastern and southeastern parts of Jiangxi Province.

3.5 Changes of soil fertilizer grades in the farmland of Jiangxi Province

As regulated by the national standard of nutrients classification issued by the Chinese government, the soil samples

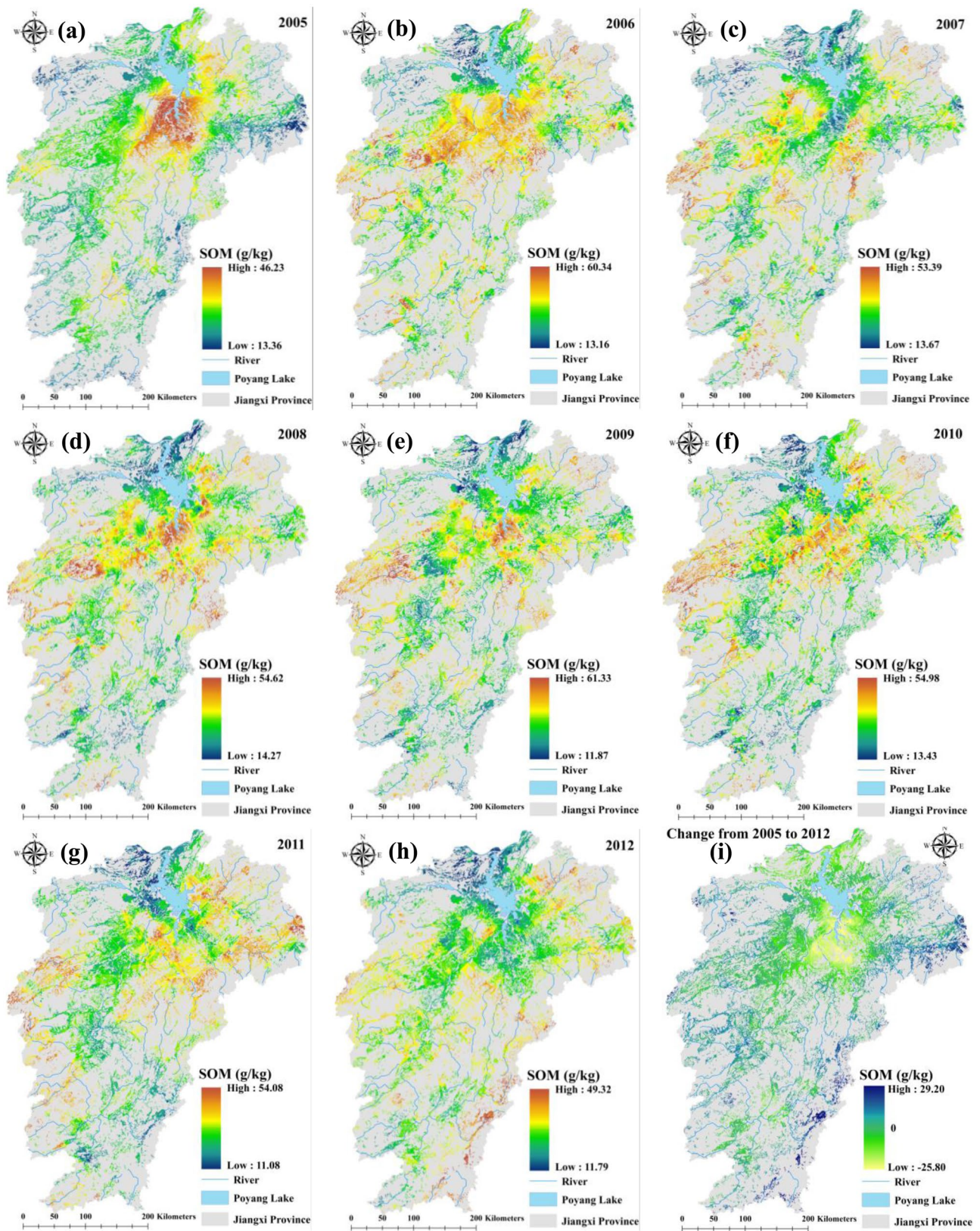


Fig. 3 Spatio-temporal variation of soil organic matter (SOM) in the farmland of Jiangxi Province

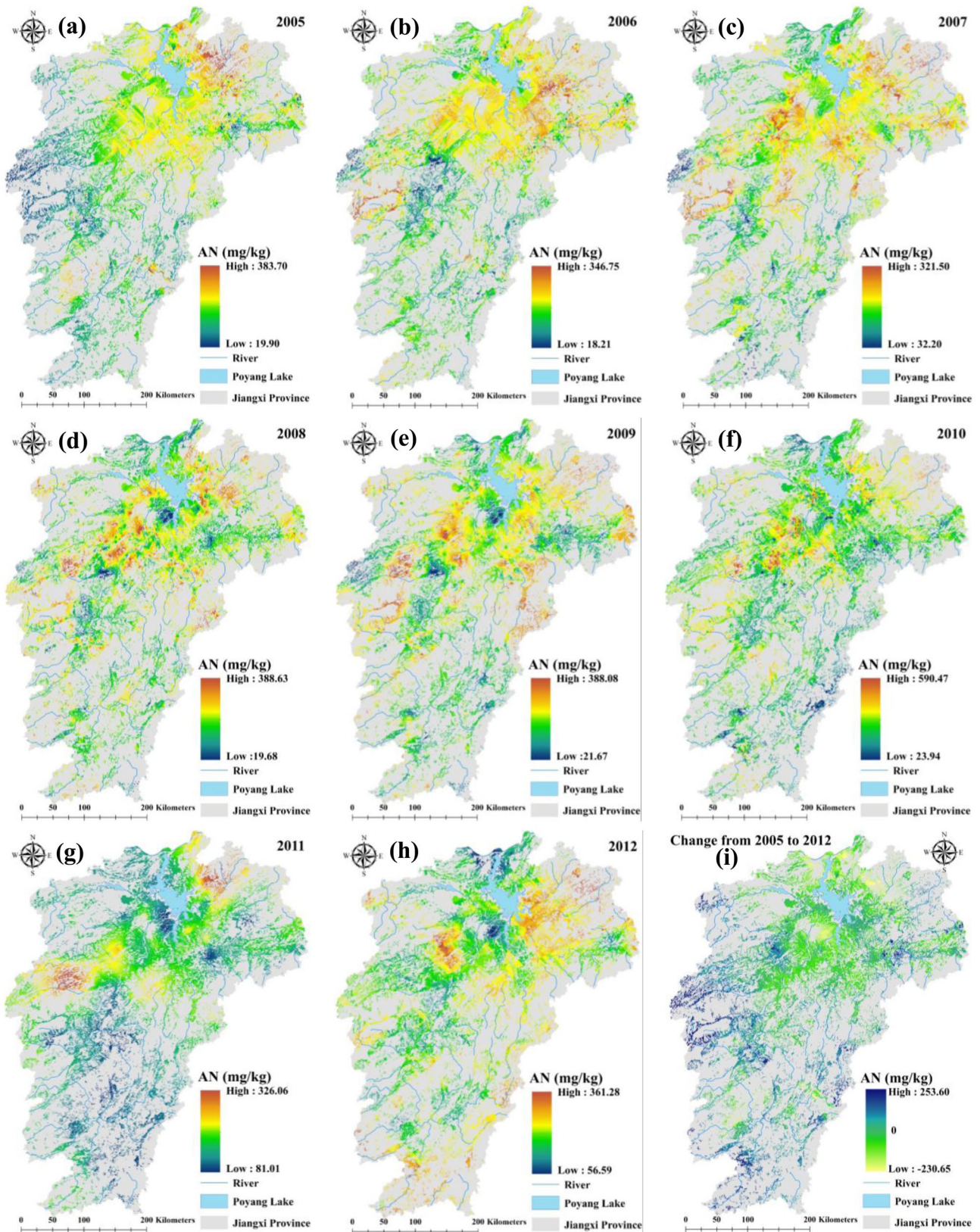


Fig. 4 Spatio-temporal variation of alkali-hydrolyzable nitrogen (AN) in the farmland of Jiangxi Province

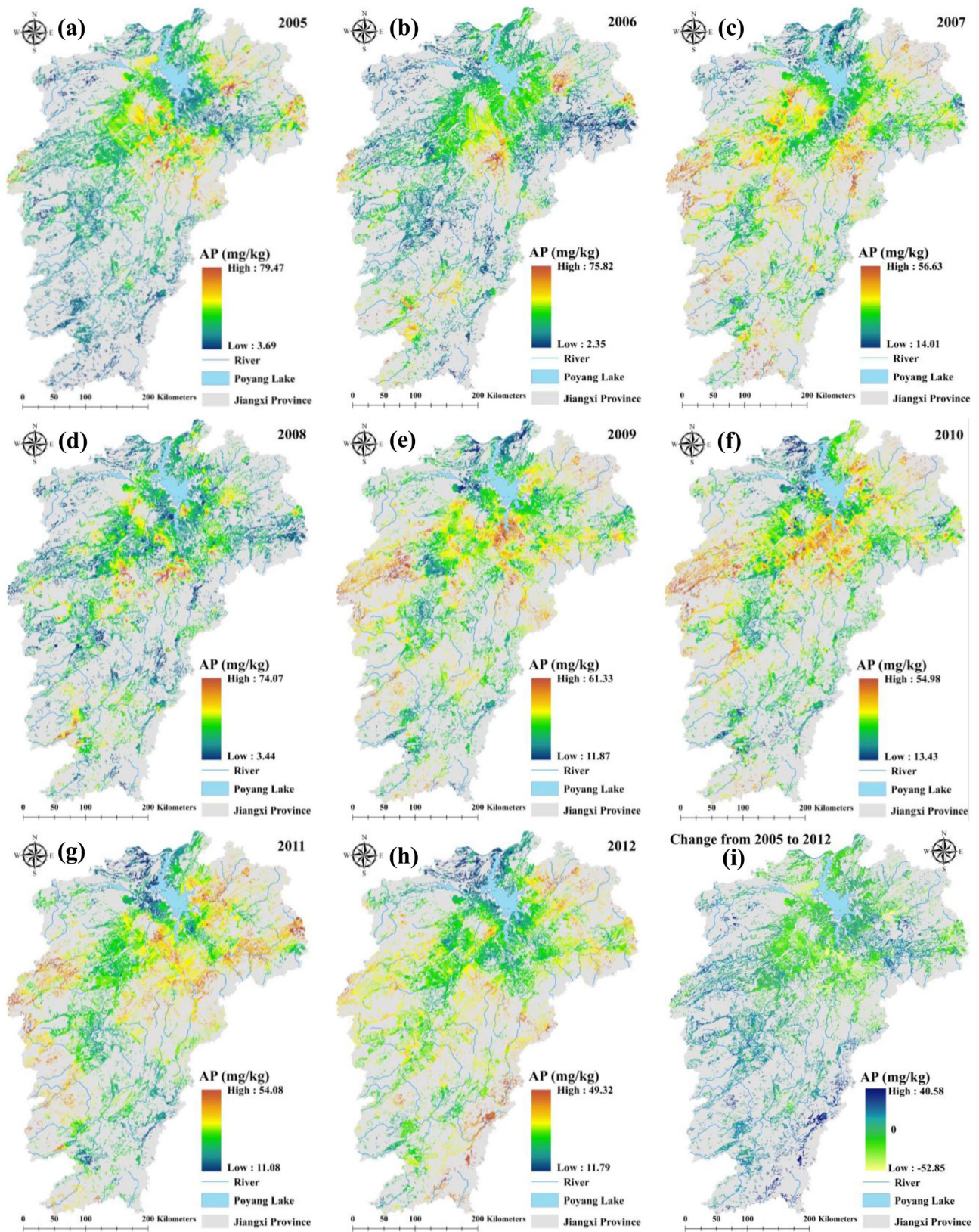


Fig. 5 Spatio-temporal variation of available phosphorus (AP) in the farmland of Jiangxi Province

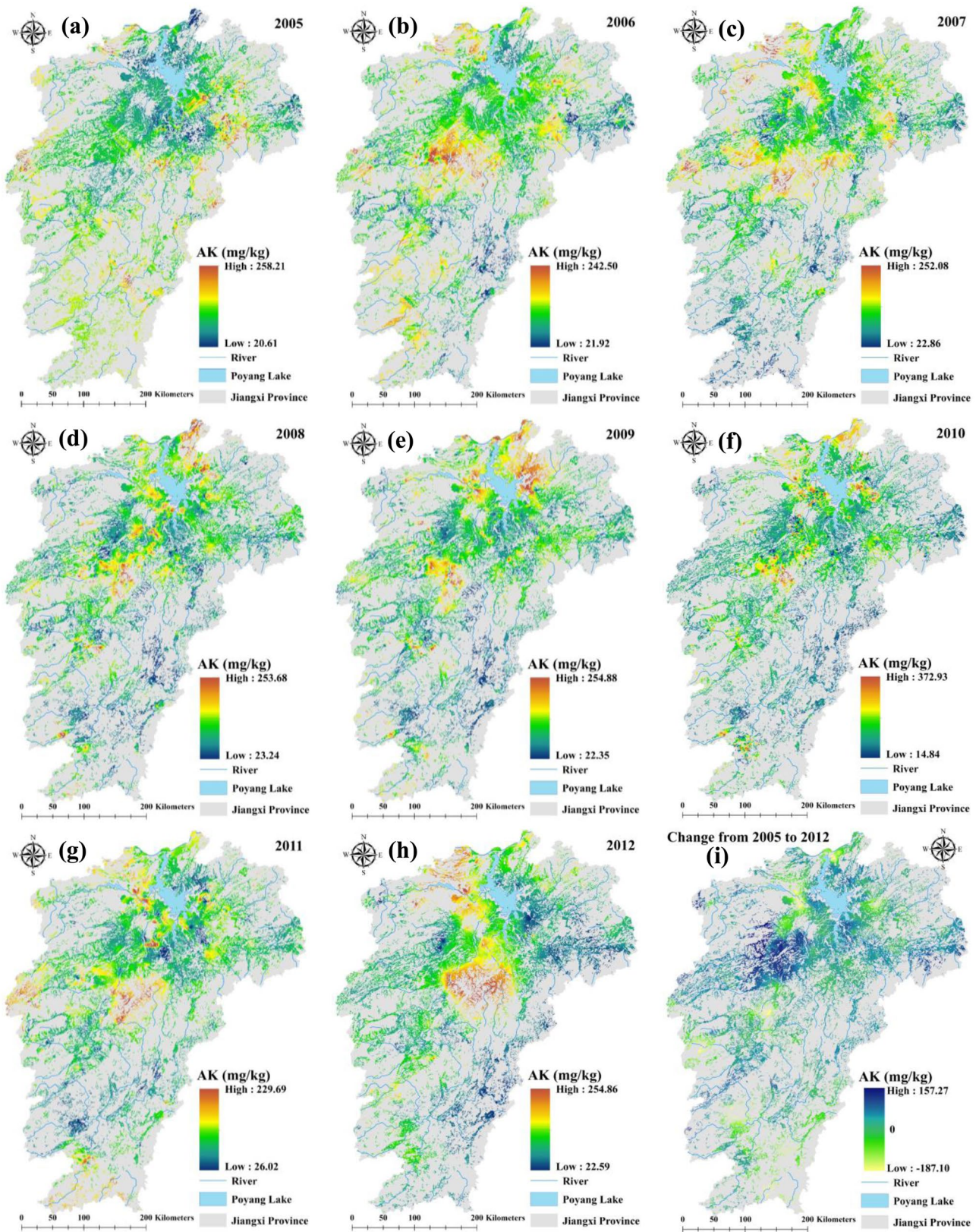


Fig. 6 Spatio-temporal variation of available potassium (AK) in the farmland of Jiangxi Province

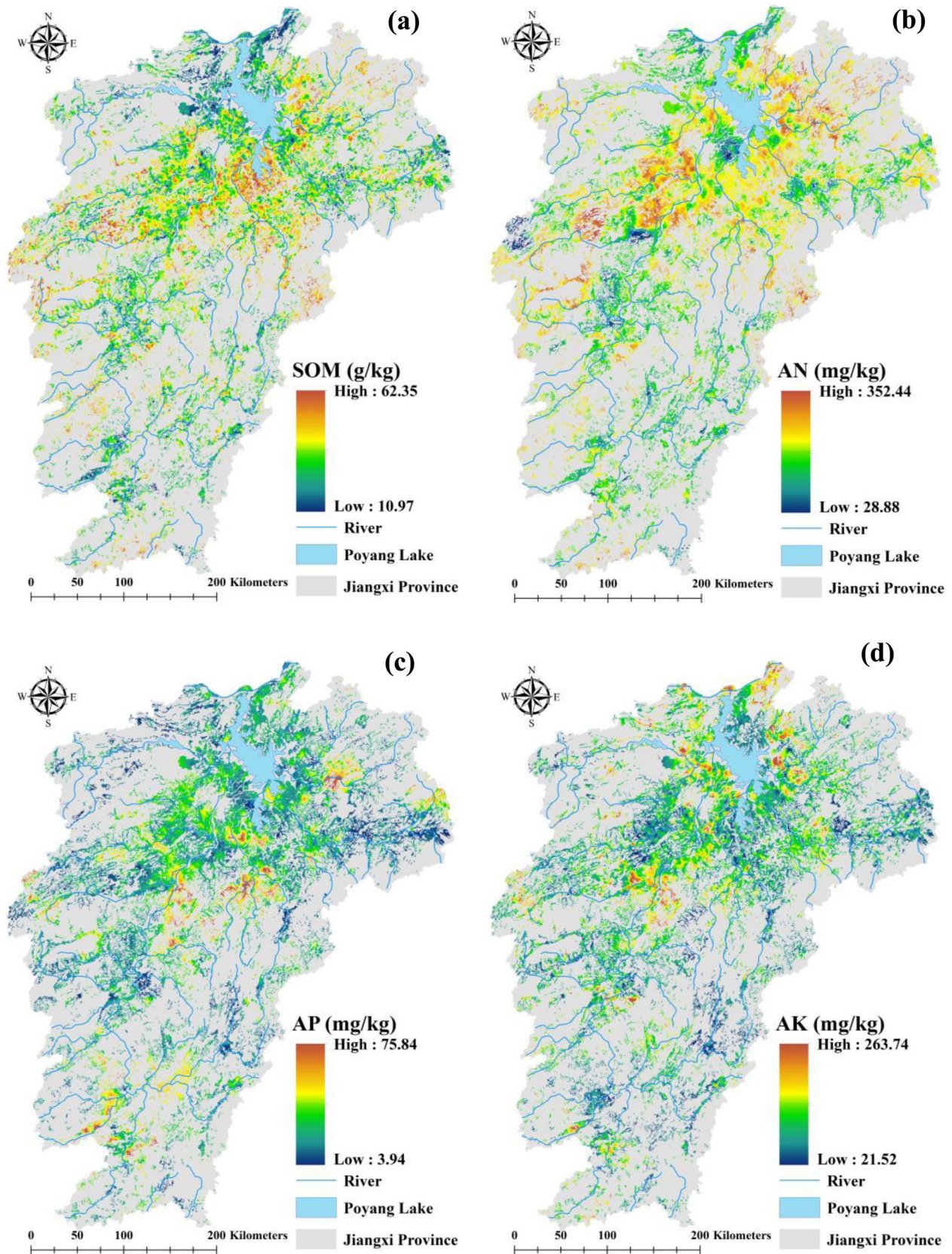


Fig. 7 Spatial pattern of soil organic matter (SOM) (a), alkali-hydrolyzable nitrogen (AN) (b), available phosphorus (AP) (c), available potassium (AK) (d) in the farmland of Jiangxi Province which compiled all the soil samples collected between 2005 and 2012

were classified into six grades: class 1 (extremely high), class 2 (very high), class 3 (high), class 4 (moderate), class 5 (low), and class 6 (very low) (Table S4). The proportion of soil samples with SOM concentration at class 1 and class 2 decreased from 2005 to 2012, while the proportion of class 3, class 4, and class 5 increased. The SOM concentration of most of soil samples belongs to class 1 and class 4 from 2005 to 2012.

The ratio of soil samples with available N concentration which belongs to classes 1, 4, 5, and 6 slightly decreased, while the proportion of soil samples with available N concentration which belongs to classes 2 and 3 increased from 2005 to 2012 (Table S5). In terms of the available P, the proportion of soil samples with available P concentration which belongs to class 1 dramatically dropped by 11.7%. In contrast, the proportion of soil samples which belong to class 5 slightly decreased and the proportion of soil samples which belong to classes 2, 3, and 4 increased. For available K, the proportion of soil samples with available K concentration which belongs to classes 1, 2, 5, and 6 increased, while the proportion of soil samples which belong to classes 3 and 4 decreased. It is worth noting that the apparent lack of K fertility is detected in farmland of Jiangxi Province since the available K concentration in most soil samples belongs to classes 3, 4, 5, and 6. Lacking K would lead to the delay or advance of the natural growth and development process of crop hence cause reduction of quality and yield of crop. Therefore, applying K fertilizer is recommended to enhance the K nutrient supply for the crop.

3.6 The effects of different covariates on soil nutrients and SOM

We also quantified the relative importance of variables for affecting soil nutrients and SOM variation in farmland of Jiangxi Province (Fig. 8), and listed the top ten most important variables for different soil nutrients and SOM (Table 1). The results indicate that straw return amount, mean annual precipitation, and mean annual temperature were the most important variables for affecting variation of SOM. At lower

magnitude, elevation, population density, the input of N fertilizer, the input of phosphate fertilizer, the input of potash fertilizer, available silicon, and multi-resolution valley bottom flatness also affected variation of SOM. These factors were ranked as the top ten variables for affecting variation of SOM. Concerning available N, the mean annual precipitation, straw return amount, mean annual temperature, population density, elevation, N fertilizer, potash fertilizer, available silicon, multi-resolution valley bottom flatness, and phosphate fertilizer were the top ten most important variables. In terms of available P, the mean annual precipitation, mean annual temperature, available silicon, elevation, population density, N fertilizer, phosphate fertilizer, potash fertilizer, multi-resolution valley bottom flatness, and exchangeable calcium were identified as most important variables which control variation of available P. Concerning available K, mean annual temperature, mean annual precipitation, elevation, population density, crop rotation system, soil available silicon, potash fertilizer, phosphate fertilizer, N fertilizer, and pH have the largest influence on variation of available K. Overall, the climate (e.g., mean annual temperature, mean annual precipitation) and soil management (e.g., straw return amount, population density, crop rotation system, N fertilizer, phosphate fertilizer, potash fertilizer) had larger effects on variation of soil nutrients and SOM.

4 Discussion

4.1 Comparison with others regions in China

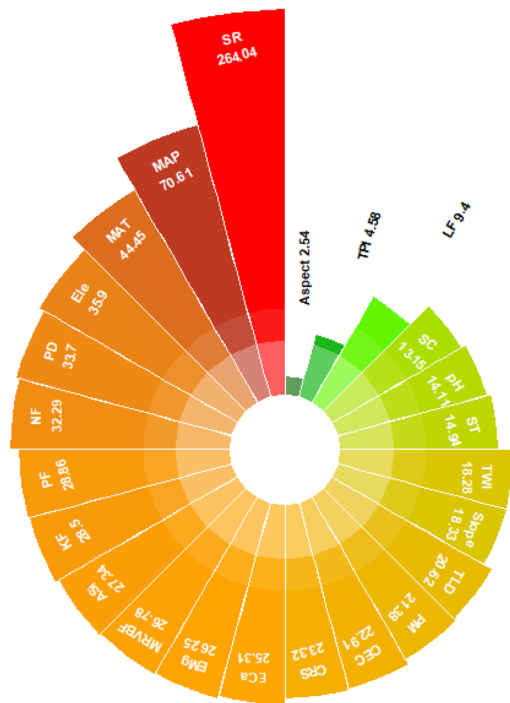
Overall, most soil samples had concentrations of SOM, and available N and P at or above the level of class 3 (high grade). This indicates the farmland in Jiangxi Province could well supply SOM and available N and P for crop growth. In contrast, the concentration of available K in most soil samples belongs to or below the level of class 4 (moderate grade). This reveals relatively low concentrations of available K in farmland soils, and more K fertilizer input

Table 1 Top ten most important variables (variables with 10 largest value of % IncMSE) for affecting variation of different soil nutrients. The yellow color represents the anthropogenic factors, the green color

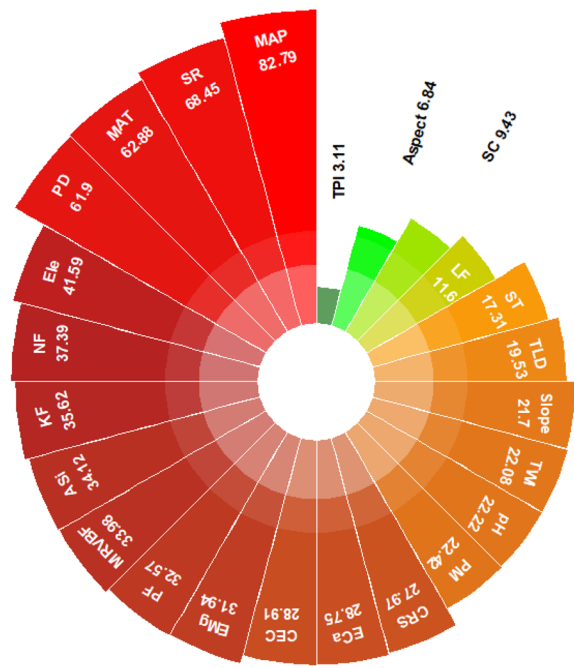
represents the climate factors, the brown color represents the relief factors, the purple color represents the soil properties

Soil properties	TOP1	TOP2	TOP3	TOP4	TOP5	TOP6	TOP7	TOP8	TOP9	TOP10
Soil organic matter	SR	MAP	MAT	Ele	PD	NF	PF	KF	ASi	MRVBF
Available Nitrogen	MAP	SR	MAT	PD	Ele	NF	KF	ASi	MRVBF	PF
Available Phosphorus	MAP	MAT	ASi	Ele	PD	NF	PF	KF	MRVBF	ECa
Available Potassium	MAT	MAP	Ele	PD	CRS	ASi	KF	PF	NF	pH

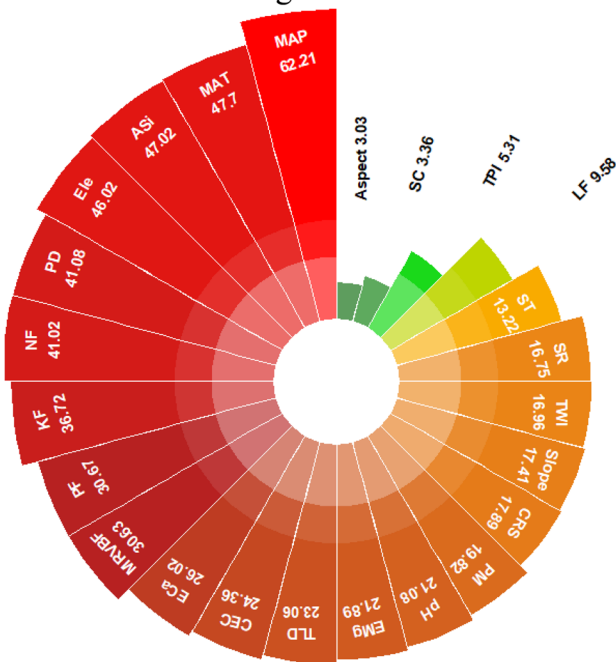
MAP mean annual precipitation, MAT mean annual temperature, Ele elevation, PD population density, NF input of nitrogen fertilizer, PF input of phosphate fertilizer, KF input of potash fertilizer, ASi available silicon, MRVBF multi-resolution valley bottom flatness, ECa exchangeable calcium, CRS crop rotation system



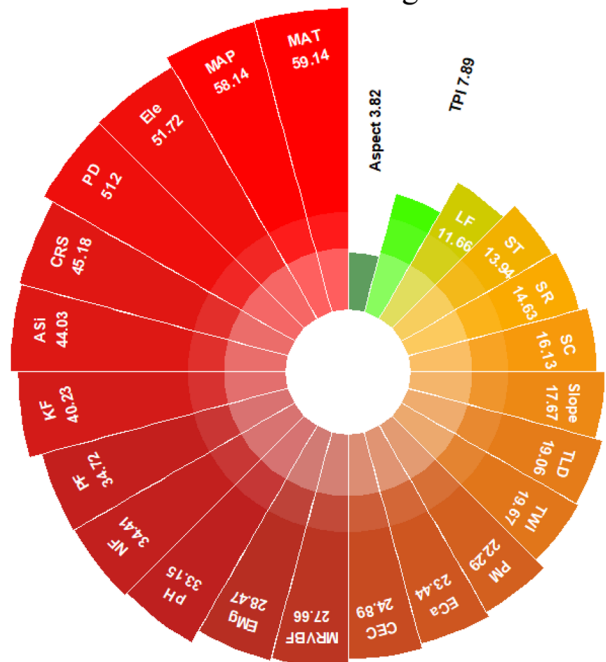
Soil organic matter



Available nitrogen



Available phosphorus



Available potassium

Fig. 8 The relative importance of different variables which affect variation of soil organic matter, available nitrogen, available phosphorus, available potassium based on % IncMSE (MAP means mean annual precipitation, MAT means mean annual temperature, Ele means elevation, PD means population density, NF means input of nitrogen fertilizer, PF means input of phosphate fertilizer, KF means input of potash

fertilizer, ASi means available silicon, MRVBF means multi-resolution valley bottom flatness, EMg means exchangeable magnesium, ECA means exchangeable calcium, CRS means crop rotation system, CEC means cation exchange capacity, PM means parental material, TLD means tillage layer depth, TWI means topographic wetness index, ST means soil type, SC means soil class, LF means landform

is urgently needed, although the average concentration of available K increased by 5.1% during the study period.

In this study, we compared soil pH, SOM, and available N, P, and K in other regions of China by lumping all the data collected from different years (Table S6). As shown in Table S6, the mean soil pH (5.21) in the farmland of Jiangxi Province was lower than these of Hunan Province and Guizhou Province and close to the soil pH in farmland of Zhejiang Province. The mean SOM in Jiangxi Province was 30.9 g/kg and belongs to a very high degree (Table S4). It was higher than the mean SOM concentration in Sichuan Province, Jiangsu Province, Fujian Province, and Beijing City, while lower than those in Guizhou Province, Hunan Province, Zhejiang Province, and Northeast China. The mean available N in the farmland of Jiangxi Province was 164.3 mg/kg and belongs to extremely high grade, which was the highest among all the regions listed in Table S6. The mean available P concentration in farmland soils of Jiangxi Province was 20.6 mg/kg and belongs to a very high grade. It was higher than those in Sichuan Province, Guizhou Province, Jiangsu Province, and Zhejiang Province, while lower than those in Liaoning Province, Hunan Province, Jilin Province, Fujian Province, Beijing City, and Northeast China. The mean available K in the farmland soil of Jiangxi Province is 87.43 mg/kg and belongs to the moderate grade (Table S4). It was higher than those in Sichuan Province, Guizhou Province, Jiangsu Province, and Zhejiang Province but lower than those in Liaoning Province, Hunan Province, Jilin Province, Fujian Province, Beijing City, and Northeast China. Overall, the soil nutrients and SOM in farmland soils of Jiangxi Province are at a high level.

4.2 Effects of climate factors on soil nutrients and SOM

Our results indicate that the climate factors (mean annual precipitation, mean annual temperature) have the most significant effect on the variation of soil nutrients and SOM in the farmland of Jiangxi Province (Figs. 8 and 9). Many researchers have proved that temperature and precipitation could greatly affect the decomposition process of SOM through the alteration of soil temperature, hydrological cycle, soil moisture, and microbial activity (Pregitzer and King 2005; Yan et al. 2021a, b). Among which, the changes in soil moisture were proved as a consequence of climate change and which could then alter soil nutrient availability as well as soil–plant microbial interactions (Emmett et al. 2004). Yuan et al. (2017) revealed that soil carbon, N, and P concentrations generally decreased with water addition in manipulative experiments but increased with annual precipitation along environmental gradients. Osland et al. (2018) reported that at the regional scale, the climate has a considerable influence on SOM. Yu et al. (2018) demonstrated that the SOM concentration decreased with the increase of mean

annual precipitation in subtropical China. Li et al. (2020) revealed a moderately negative correlation between SOM and mean annual temperature.

Moreover, the temperature and precipitation could also affect the plant cover and crop system in different regions, resulting in changes of the plant uptake of soil nutrients, which then indirectly change the cycles of soil nutrients. Pregitzer and King (2005) reported that plant nutrient uptake is influenced by changes in soil temperature. Matias et al. (2011) indicated that higher precipitation could boost microbial and plant-nutrient uptake, and hence achieve nutrient balance. All of these studies confirmed the crucial role of climate factors on the variation of soil nutrients and SOM.

4.3 Effects of soil management measures on soil nutrients and SOM

Our results found that soil management factors such as straw return and chemical fertilizer input essentially affected the variation of soil nutrients and SOM in the farmland of Jiangxi Province (Figs. 8 and 9). Many studies have confirmed that straw return could improve soil fertility, alleviate nutrient leaching, and increase crop yield and nutrient use efficiency (Wang et al. 2021a, b, c; Cui et al. 2022; Wu et al. 2022). Crop straw is a post-harvest waste material that can function as organic fertilizer. It is an important source of SOM and soil nutrients like N, K, magnesium, and sulfur in farmland (Zhu et al. 2010). Wang et al. (2015) found that straw return significantly increased the SOM and total N concentration by 10.1% and 11.0%, respectively. Zhang et al. (2021a, b) also found that straw return was the most effective way to conserve N in soil and could significantly reduce N runoff by 11.6%. Cui et al. (2022) revealed that straw return significantly increased the concentrations of SOM and available P over 4-year period.

However, Zhu et al. (2010) found a negative effect of straw return under initial high concentration of SOM, and a positive impact under initial moderate level on crop yield. In addition, the way of straw return to the field and the balance of soil nutrients can also affect the effectiveness of straw return (Huang et al. 2021; Hu et al. 2022). Moreover, excessive straw return can lead to imbalanced soil carbon and N and P stoichiometry (Jin et al. 2020). Thus, further surveys and deeper analyses are necessary to highlight the effect of straw return on soil nutrients and SOM.

The application of chemical fertilizer could also greatly affect soil nutrient variation. Generally, the input of chemical fertilizer could improve soil nutrient supply. However, as presented in Fig. 9, the application amount of N and K fertilizer per hectare showed a significantly decreasing trend, while the P fertilizer gave a non-significantly decreasing trend during the study period. This is inconsistent with the temporal trend of available N and K in the study area

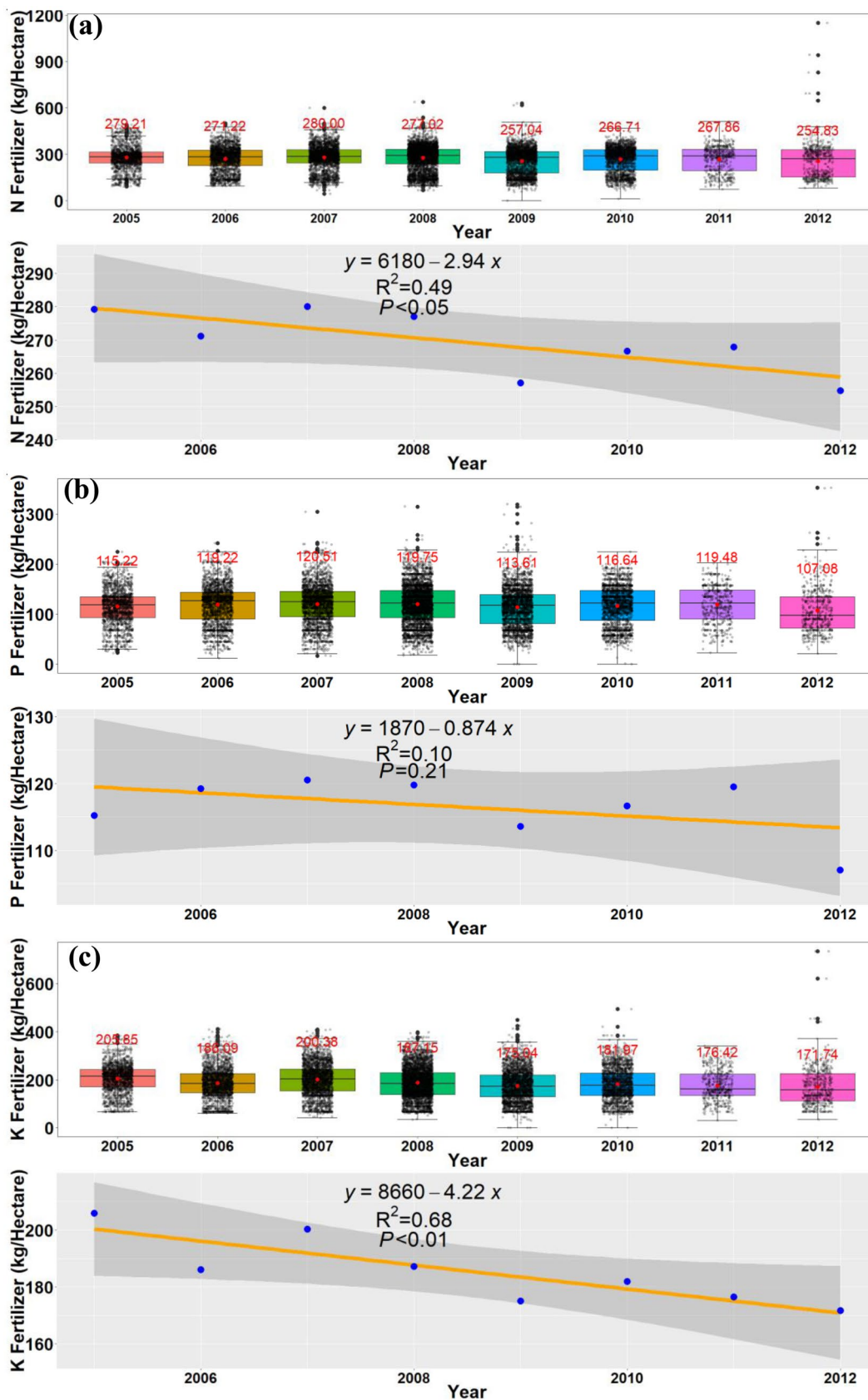


Fig. 9 Temporal trend of annual application rates (kg/ha) of nitrogen fertilizer (a), phosphate fertilizer (b), and potash fertilizer (c) per hectare in the farmland of Jiangxi Province (kg/ha)

(Fig. 2). It indicates an increasing utilization efficiency of N and K fertilizer in Jiangxi Province. It is also revealed that the soil nutrient and SOM variation are also affected by some other factors, such as soil pH and the microbial community, as well as application strategy of chemical fertilizer (Zhalnina et al. 2015). Unreasonable fertilization and over-fertilization can lead to adverse effects such as an imbalance of soil nutrients or even a decline of soil fertility (Fulford et al. 2018). Therefore, more attention should be paid to increasing the utilization efficiency of chemical fertilizers instead of overuse of chemical fertilizers, hence reducing the related environmental risks and economic costs of the landowner (Zhao et al. 2014). Specifically, chemical fertilizers combined with straw return can improve the availability of the nutrient, which reduces the input of chemical fertilizers and thus plays a positive role in maintaining nutrient balance (Wang et al. 2022).

Crop rotation is another major factor, which determines the variation of soil nutrients and SOM (Figs. 8 and 9). It can maintain soil fertility, improve soil physicochemical properties, increase soil microbial diversity, and affect various natural processes such as N-enrichment of the soil by leguminous plants (Malobane et al. 2020; Town et al. 2022). Using different species in rotation allows for increased SOM and adds nutrients to the soil (Malobane et al. 2020; Hu et al. 2022). Song et al. (2016) reported an increased soil organic carbon concentration in the rice–wheat rotation system compared to the conventional plow system. Haruna and Nkongolo (2019)

revealed that no-till management and corn-soybean rotation significantly improve total carbon compared with continuous corn and soybean production. Malobane et al. (2020) showed that crop rotation increased soil N by 6.0% in marginal soils of South Africa. Town et al. (2022) found that different crop rotations affect the bacterial and fungal communities in the root, rhizosphere, and bulk soil, and impact soil microbial processes, which then essentially affect the availability of soil nutrients and crop yield. However, further work is needed to explore and compare the effects of various crop rotations on soil nutrients, SOM, and crop yield.

4.4 Effects of soil properties on soil nutrients and SOM

Compared with climate factors and soil management measures, the soil properties like soil available silicon, exchangeable Ca, and pH had slight but significant effects on the variation of soil nutrients and SOM (Figs. 8 and 9). As shown in Fig. 10, the soil available Si was significantly and positively correlated with available K. Meanwhile, it was significantly and negatively correlated with SOM and available N and P, which is consistent with the results of Yanai et al. (2016). Silicon is the second most common element in the Earth’s crust, and it has been recognized as beneficial for crop production by alleviating various biotic and abiotic stresses (Skinner 1979; Wang et al. 2020). Silicon could modify the uptake and acquisition of nutrients differently for different plant species (Islam and Saha 1969; Greger et al.

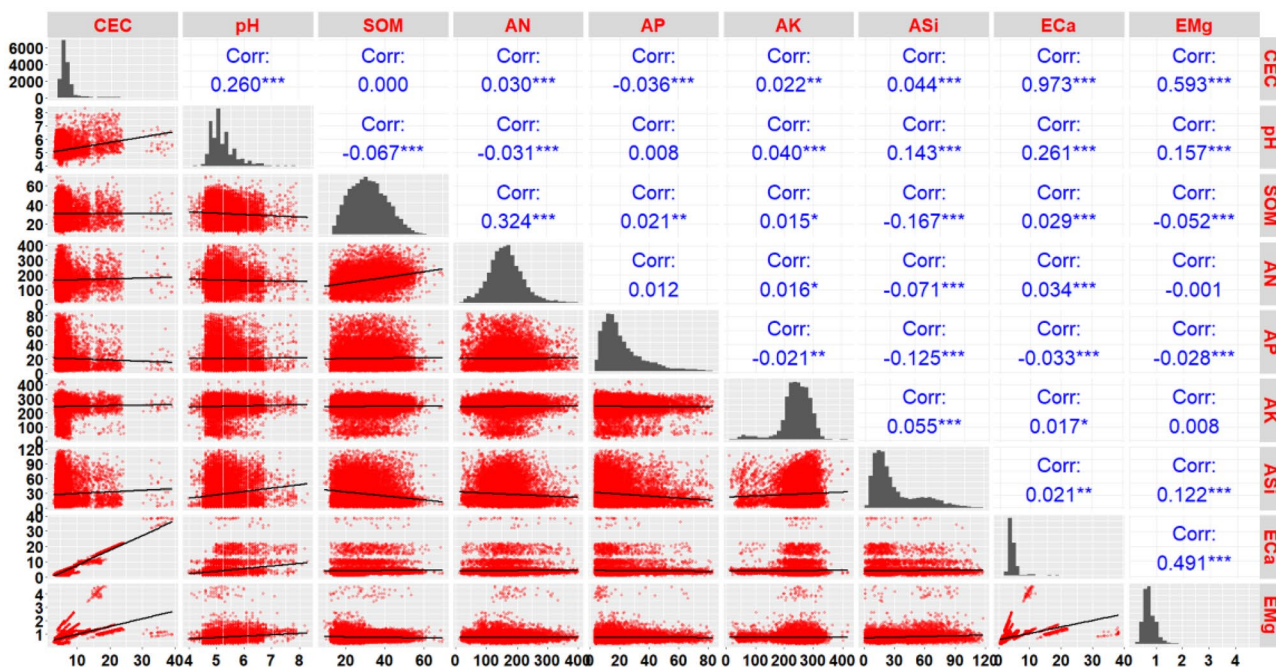


Fig. 10 The correlation between soil nutrients and soil properties. SOM, soil organic matter; AN, alkali-hydrolyzable nitrogen; AP, available P; AK, available potassium; MAP, mean annual precipitation; MAT, mean

annual temperature; ASi, available silicon; ECa, exchangeable calcium; EMg, exchangeable magnesium; CEC means cation exchange capacity

2018). According to Wallace (1989) and Ma et al. (1990), the uptake of N, P, K, Mg, and Ca by the plants is influenced by silicon in different ways. De Tombeur et al. (2020) also confirmed that the SOM and soil available Si are closely related to phytolith concentration, releasing silicon in soil solution through dissolution.

The exchangeable Ca is significantly and positively correlated with SOM and available N and K. In contrast, it was significantly but negatively linked to available P. High concentrations of exchangeable calcium will hinder the uptake of soil nutrients by crops since the cation Ca^{2+} can directly compete with other soil nutrients on adsorption sites (Mei et al. 2016).

Moreover, the pH correlated significantly and positively with available K while negatively with SOM and available N, which is consistent with previous studies, such as Zhao et al. (2011) and Qian et al. (2015). This may attribute to the fact that the microbial decomposition and transformation of straw returning to the field could increase the concentration of SOM. It can also lead to the increase of cellulose, lignin, polysaccharide, and humic acid, which may decrease soil pH. The mean value of soil pH in Jiangxi Province was 5.2 and belongs to the acidic grade (Table S6). Moreover, Guo et al. (2018) reported that excessive fertilizer application and acid rain intensity led to an overall 0.6-unit decrease of soil pH over the farmland of Jiangxi Province between the 1980s and the 2010s. Soil pH significantly influences the concentration of various nutrients and SOM in the soil by affecting the availability of soil nutrients and microbial activity (Zhalnina et al. 2015; Chen et al. 2019). Wright et al. (2009) reported that soil pH strongly affected the availability of soil nutrients. For example, the increase of soil pH contributes to the rise of negative charge of the colloid and the change of the colloid-adsorbed chaperone ions, which leads to the improvement of K availability (Qian et al. 2015).

Additionally, we found no significant relationship between the cation exchange capacity and SOM (Table 1), which is consistent with the result reported by Petersen et al. (1996). However, some other researchers reported significant relationships between cation exchange capacity and SOM (Lourenco et al. 2021; Zhao et al. 2022). The relationship between cation exchange capacity and SOM may also be affected by many other factors, such as clay type, parental material, and soil texture (Jackson et al. 1986; Solly et al. 2020). This may lead to the various relations between cation exchange capacity and SOM reported by different studies. Thus, further investigation is still necessary to make this issue more clearly.

4.5 Effects of relief on soil nutrients and SOM

In this study, we found relief factors (e.g., elevation and Multi-resolution valley bottom flatness) had small but significant effects on soil nutrients and SOM. The relief factors

could indirectly affect the concentrations of soil nutrients and SOM through redistribution of water and radiation in soil, and migration of soil nutrients and SOM (Fiedler et al. 2004; Moser et al. 2009). For example, in soils with high moisture, irons play a critical role in P adsorption, retention, and release (Aldous et al. 2005), while Al can likewise affect P availability. Bruland and Richardson (2005) confirmed that the decreasing inorganic N and total P concentrations leads to the micro-topographic gradient from higher to lower elevations. Clemens et al. (2010) found that the middle and lower slope positions are the most prone to erosion and long-term intensive tillage led to poor soil fertility in this position. Furthermore, the topographical factors can also affect delineating of agricultural management zones and the selection of crop planting systems (Pilesjo et al. 2005); hence affect the soil nutrient recycling.

4.6 Limitations and recommendations

Although we made some progress in this study, there are still several limitations, which need to be overcome in further work. Firstly, in this study, different number of soil samples is taken in different years. The soil sampling locations also varied in different years, which may pose bias on the spatio-temporal variation prediction. Secondly, some studies have reported apparent intra-annual variations in soil nutrients and SOM (Conyers et al. 1997; Winterdahl et al. 2014). For example, Conyers et al. (1997) revealed a complex and fluctuating intra-annual temporal trend of soil water content, pH, and exchangeable aluminum. The soil samples in this study were collected in different months over several years. Nevertheless, due to limited data availability, we can only explore the inter-annual variability of soil nutrients and SOM, and hard to explore the intra-annual variation of nutrients and SOM. In addition, soil nutrients and SOM are affected by many factors, and the interactions between these factors are not fully understood (Hu et al. 2022). Moreover, in this study, we analyzed the spatial–temporal variation of soil nutrients and SOM by separately producing maps of soil nutrients and SOM in different years using the geostatistical method. This way neglects the temporal dependence on soil nutrients and SOM. Finally, some information, such as the amount of straw return and input of chemical fertilizers, is provided by the landowners, which may lead to bias on the data due to record errors, although many measures have been taken to ensure the reliability and quality of the dataset.

Nevertheless, our results could still provide important and valuable implications for soil management and sustainable agriculture development. First of all, our study confirmed the practical and vital role of straw in enhancing soil fertility and soil carbon sequestration in the farmland. This is crucial for archiving sustainable agriculture, carbon neutralization strategy, and regulating climate changes, and could

also contribute to realizing sustainable development goals adopted by the United Nations (Huang et al. 2020; Liu et al. 2021a, b). Secondly, our results indicate that the soil nutrients and SOM in the farmland of Jiangxi Province are at a high grade. As presented in Figs. 2 and 9, reduced use of chemical fertilizers did not lead to a reduction in availability of nutrients and SOM. This enlightens us that environmentally friendly methods like straw return, coupled with appropriate agricultural management measures, can fill the gaps between the supply of soil nutrients and chemical fertilizer input. Finally, the nutrients and SOM usually showed clear intra-annual variation during different growth stages of crops (Conyers et al. 1997; Xiang et al. 2022); thus, more attention should be paid to monitor the intra-annual variation of soil nutrients and SOM. When the study is focused on analyzing the inter-annual variability of soil nutrients and SOM, the sampling time should be as consistent as possible to reduce the bias caused by intra-annual variation of soil nutrients and SOM.

5 Conclusion

This study revealed that SOM and available P showed an insignificant decreasing trend, while the available N and K showed a significant increasing trend in the farmland soils across Jiangxi Province during the study period. The soil nutrients and SOM showed weak to moderate spatial dependence in the farmland. In addition, clear spatio-temporal variability was detected for soil nutrients and SOM. Referring to the national standard of China, the SOM and available N and P in most soil samples are kept at a relatively high level. In contrast, the concentration of available K in most soil samples is kept at a relatively low level. This highlights the urgent need for K fertilizer in the farmland. Finally, climate and soil management factors have dominant impacts on soil nutrient variation. The straw return is widely applied in farmland due to its benefit on improving soil fertility and enhancing carbon sequestration.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11368-023-03471-5>.

Acknowledgements Thanks all the editors and reviewers for their very helpful and constructive comments and suggestions, which essentially improved our manuscript. We gratefully acknowledge Dr. Hocine Bourennane from INRAE-National Research Institute for Agriculture, Food and the Environment (France) and Jie Hu from University of Wisconsin-Madison for editing the language.

Funding This work was financially supported by the National Natural Science Foundation of China (No. 42201073), the Social Science Foundation of Jiangxi Province (No. 21YJ43D), the Humanities and Social Sciences Project of Jiangxi Education Department (No. GL21217), the National Natural Science Foundation of China (No. 42071068), the Project of Department of Education Science and Technology of Jiangxi Province (No. GJJ210541), and the Key Laboratory

of Finance & Economics Data Science (Jiangxi University of Finance and Economics).

the Social Science Foundation of Jiangxi Province, 21YJ43D, Bifeng Hu, the Humanities and Social Sciences Project of Jiangxi Education Department, GL21217, Bifeng Hu, the National Natural Science Foundation of China, 42071068, Hongyi Li, the Project of Department of Education Science and Technology of Jiangxi Province, GJJ210541, Bifeng Hu, Natural Science Foundation of Jiangxi Province, 20202BABL205025, Hongyi Li

Data availability The data used in this study was not permitted to share.

Declarations

Competing interest The authors declare no competing interests.

References

- Aldous A, McCormick P, Ferguson C, Graham S, Craft C (2005) Hydrologic regime controls soil phosphorus fluxes in restoration and undisturbed wetlands. *Restor Ecol* 13:341–347. <https://doi.org/10.1111/j.1526-100X.2005.00043.x>
- Bao SD (2000) Soil and agricultural chemistry analysis. Chinese Agricultural Press, Beijing, China (In Chinese)
- Breiman L (2001) Random forests. *Mach Learn* 45:5–32. <https://link.springer.com/article/10.1023/a:1010933404324>
- Bruland GL, Richardson CJ (2005) Hydrologic, edaphic, and vegetative responses to microtopographic reestablishment in a restored wetland. *Restor Ecol* 13:515–523. <https://doi.org/10.1111/j.1526-100X.2005.00064.x>
- Chen SC, Liang ZZ, Webster R, Zhang GL, Zhou Y, Teng HF, Hu BF, Arrouays D, Shi Z (2019) A high-resolution map of soil pH in China made by hybrid modelling of sparse soil data and environmental covariates and its implications for pollution. *Sci Total Environ* 655:273–283. <https://doi.org/10.1016/j.scitotenv.2018.11.230>
- Clemens G, Fiedler S, Cong ND, Van Dung N, Schuler U, Stahr K (2010) Soil fertility affected by land use history, relief position, and parent material under a tropical climate in NW-Vietnam. *CATENA* 81:87–96. <https://doi.org/10.1016/j.catena.2010.01.006>
- Conyers MK, Uren NC, Helyar KR, Poile GJ, Cullis BR (1997) Temporal variation in soil acidity. *Aust J Soil Res* 35:1115–1130. <https://doi.org/10.1071/S97022>
- Cui H, Luo Y, Chen J, Jin M, Li Y, Wang Z (2022) Straw return strategies to improve soil properties and crop productivity in a winter wheat-summer maize cropping system. *Eur J Agron* 133:126436. <https://doi.org/10.1016/j.eja.2021.126436>
- De Tombeur F, Turner BL, Laliberte E, Lambers H, Mahy G, Faucon MP, Zemunik G, Cornelis JT (2020) Plants sustain the terrestrial silicon cycle during ecosystem retrogression. *Science* 369:1245–1248. <https://doi.org/10.1126/science.abc0393>
- Emmett BA, Beier C, Estiarte M, Tietema A, Kristensen HL, Williams D, Pen˜uelas, J., Schmidt, I., Sowerby, A., (2004) The response of soil processes to climate change: results from manipulation studies of shrublands across an environmental gradient. *Ecosystems* 7:625–637. <https://doi.org/10.1007/s10021-004-0220-x>
- Farooq TH, Kumar U, Mo J, Shakoar A, Wang J, Rashid MH, Tufail MA, Chen XY, Yan WD (2021) Intercropping of peanut-tea enhances soil enzymatic activity and soil nutrient status at different soil profiles in subtropical southern China. *Plants* 10:881. <https://doi.org/10.3390/plants10050881>
- Fiedler S, Wagner D, Kutzbach L, Pfeiffer E (2004) Element redistribution along hydraulic and redox gradients of low-centered

- polygons, Lena Delta, northern Siberia. *Soil Sci Soc Am J* 68:1002–1011. <https://doi.org/10.2136/sssaj2004.1002>
- Fu TT, Zhao RY, Hu B., Jia XX, Wang ZG, Zhou LQ, Huang MX, Li Y, Shi Z (2021) Novel framework for modelling the cadmium balance and accumulation in farmland soil in Zhejiang Province, East China: sensitivity analysis, parameter optimisation, and forecast for 2050. *J Clean Prod* 279:123674. <https://doi.org/10.1016/j.jclepro.2020.123674>
- Fulford AM, Culman SW (2018) Over-fertilization does not build soil test phosphorus and potassium in Ohio. *Agron J* 110:56–65. <https://doi.org/10.2134/agronj2016.12.0701>
- Granger SJ, Harris P, Upadhyay HR, Sint H, Pulley S, Stone M, Krishnappan BG, Collins AL (2021) Novel approaches to investigating spatial variability in channel bank total phosphorus at the catchment scale. *Catena* 202:105223 <https://doi.org/10.1016/j.catena.2021.105223>
- Greger M, Landberg T, Vaculík M (2018) Silicon influences soil availability and accumulation of mineral nutrients in various plant species. *Plants* 7:41. <https://doi.org/10.3390/plants7020041>
- Guo X, Li HY, Yu HM, Li WF, Ye YC, Biswas A (2018) Drivers of spatio-temporal changes in paddy soil pH in Jiangxi Province, China from 1980 to 2010. *Sci Rep* 8:2702. <https://doi.org/10.1038/s41598-018-20873-5>
- Haruna SI, Nkongolo NV (2019) Tillage, cover crop and crop rotation effects on selected soil chemical properties. *Sustainability* 11:2770. <https://doi.org/10.3390/su11102770>
- Hillel D (1980) Applications of soil physics. Academic press, New York 385
- Hu BF, Wang JY, Jin B, Li Y, Shi Z (2017) Assessment of the potential health risks of heavy metals in soils in a coastal industrial region of the Yangtze River Delta, China. *Environ Sci Pollut R* 24:19816–19826. <https://doi.org/10.1007/s11356-017-9516-1>
- Hu BF, Shao S, Fu ZY, Li Y, Ni H, Chen SC, Zhou Y, Jin B, Shi Z (2019) Identifying heavy metal pollution hot spots in soil-rice systems: a case study in South of Yangtze River Delta, China. *Sci Total Environ* 658:614–625. <https://doi.org/10.1016/j.scitotenv.2018.12.150>
- Hu BF, Zhou Y, Jiang YF, Ji WJ, Fu ZY, Shao S, Li S, Huang MX, Zhou LQ, Shi Z (2020a) Spatio-temporal variation and source changes of potentially toxic elements in soil on a typical plain of the Yangtze River Delta, China (2002–2012). *J Environ Manage* 271:110943. <https://doi.org/10.1016/j.jenvman.2020.110943>
- Hu BF, Xue J, Zhou Y, Shao S, Fu ZY, Li Y, Chen SC, Qi L, Shi Z, (2020b) Modelling bioaccumulation of heavy metals in soil-crop ecosystems and identifying its controlling factors using machine learning. *Environ Pollut* 262:114308. <https://doi.org/10.1016/j.envpol.2020.114308>
- Hu BF, Bourennane H, Arrouays D, Denoroy P, Lemerrier B, Saby NPA (2021a) Developing pedotransfer functions to harmonize extractable soil phosphorus content measured with different methods: a case study across the mainland of France. *Geoderma* 381:114645. <https://doi.org/10.1016/j.geoderma.2020.114645>
- Hu BF, Zhou Q, He CY, Duan LX, Li WY, Zhang GL, Ji WJ, Peng J, Xie HX (2021b) Spatial variability and potential controls of soil organic matter in the Eastern Dongting Lake Plain in southern China. *J Soil Sediment* 21:2791–2804. <https://doi.org/10.1007/s11368-021-02906-1>
- Hu BF, Xie MD, Li HY, Zhao WR, Hu J, Jiang YF, Ji WJ, Li S, Hong YS, Yang MH, Optiz T, Shi Z (2022) Stoichiometry of soil carbon, nitrogen, and phosphorus in farmland soils in Southern China: spatial pattern and related dominates. *Catena* 217:106468. <https://doi.org/10.1016/j.catena.2022.106468>
- Huang N, Wang L, Song XP, Black TA, Jassal RS, Myneni RB, Wu CY, Wang L, Song WJ, Ji DB, Yu SS, Niu Z (2020) Spatial and temporal variations in global soil respiration and their relationships with climate and land cover. *Sci Adv* 6:eabb8508. <https://doi.org/10.1126/sciadv.abb8508>
- Huang T, Yang N, Lu C, Qin X, Siddique KH (2021) Soil organic carbon, total nitrogen, available nutrients, and yield under different straw returning methods. *Soil Till Res* 214:105171. <https://doi.org/10.1016/j.still.2021.105171>
- Islam A, Saha RC (1969) Effects of silicon on the chemical composition of rice plants. *Plant Soil* 30:446–458
- Jackson ML, Lim CH, Zelany LW (1986) Oxides, hydroxides and alumina silicates. In *Methods of Soil Analysis. Part 1. Physics and mineralogical method*. Soil Sci Soc Am Mad WI 101–150
- Jia XL, Fu TT, Hu BF, Shi Z, Zhou LQ, Zhu YW (2020) Identification of the potential risk areas for soil heavy metal pollution based on the source-sink theory. *J Hazard Mater* 393:122424. <https://doi.org/10.1016/j.jhazmat.2020.122424>
- Jin ZQ, Shah T, Zhang L, Liu HY, Peng SB, Nie LH (2020) Effect of straw returning on soil organic carbon in rice–wheat rotation system: a review. *Food Energy Secur* 9:e200. <https://doi.org/10.1002/fes3.200>
- Li Q, Li A, Dai T, Fan ZM, Luo YL, Li S, Yuan DG, Zhao B, Tao Q, Wang CQ, Li B, Gao XS, Li YD, Li HX, Wilson JP (2020) Depth-dependent soil organic carbon dynamics of croplands across the Chengdu Plain of China from the 1980s to the 2010s. *Glob Chang Biol* 26(7):4134–4146. <https://doi.org/10.1111/gcb.15110>
- Liaw A, Wiener M (2002) Classification and regression by randomForest. *R News* 2:18–22
- Liu F, Wu H, Zhao YG, Li DC, Yang JL, Song XD, Shi Z, Zhu AX, Zhang GL (2022) Mapping high resolution national soil information grids of China. *Sci Bull* 67:328–340. <https://doi.org/10.1016/j.scib.2021.10.013>
- Liu M, Han G, Li X (2021a) Comparative analysis of soil nutrients under different land-use types in the Mun River basin of Northeast Thailand. *J Soil Sediment* 21:1136–1150. <https://doi.org/10.1007/s11368-020-02870-2>
- Liu Z, Hou L, Zhu Y, Xu X (2021b) Vertical distribution and regulation of Olsen-phosphorus in 6-m soil profiles after farmland-to-apple orchard conversion on the Chinese Loess Plateau. *Catena* 202:105254. <https://doi.org/10.1016/j.catena.2021.105254>
- Lourenco J, Newman EA, Ventura JA, Milanez CRD, Thomaz LD, Wandekoken DT, Enquist BJ (2021) Soil-associated drivers of plant traits and functional composition in Atlantic Forest coastal tree communities. *Ecosphere* 12:e03629. <https://doi.org/10.1002/ecs2.3629>
- Ma JF, Takahashi E (1990) Effect of silicon on growth and phosphorus uptake of rice. *Plant Soil* 126:115–119. <https://linkspringer.53y.com/article/https://doi.org/10.1007/BF00041376>
- Malobane ME, Nciizah AD, Mudau FN, Wakindiki II (2020) Tillage, crop rotation and crop residue management effects on nutrient availability in a *sweet sorghum*-based cropping system in marginal soils of South Africa. *Agronomy* 10:776. <https://doi.org/10.3390/agronomy10060776>
- Matias L, Castro J, Zamora R (2011) Soil-nutrient availability under a global-change scenario in a Mediterranean mountain ecosystem. *Global Change Biol* 17:1646–1657. <https://doi.org/10.1111/j.1365-2486.2010.02338.x>
- Mei XY, Gao JS, Yang XY, Huang J, Cai ZJ, Li DC, Wang BR, Liu KL, Xu MG, Zhang HM (2016) The response of soil potassium availability in rhizospheric soil of winter wheat to acidified and limed red soil. *J Plant Nutr Fertil* 22:1568–1577 (in Chinese)
- Moser KF, Ahn C, Noe GB (2009) The influence of microtopography on soil nutrients in created mitigation wetlands. *Restor Ecol* 17:641–651. <https://doi.org/10.1111/j.1526-100X.2008.00393.x>
- Munnaf MA, Mouazen AM (2022) Removal of external influences from on-line vis-NIR spectra for predicting soil organic carbon using machine learning. *Catena* 211:106015. <https://doi.org/10.1016/j.catena.2022.106015>


- Nelson DW, Sommers LE (1983) Total carbon, organic carbon, and organic matter. *Methods Soil Anal Part 2 Chem Microbiol Prop* 9:539–579
- Office of the National Soil Survey (1998) *Soil in China*. China Agricultural Press, Beijing
- Osland MJ, Gabler CA, Grace JB, Day RH, McCoy ML, McLeod JL, From AS, Enwright NM, Feher LC, Hartley SB (2018) Climate and plant controls on soil organic matter in coastal wetlands. *Global Change Biol* 24:5361–5379. <https://doi.org/10.1111/gcb.14376>
- Peng J, Biswas A, Jiang QS, Zhao RY, Hu J, Hu BF, Shi Z (2019) Estimating soil salinity from remote sensing and terrain data in southern Xinjiang Province, China. *Geoderma* 337:1309–1319. <https://doi.org/10.1016/j.geoderma.2018.08.006>
- Petersen LW, Moldrup P, Jacobsen OH, Rolston DE (1996) Relations between specific surface area and soil physical and chemical properties. *Soil Sci* 161:9–21. <https://doi.org/10.1097/00010694-199601000-00003>
- Pilesjo P, Thylen L, Persson A (2005) Topographical data for delineation of agricultural management zones[C]//Precision agriculture'05. Papers presented at the 5th European Conference on Precision Agriculture, Uppsala, Sweden. *Wagen Acad Publ* 819–826. <https://www.cabdirect.org/cabdirect/abstract/20053127887>
- Pregitzer KS, King JS (2005) Effects of soil temperature on nutrient uptake. In *Nutr Acqu Plants* (pp. 277–310). Springer, Berlin, Heidelberg
- Qian XJ, Zhang XF, Zeng WL, Jiang DB, Xiong DZ (2015) A study of soil pH spatial distribution and its correlation with the available nutrients in tobacco-growing areas of Longyan City. *J Suzhou Univ Sci Technol (Natural Science)* 32:75–80 (In Chinese)
- R Development Core Team (2013) *R: a language and environment for statistical computing*
- RESDC (2017) *Resources and Environmental Sciences Data Center*. Chin Acad Sci. Available from: <http://www.resdc.cn/>. Accessed 11 Nov 2021
- Schollenberger CJ, Simon RH (1945) Determination of exchange capacity and exchangeable bases in soils – ammonium acetate method. *Soil Sci* 59:13–24
- Sheng H, Yin ZR, Zhou P, Thompson ML (2022) Soil C: N: P ratio in subtropical paddy fields: variation and correlation with environmental controls. *J Soil Sediment* 22:21–31. <https://doi.org/10.1007/s11368-021-03046-2>
- Skinner BJ (1979) Earth resources. *Proc Natl Acad Sci USA* 76:4212–4217. <https://doi.org/10.1073/pnas.76.9.4212>
- Solly EF, Weber V, Zimmermann S, Walthert L, Hagedorn F, Schmidt WI (2020) A critical evaluation of the relationship between the effective cation exchange capacity and soil organic carbon content in Swiss forest soils. *Front for Glob Chang* 3:98. <https://doi.org/10.3389/ffgc.2020.00098>
- Song K, Yang J, Xue Y, Lv W, Zheng X, Pan J (2016) Influence of tillage practices and straw incorporation on soil aggregates, organic carbon, and crop yields in a rice-wheat rotation system. *Sci Rep* 6:36602. <https://doi.org/10.1038/srep36602>
- Souza LF, Billings SA (2021) Temperature and pH mediate stoichiometric constraints of organically derived soil nutrients. *Global Change Biol* 28:1630–1642. <https://doi.org/10.1111/gcb.15985>
- Spargo JT, Alley MM (2008) Modification of the Illinois soil nitrogen test to improve measurement precision and increase sample throughput. *Soil Sci Soc Am J* 72:823–829. <https://doi.org/10.2136/sssaj2007.0269>
- Town JR, Gregorich EG, Drury CF, Lemke R, Phillips LA, Helgason BL (2022) Diverse crop rotations influence the bacterial and fungal communities in root, rhizosphere and soil and impact soil microbial processes. *Appl Soil Ecol* 169:104241. <https://doi.org/10.1016/j.apsoil.2021.104241>
- Wallace A (1989) Relationships among nitrogen, silicon, and heavy metal uptake. *Soil Sci* 147:457–460. <https://doi.org/10.1097/00010694-198906000-00019>
- Wang J, Wang X, Xu M, Feng G, Zhang W (2015) Crop yield and soil organic matter after long-term straw return to soil in China. *Nutr Cycl Agroecosys* 102:371–381. <https://doi.org/10.1007/s10705-015-9710-9>
- Wang L, Ashraf U, Chang C, Abrar M, Cheng X (2020) Effects of silicon and phosphatic fertilization on rice yield and soil fertility. *J Soil Sci Plant Nut* 20:557–565. <https://doi.org/10.3389/fmicb.2021.749946>
- Wang R, Zou R, Liu J, Liu L, Hu Y (2021b) Spatial distribution of soil nutrients in farmland in a hilly region of the Pearl River Delta in China based on geostatistics and the inverse distance weighting method. *Agric Basel* 11:50
- Wang S, Huang X, Zhang Y, Yin C, Richel A (2021b) The effect of corn straw return on corn production in Northeast China: an integrated regional evaluation with meta-analysis and system dynamics. *Resour Conserv Recy* 167:105402. <https://doi.org/10.1016/j.resconrec.2021.105402>
- Wang X, Hu W, Ning X, Wei W, Tang Y, Gu Y (2022) Effects of potassium fertilizer and straw on maize yield, potassium utilization efficiency and soil potassium balance. *Arch Agron Soil Sci* 1–14. <https://doi.org/10.1080/03650340.2022.2025997>
- Wang YL, Wu PN, Mei FJ, Ling Y, Qiao YB, Liu CS, Leghari SJ, Guan XK, Wang TC (2021c) Does continuous straw returning keep China farmland soil organic carbon continued increase? A meta-analysis. *J Environ Manage* 288:12391. <https://doi.org/10.1016/j.jenvman.2021.112391>
- Webster R, Oliver MA (2007) *Geostatistics for environmental scientists*. John Wiley & Sons
- Winterdahl M, Erlandsson M, Futter MN, Weyhenmeyer GA, Bishop K (2014) Intra-annual variability of organic carbon concentrations in running waters: drivers along a climatic gradient. *Global Biogeochem Cy* 28:451–464. <https://doi.org/10.1002/2013GB004770>
- Wright AL, Hanlon EA, Sui D, Rice R (2009) Soil pH effects on nutrient availability in the Everglades Agricultural Area. *EDIS* 2009
- Wu T, Li C, Xing X, Pan X, Liu C, Tian Y, Wang ZY, Zhao JS, Wang J, P., He, B., (2022) Straw return and organic fertilizers instead of chemical fertilizers on growth, yield and quality of rice. *Earth Sci Inform* 15:1363–1369. <https://doi.org/10.1007/s12145-021-00745-9>
- Wu Z, Liu Y, Han Y, Zhou J, Liu J, Wu J (2021) Mapping farmland soil organic carbon density in plains with combined cropping system extracted from NDVI time-series data. *Sci Total Environ* 754:142120. <https://doi.org/10.1016/j.scitotenv.2020.142120>
- Xia F, Hu BF, Shao S, Xu DY, Zhou Y, Zhou Y, Huang MX, Li Y, Chen SC, Shi Z (2019) Improvement of spatial modeling of Cr, Pb, Cd, As and Ni in soil based on portable X-ray fluorescence (PXRF) and geostatistics: a case study in East China. *Int J Env Res Pub He* 16:2694. <https://doi.org/10.3390/ijerph16152694>
- Xia F, Zhu YW, Hu BF, Chen XY, Li HY, Shi KJ, Xu LC (2021) Pollution characteristics, spatial patterns, and sources of toxic elements in soils from a typical industrial city of Eastern China. *Land* 10:1126. <https://doi.org/10.3390/land10111126>
- Xiang XM, De KJ, Feng TX, Lin WS, Qian SW, Wei XJ, Wang W, Xu CT, Zhang L, Geng XP, (2022) Effect of exogenous nitrogen addition on inter-monthly variation of plant-soil nutrients in alpine meadow. *Acta Agrestia Sinica* 1–18[2022–07–16]. <http://kns.cnki.net/kcms/detail/11.3362.S.20220509.0958.004.html>. Accessed 12 Dec 2022
- Xie MD, Li HY, Zhu YW, Xue J, You QH, Jin B, Shi Z (2021) Bioaccumulation of potentially toxic element in soil-rice systems using multi-source data and machine learning methods: a case study of an industrial city in Southeast China. *Land* 10:558. <https://doi.org/10.3390/land10060558>
- Yan FP, Shanguan W, Zhang J, Hu BF (2020) Depth-to-bedrock map of China at a spatial resolution of 100 meters. *Sci Data* 7:1–13. <https://doi.org/10.1038/s41597-019-0345-6>

- Yan K, Dong Y, Gong Y, Zhu Q, Wang Y (2021a) Climatic and edaphic factors affecting soil bacterial community biodiversity in different forests of China. *Catena* 207:105675. <https://doi.org/10.1016/j.catena.2021.105675>
- Yan X, Yang W, Muneer MA, Zhang S, Wang M, Wu L (2021b) Land-use change affects stoichiometric patterns of soil organic carbon, nitrogen, and phosphorus in the red soil of Southeast China. *J Soil Sediment* 21:1–11. <https://doi.org/10.1007/s11368-021-02953-8>
- Yanai J, Taniguchi H, Nakao A (2016) Evaluation of available silicon content and its determining factors of agricultural soils in Japan. *Soil Sci Plant Nutr* 62(5–6):511–518. <https://doi.org/10.1080/00380768.2016.1232601>
- Yu Z, Wang M, Huang Z, Lin TC, Vadeboncoeur MA, Searle EB, Chen HYY (2018) Temporal changes in soil C-N-P stoichiometry over the past 60 years across subtropical China. *Global Change Biol* 24:1308–1320. <https://doi.org/10.1111/gcb.13939>
- Yuan ZY, Jiao F, Shi XR, Sardans J, Maestre FT, Delgado-Baquerizo M, Reich PB, Peñuelas J (2017) Experimental and observational studies find contrasting responses of soil nutrients to climate change. *Elife* 6:e23255. <https://doi.org/10.7554/eLife.23255.001>
- Zhalnina K, Dias R, de Quadros PD, Davis-Richardson A, Camargo FA, Clark IM, McGrath SP, Hirsch PR, Triplett EW (2015) Soil pH determines microbial diversity and composition in the park grass experiment. *Microb Ecol* 69:395–406. <https://doi.org/10.1007/s00248-014-0530-2>
- Zhang S, Zhang G, Wang D, Liu Q (2021a) Long-term straw return with N addition alters reactive nitrogen runoff loss and the bacterial community during rice growth stages. *J Environ Manage* 292:112772. <https://doi.org/10.1016/j.jenvman.2021.112772>
- Zhang S, Zhang G, Wang D, Liu Q (2021b) Abiotic and biotic effects of long-term straw retention on reactive nitrogen runoff losses in a rice-wheat cropping system in the Yangtze Delta region. *Agr Ecosyst Environ* 305:107162. <https://doi.org/10.1016/j.agee.2020.107162>
- Zhao J, Dong Y, Xie XB, Li X, Zhang XX, Shen X (2011) Effect of annual variation in soil pH on available soil nutrients in pear orchards. *Acta Ecol Sin* 31:212–216. <https://doi.org/10.1016/j.chnaes.2011.04.001>
- Zhao XL, Gao S, S., Lu, D, J., Chen, X.Q., Feng, W.Q., Wang, Y., Zhao, S.M., Wang, H.Y., (2022) Analysis of mechanisms of soil potassium-holding capacity using different soils of China. *Agron J* 114:825–834. <https://doi.org/10.1002/agj2.20961>
- Zhao S, He P, Qiu S, Jia L, Liu M, Jin J, Johnston AM (2014) Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. *Field Crop Res* 169:116–122. <https://doi.org/10.1016/j.fcr.2014.09.017>
- Zhou Y, Chen S, Zhu AX, Hu B, Shi Z, Li Y (2021) Revealing the scale-and location-specific controlling factors of soil organic carbon in Tibet. *Geoderma* 382:114713. <https://doi.org/10.1016/j.geoderma.2020.114713>
- Zhu HH, Wu JS, Huang DY, Zhu QH, Liu SL, Su YR, Wei WX, Syers JK, Li Y (2010) Improving fertility and productivity of a highly-weathered upland soil in subtropical China by incorporating rice straw. *Plant Soil* 331:427–437. <https://doi.org/10.1007/s11104-009-0263-z>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Bifeng Hu^{1,2} · Modian Xie^{1,2} · Hongyi Li^{1,2}  · Rebin He¹ · Yue Zhou³ · Yefeng Jiang^{1,2,4} · Wenjun Ji⁵ · Jie Peng⁶ · Fang Xia⁷ · Zongzheng Liang⁸ · Wanming Deng¹ · Junjie Wang¹ · Zhou Shi^{5,9}

✉ Hongyi Li
lihongyi1981@zju.edu.cn

¹ Department of Land Resource Management, School of Public Finance and Public Administration, Jiangxi University of Finance and Economics, Nanchang 330013, China

² Key Laboratory of Data Science in Finance and Economics, Jiangxi University of Finance and Economics, Nanchang 330013, China

³ Earth and Life Institute, Catholic University of Louvain, 1348 Louvain-La-Neuve, Belgium

⁴ Institute of Agricultural Remote Sensing and Information Technology Application, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310058, China

⁵ College of Land Science and Technology, China Agricultural University, Beijing 100085, China

⁶ College of Plant Science, Tarim University, Alar 843300, China

⁷ College of Economics and Management, Zhejiang A&F University, Hangzhou 311300, China

⁸ Academy of Regional and Global Governance, Beijing Foreign Studies University, Beijing 100089, China

⁹ Key Laboratory of Environment Remediation and Ecological Health, Ministry of Education, College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 310058, China