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Spatiotemporal prediction and optimization of environmental suitability in citrus-producing areas

Zhenyu Wu[1], Shizhao Zou[1], Yong Yang[1], Xue Yang[1], Qingzhong Han[2], Chang Chen[1]*, Mingxia Wang[1] and Wenfeng Tan[1]

[1]State Environmental Protection Key Laboratory of Soil Health and Green Remediation, College of Resources and Environment, Huazhong Agricultural University, Wuhan, China, [2]Agricultural Science and Technology Service Center of Zigui County, Yichang, Hubei, China

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EDITED BY
Qingsong He,
Huazhong University of Science and Technology, China

REVIEWED BY
Xufeng Fei,
Zhejiang Academy of Agricultural Sciences, China
Linchuan Fang,
Northwest A&F University, China

*CORRESPONDENCE
Chang Chen,
changchen@mail.hzau.edu.cn

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The increasing need for citrus has driven the rapid expansion of citrus planting areas. However, not all areas are suitable for growing citrus. It is necessary to understand the future changing trend of environmental suitability in citrus-producing areas. Here, based on the soil nutrient data of citrus cultivation from 2006 to 2018, the spatiotemporal kriging method was used to predict the spatiotemporal distribution of soil nutrients in Zigui County, Hubei Province. Then, geographical and meteorological conditions were combined to evaluate the suitability for citrus cultivation at temporal and spatial levels, and the results were verified by the yield and quality data of citrus. The results showed that from 2018 to 2027, the overall suitability of the citrus-producing area displayed a gradually rising trend, with the “suitable” producing area increasing from 4.5% to 20.16%. The validation results indicated that the mean relative errors of spatiotemporal predictors were less than 30% except for the effective iron. Correlation analysis revealed that the proportion of “moderately suitable” and “suitable” orchards had significant positive correlations with annual yield. The low suitability of Maoping town was mainly attributed to its soil acidification and available P content, and that of Shazhenxi town was ascribed to its low soil contents of available P and N. The optimal fertilization scheme was constructed by an artificial neural network to optimize the fertilization status of some citrus producing areas. This study has created a dynamic assessment of the environmental suitability of citrus production areas to support improvements in citrus production.

KEYWORDS

citrus, spatiotemporal kriging, environmental suitability, artificial neural network, regulation optimization

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Introduction

Citrus is one of the most important fruit industries in the world and was planted in approximately 140 countries or regions with a planting area of more than 6.8 million ha and an annual yield of approximately 120 million tons in 2019. However, a specific environment and nutrition are required for citrus cultivation. A suitable planting environment can improve the flavor quality of citrus and reduce the use of pesticides and chemical fertilizers. As a perennial plant, citrus has a very long life cycle. Once planted, the planting environment will have a great impact on the quality of citrus throughout its whole life cycle. Therefore, the choice of an appropriate location for citrus planting is significant. In recent years, with the aim of pursuing greater economic benefits, planting citrus has become increasingly intensified, leading to an unsustainable expansion of citrus production areas (David et al., 2002). Many essential nutrients are required for the normal growth, development and fruiting of citrus trees. The selection and breeding of new varieties and cultivation optimization are the main approaches to promote yield and quality; moreover, fertilization is an even more critical factor that determines yield and quality (Ramana et al., 1981). Due to the different effects of different nutrients on the growth and quality of citrus, both excessive and inadequate application of certain nutrients will cause imbalanced soil nutrition for citrus fruit (Srivastava et al., 2002). Typical examples include a large excess of nitrogen (average 712 kg N ha^{-1}), phosphorus (average 364 kg P_2O_5 ha^{-1}), and potassium fertilizers (average 565 kg K_2O ha^{-1}) applied annually (Li et al., 2020). This unbalanced fertilization aggravated soil Mg depletion in 89% of citrus orchards (Yuheng et al., 2022). In addition, magnesium deficiency induces lignification, enlargement and cracking of citrus leaves (Xin et al., 2021).

The quality and yield of citrus are jointly affected by various factors, such as terrain, thickness of the effective soil layer, temperature, precipitation, and soil fertility (Francis, 1963). Hence, some researchers have introduced the concept of environmental suitability into citrus cultivation, which can facilitate better utilization of agricultural resources in citrus-producing areas (Marzieh and Abbas, 2018). Previous studies have demonstrated that altitude, precipitation, extreme weather, and soil fertility are all key factors determining land sustainability for citrus production. Among the geomorphological parameters, aspect has a relatively weak influence on citrus yield (Hasan et al., 2015). The location selection of citrus orchard and the average temperature in the winter season were determined to be the most crucial sub-criteria for citrus cultivation, followed by elevation, the average temperature in the flowering period, land use capability, daily average sunshine time, annual average precipitation, proximity to irrigation ponds and dam lakes, and others. (Emre and Mehmet, 2020). Edward compared the evaluation results of experts and farmers on the suitability of citrus planting and found that there were great differences in the judgment between experts and farmers, and these differences were mainly related to the consideration of soil surface properties. Hence, understanding and monitoring the dynamics of surface soil are the basis for decision making in land utilization (Edward et al., 2019). In previous studies, GIS and multicriteria decision analysis constituted vital methods used to determine the optimal cultivation areas for citrus. These research frameworks usually used land utilization/land cover ratio, meteorological data, landform and irrigation areas as the key evaluation indices (Orhan, 2021), and this approach requires the support of large spatial data and is therefore difficult to implement. To address this need, the spatiotemporal kriging method, which has been widely used to determine the spatial distribution of rainfall, PM2.5 and heavy metals, can be used. However, there has been no report about the application of the spatiotemporal kriging method to environmental suitability (Dangui et al., 2017) evaluations of citrus production, and this method could be used to predict the spatiotemporal changes in the environmental suitability of citrus-producing areas and facilitate the formulation of more reasonable management measures for citrus orchards.

Therefore, this study predicted the pH and nutrients in citrus orchards with the spatiotemporal kriging method by combining the geographical characteristics and climate conditions of the study area. The results were then validated based on the field data of yield and fruit quality. Furthermore, the reasons behind areas having lower suitability for fruit production were analyzed, and some strategies for improving suitability were proposed. Finally, some approaches for optimizing citrus orchards were suggested from the perspective of fertilization. The findings are expected to help promote soil fertility and improve management to enhance citrus orchard yield and fruit quality.

Materials and methods

Overview of the study area

The study area is Zigui County (110°18′–111°0′E; 30°38′–31°11′N) located at the head of the Three Gorges Reservoir area, Hubei Province, China. Zigui County consists of twelve towns, including Maoping, Quyuan, Guizhou, Shuitianba, Xietan, Shazhenxi, Lianghekou, Meijiahe, Moping, Guojiaba, Yanglinqiao, and Jiuwanxi, with a total area of 2,427 km^2 (Figure 1). Forestland, arable land and grassland are the dominant land utilization patterns. By the end of 2020, the citrus-producing area in Zigui County reached more than 23,200 ha, which accounted for nearly 69% of the total arable land, and the annual yield of citrus fruit was 609,500 tons.

Soil physical and chemical properties, particularly nutrients, vary greatly depending on the properties of the soil parent material (Oyatokun et al., 2017). To ensure a scientific and reasonable prediction, the distribution map of soil types in Zigui County

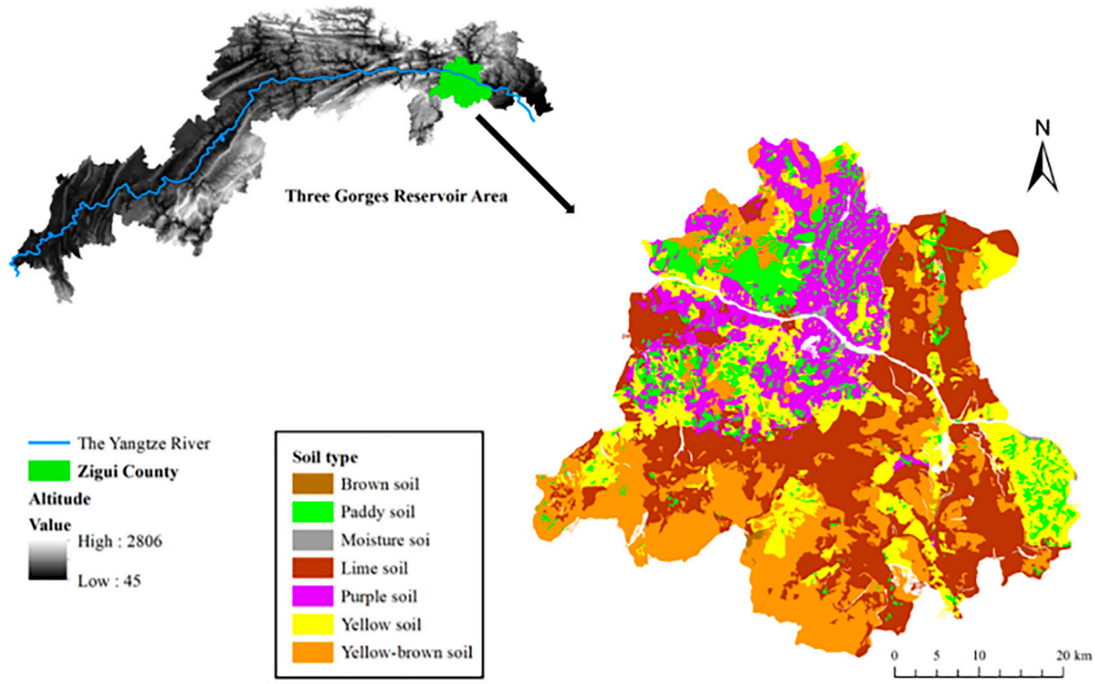

FIGURE 1
Geographical location and soil type of Zigui country in the Three Gorges Reservoir area.

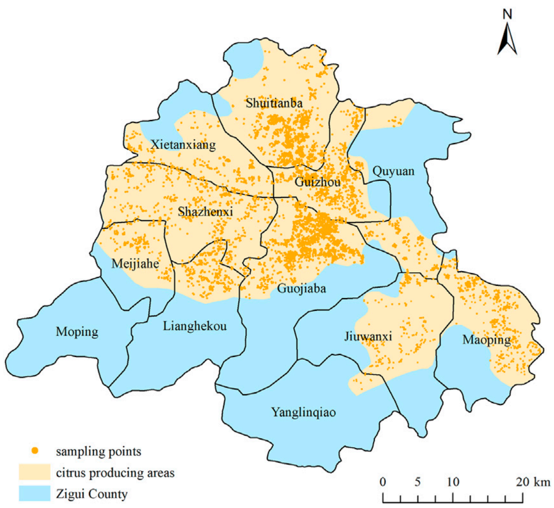

FIGURE 2
The spatial distribution of the soil samples in Zigui County.

was first obtained. Then, more advanced spatial processing was conducted according to the soil types of the sampling sites, and the boundaries of the citrus-producing areas were determined based on the distribution of the soil sampling sites. The evaluation area of citrus environmental suitability was 33,629 ha.

Data collection

The soil samples (7,709 samples) were derived from the sampling sites used to test soil for formulated fertilization (2006–2018) at the Agricultural Science and Technology Service Center of Zigui County. The spatial distribution of sampling points is shown in Figure 2. The physical and chemical properties of the sampling points are determined by the inspectors of Zigui County agricultural and rural bureau every year. The soil pH was determined at a soil/water ratio of 1: 2.5. The sodium bromate digestion method was used to determine the soil organic matter (SOM) content. The available P was extracted with 0.5 M $NaHCO_3$ (pH 8.5) and analyzed using molybdenum blue calorimetry. The content of $NH4^+$-N in each treatment was analyzed by the phenol hypochlorite method. The content of NO^{3-}-N was analyzed using the UV spectroscopy method (Liu et al., 2020), and the sum of $NH4^+$-N and NO^{3-}-N content was taken as the content of available N. Ammonium acetate (1 mol L^{-1} NH_4OAc pH 7.0) was used to extract available K, which was measured using a flame photometer (SherwoodM410). Available manganese (Mn), copper (Cu), and zinc (Zn) in the soil were determined by inductively coupled plasma–mass spectrometry. Spectrophotometric determination of available iron (Fe) in the soil was conducted with potassium thiocyanate in the presence of Emulgent OP.

The citrus yield data were derived from the 2021 report of the Zigui government, and the determination and grading of citrus fruit quality were conducted according to the national standard GB/T 21488-2008 (Li et al., 2015). For quality determination, fruit samples were collected from orchards with different suitability levels, and the topographic data were derived from the Geospatial Data Cloud (2020) ASTER GDEM 30M http://www.gscloud.cn/sources/accessdata/310?pid=302.cn/[Accessed 16 May 2020].

Previous research has demonstrated that an excessively high or low altitude has significant impacts on illumination intensity and temperature, thereby affecting the growth and development of citrus (Jenkins et al., 2015). Hence, by combining relevant research findings and the local situation, an altitude of 600 m was set as the threshold of suitability for citrus cultivation. Accordingly, the areas above 600 m in altitude were set as unsuitable areas for citrus cultivation, and the influence factor map of altitude was obtained through digital elevation model analysis (Supplementary Figure S1). The slope of cultivated land has significant impacts on agricultural production as well. If the slope is too large, then it is likely to cause soil erosion. The Law of People's Republic of China on Water and Soil Conservation stipulates that a slope >25° is the slope limit for land reclamation where the cultivation of crops is prohibited. If an area with this slope has been reclaimed as cultivated land, then it must be gradually returned from farmland to forest and grassland. Accordingly, the areas with a slope exceeding 25° were regarded as unsuitable for citrus cultivation, and the influence factor map of the slope was obtained (Supplementary Figure S2) (Xu et al., 2012). The precipitation and temperature data were obtained from the meteorological station of Zigui County and the WheatA Meteorological Data System. It has been reported that the precipitation amount suitable for citrus growth and development is 1,000–1,500 mm (Traboulsi, 2013). The annual mean precipitation of Zigui County is 1,000–1,400 mm, and the annual mean temperature is approximately 15°C; thus, both precipitation and temperature are within the suitable range for the growth of citrus (Rafael et al., 2019).

Spatiotemporal prediction and accuracy verification method

The spatiotemporal kriging method was adopted to determine the soil pH and nutrients, aiming to predict the attribute values of undetermined space-time points by utilizing the determined values of some adjacent space-time points (Yong et al., 2015) (Bei and Yong, 2017) (Yong et al., 2018). First, the spatiotemporal variables were defined as $Z(x) = \{ Z(s, t) | s \in S, t \in T \}$, where S represents the spatial domain, $S \in R^2$, T represents the time domain, $T \in R$, s represents the specific spatial coordinates, t represents the time value, and R represents the set of real numbers. The purpose of spatiotemporal kriging is to use the attribute values of several measured spatiotemporal points to predict the target attribute values of unmeasured spatiotemporal points (S0, t0):

$$Z_0 = \sum_{i=1}^{n} \lambda i Z i, \ \sum_{i=1}^{n} \lambda i = 1 \tag{1}$$

where Z_0 is the unknown point, Zi (i = 1…,n) indicates several known points, and λi is the weight coefficient. Therefore, under Eigen's hypothesis, the spatiotemporal variogram was defined to calculate the spatiotemporal semivariance of the test.

$$f(h_S, h_T) = \frac{1}{2N(h_S, h_T)} \sum_{i=1}^{N(h_S,h_T)} [Z(s,t) - Z(s + h_S, t + h_T)]^2 \tag{2}$$

where $h_S$and h_T are space and time interval variables, respectively, and $N(h_S, h_T)$ is the number of point pairs in the sample that meet the defined space and time interval. When the theoretical spatiotemporal variogram is determined, the spatiotemporal kriging method is similar to common kriging interpolation. In this study, based on the model of space-time combination determined by the Bilonick formula (Richard, 1988), the spatiotemporal comprehensive variation structure model is defined as:

$$\gamma(h_S, h_T) = \gamma_S(h_S) + \gamma_T(h_T) + \gamma_{ST}(h_{ST}) \tag{3}$$

where $\gamma(h_S, h_T)$ is a theoretical spatiotemporal variation value, $\gamma_S(h_S)$ and $\gamma_T(h_T)$ are spatial and temporal variation models, respectively, and $\gamma_{ST}(h_{ST})$ represents pure geometric variation in space-time, which does not include banded variation with space or time. These three theoretical variograms follow the form of spatial variograms, such as hemispherical model, exponential model, Gaussian model, linear model, *etc.*

Precision validation was performed with the cross test method. Mean relative error (MRE) was used to evaluate the precision of the predicted values, with a lower MRE value indicating higher precision. The MRE was calculated with Eq. 4 as follows:

$$MRE = \frac{1}{n} \sum_{i=1}^{n} |Z(x_i) - Z^*(x_i)| / Z(x_i) \tag{4}$$

where $Z(x_i)$ is the actual value of the sample and $Z^*(x_i)$ is the predicted value.

Evaluation of environmental suitability

In this study, the environmental suitability for citrus-producing areas refers to the suitability of the planting environment of citrus orchards for citrus growth. Annual mean precipitation, annual mean temperature, altitude, slope, SOM, available N, available P, available K, pH, available Fe, available Mn, available Cu and available Zn were taken as factors affecting the environmental suitability for growing citrus in the study area. Three thematic indicators, including climate, geography and soil fertility, were used in assessing environmental suitability.

The analytical hierarchy process (AHP) method was used to calculate the weight of each prediction indicators (Satiprasad et al., 2016). The relative importance of each indicator is determined by a number of local citrus planting experts. By combining the membership function, the status of the evaluation indices and their relationship with the suitability of citrus cultivation were assessed. The evaluation indices were nondimensionalized, and the subordinating degree function was set at 0–1, with a higher value indicating a higher suitability (Eddie et al., 2002). According to the relationship of different nutrients with citrus growth, the S-shape function was adopted for four soil fertility indices, organic matter, available N, available P, and available K, and the trapezoid function was adopted for other indices, as shown in Supplementary Table S1. The degree of membership was calculated with Eqs 5, 6.

$$f(x) = \begin{cases} 1.0 & x \geq x_2 \\ 0.9(x - x_1)/(x_2 - x_1) + 0.1 & x_1 \leq x < x_2 \\ 0.1 & x < x_1 \end{cases} \tag{5}$$

$$f(x) = \begin{cases} 1.0 - 0.9(x - x_3)/(x_4 - x_3) & x_3 < x \leq x_4 \\ 1.0 & x_2 \leq x \leq x_3 \\ 0.9(x - x_1)/(x_2 - x_1) + 0.1 & x_1 \leq x < x_2 \\ 0.1 & x < x_1, x > x_4 \end{cases} \tag{6}$$

The threshold value of the membership function was determined through data and results related to long-term planting, production, and practice and previous research. In this study, the threshold value of the membership function was set according to the classification indices of soil nutrients in citrus orchards in Hubei Province (Supplementary Table S2) and the Three Gorges Reservoir Region.

Layer rasterization was performed to assign suitable areas with a value of one and problematic areas with a value of 0 for citrus cultivation in terms of terrain, precipitation, and temperature. The values of all rasters were first summed and then multiplied by the assigned value (0 or 1) of each influencing factor to evaluate cultivation suitability.

Regulation of soil fertility

An artificial neural network is a nonlinear complex network composed of many simple neurons; effective in pattern recognition, program decision and knowledge management with incomplete information; and particularly suitable for solving nonlinear problems (Yusuf et al., 2008). Here, soil pH and various nutrients were taken as the input variables of the neural network, and the fertilization status was taken as the output variable for the fitting of the neural network. Then, the optimal fertilization regime was obtained by using the well-trained neural network with the optimal fertilizer parameters as the input.

Results and discussion

Spatiotemporal prediction and precision validation of the evaluation indices

With the change in years, most of the evaluation indices tend to improve, but some of them remain stable or even deteriorate.

As shown in Supplementary Figures S3, S4, S10, S11, the pH, available N, available Cu and available Zn were relatively stable in the citrus-producing area from 2018 to 2027. In the orchards of Shuitianba and Maoping towns, 1,101.78 ha and 3,064.88 ha of the soils showed relatively severe acidification (pH < 5.5), accounting for 26.83% and 36.06% of the orchard area, respectively. The soils in most orchards of the other towns had pH values >6.5, which is relatively alkaline for the growth of citrus. In addition, the area of orchard soils with "deficient" available N was 33176.25 ha, accounting for 79.53% of the main producing area. Available Cu is highly stable but was always "deficient" in some orchards in Shuitianba, Guizhou, and Guojiaba, while it was "excessive" in almost 50% of the orchard soil in Maoping. Moreover, available Zn was "extremely deficient" in the soils of some orchards in Shuitianba, Guizhou and Guojiaba and was at an "appropriate" level in most orchards in the other towns.

According to Supplementay Figures S5, S7, S8, available P in the orchards of Shuitianba, Guizhou, Guojiaba and Lianghekou towns was at an "appropriate" level during the 10 years, while it was "deficient" in the orchards of the other towns and gradually improved to an "appropriate" level in some orchards with time. The organic matter content in the whole main producing area gradually increased each year, and the area with "appropriate" organic matter increased from 59.08% in 2018 to 80.91% in 2027, which was consistent with the goal of local citrus planting policies. In addition, available Mn in the soil of the whole main producing area increased gradually as well and was generally at the "appropriate" or "abundant" level.

As shown in Supplementay Figures S6, S9, available K was "deficient" in the soil of most orchards, particularly in the orchards in Maoping town. The level of available K showed an increasing tendency in the orchards in Shuitianba town, while there was a decreasing trend in available K in Guojiaba town. The level of available Fe exhibited an apparent declining trend, decreasing from an "abundant" status to a "deficient" and "appropriate" status in Shazhenxi town and to a "deficient" status in most of the orchards in Shuitianba and Xietan town. Moreover, the available Fe level was maintained at a "deficient" status for 10 years in the orchards in Guojiaba and Jiuwanxi towns.

By taking the data of 2017 as an example, the precision of the predicted results was validated based on the MRE with 70% of the sampling sites as the training set and the remaining 30% of the sampling sites as the testing set. The results are presented in Supplementay Table S3. It can be intuitively seen that the prediction results have high precision and reliability.

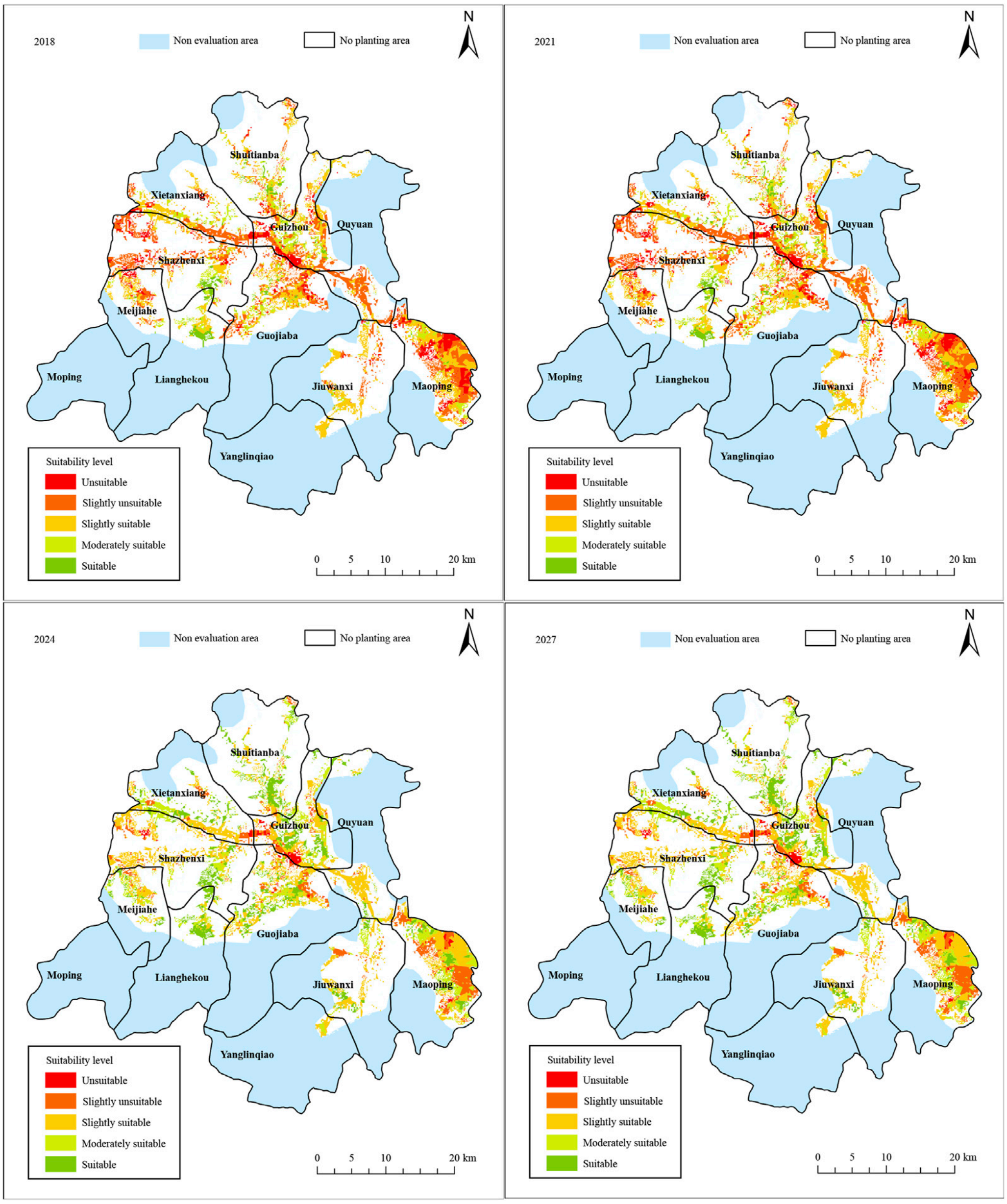

FIGURE 3
Prediction results of environmental suitability for citrus cultivation in Zigui County.

Spatiotemporal prediction of the environmental suitability of citrus cultivation

According to expert scoring, the weights of the influencing factors on environmental suitability were calculated by the AHP, and the results are shown in Supplementay Table S4. Furthermore, the weights of the influencing factors on environmental suitability under different conditions were calculated based on the membership function of each factor. The weight of each influencing factor was slightly adjusted, as shown in Supplementay Table S5.

As shown in Figure 3, from 2018 to 2027, the overall environmental suitability of the citrus-producing area shows a gradually rising trend, with the "suitable" land area increasing from 4.5% to 20.16% and the "slightly suitable" and "moderately suitable" areas increasing from 37.15% to 9.92%–43.86% and 18.83%, respectively. The reason for the increase may have been

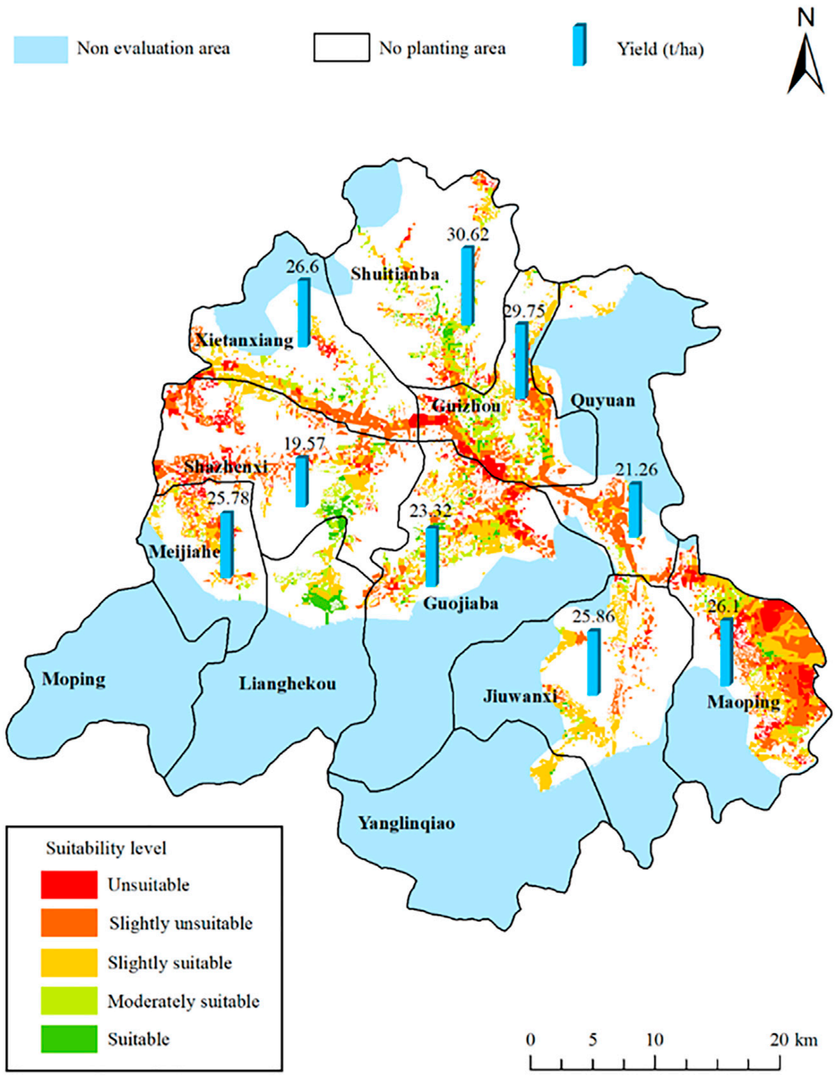

FIGURE 4
Correlations of environmental suitability with citrus yield in Zigui County.

that the local government provides excellent support to the citrus industry. For instance, the government has delivered a series of lectures to enhance the awareness of farmers on the science related to planting local orchards, and it often holds appraisal conferences to increase the enthusiasm of farmer households for citrus planting. In addition, the local government also attempts to provide solutions to the problems that occur in different orchards. For example, to address high soil acidity and low nutrient contents in some soils, biochar plus calcium silicate was proposed in combination with increasing applications of organic fertilizer and green manure to improve the soil environment (Hafeez et al., 2012). Together, these measures can promote N fixation and organic matter content, improving the fertility of orchard soil and enhancing the suitability for citrus cultivation. With these efforts, gradual increases in citrus cultivation suitability has occurred in the orchards in Zigui County. The spatial distribution of the different levels of suitability also showed apparent differences. The "unsuitable" land was mainly concentrated in the junction area between Guizhou and Guojiaba towns and Maoping and Shazhenxi towns.

Correlations of environmental suitability with citrus yield and quality

Correlation analysis revealed that the proportions of "moderately suitable" and "suitable" orchards had significant

TABLE 1 Correlations of environmental suitability with citrus quality in Zigui County.

Village	Suitability	Cultivar	High-grade (%)	First-grade (%)	Second-grade (%)	Off-grade (%)
Shangba	suitable	New hall	89	11		
Xiaba	moderately suitable	New hall	50	50		
Xiangjiawan	slightly suitable	Chang hong	22.2	55.6		22.2
Quyuanmiao	slightly unsuitable	Jiuyue hong	11.1	33.3	33.3	22.2
Pengjiapo	unsuitable	Cara	33.3	33.3		33.3

positive correlations with annual yield ($p < 0.05$) (Figure 4). Among the different towns, Shuitianba town had "moderately suitable" and "suitable" orchards, accounting for 23.19% and 11.56% of its orchards, respectively, and their annual yield was 30.62 t/ha; in contrast, Quyuan town exhibited the lowest suitability for citrus cultivation, with "moderately suitable" and "suitable" orchards accounting for 6.33% and 5.7% of its orchards, respectively, and their annual yield was as low as 21.26 t/ha.

Table 1 shows that high-grade fruit accounts for nearly 89% of the fruit from the citrus orchards with the highest suitability. From the "slightly unsuitable" orchards, second-grade and off-grade fruit appeared, and these orchards had decreasing suitability for citrus cultivation. Off-grade fruit accounted for a maximum of 33.3% in the orchards with the lowest suitability.

Analysis of areas with low suitability for citrus cultivation

In 2027, "slightly unsuitable" and "slightly suitable" orchards will still account for 30.06% and 35.29% of the orchards in Maoping town, respectively, which may be mainly attributed to the soil acidification and available P content.

As seen from Supplementary Figure S5, in the orchards in Maoping town, approximately 35.52% of the orchards show soil acidification, and 27.02% of orchards are "deficient" in available P. Soil acidification in citrus orchards can cause frequent occurrence of root rotting and death as well as decreases in the resistance of the citrus trees, which will result in increases in disease and pest damage and smaller and sour fruit (Raquel et al., 2015). A deficiency in available P can lead to the maldevelopment of fruit trees and red–purple leaves and thereby lower yield (Bouma, 1956). Moreover, soil acidification can reduce the activity of P. Therefore, the environmental suitability for citrus cultivation in this area may be promoted by the application of biochar plus calcium silicate to increase the soil pH (Zwieten et al., 2010) and at the same time by an increase in the application ratio of phosphorus fertilizer.

In 2027, "slightly suitable" orchards will still account for 56.74% of the total in Shazhenxi town, and some orchards will even be "slightly unsuitable" or "unsuitable", accounting for 8.17% and 2.34% of the total planting area, respectively. An analysis of soil pH and nutrients demonstrated that the low suitability levels could be mainly ascribed to the low contents of available P and N.

In Shazhenxi town, approximately 76.54% of citrus orchards were "deficient" in available N, and the orchards with "appropriate" available N accounted for only 22.7% of the total planting area. In addition, the soil in 77.19% of orchards was "deficient" in available P. A deficiency in available N can cause retarded growth of citrus trees, small canopies, poor flower bud differentiation, and low fruit setting rates, leading to serious yield reduction (Ling et al., 2019). The low N and P contents in this area were mainly due to the poor soil and water conservation measures for the sloping citrus orchards, which resulted in the loss of large quantities of N and P due to frequent water and soil loss (Zhiguo et al., 2017). Therefore, the conservation capacity of water and nutrients in this area should be enhanced through activities such as planting green manure, applying decomposed organic fertilizer (Peina et al., 2020), and integrating water and fertilizer to improve the fertility of the soil (Belén et al., 2016).

As shown in Figure 3, the joint area of Guojiaba and Guizhou towns is characterized by its "unsuitable" and "slightly unsuitable" status. The low suitability of this area can be mainly attributed to the high soil pH and low contents of organic matter and available N. Approximately 63.65% of citrus orchards had relatively alkaline soils, and 10.55% and 77.78% of the soil were "extremely deficient" and "deficient" in available N, respectively. High soil pH can reduce tree vigor and lead to the yellowing of citrus leaves (Syvertsen et al., 1993). Moreover, low organic matter content and a minimal application of organic fertilizer will result in poor soil physical and chemical properties in citrus orchards and, accordingly, poor soil structure, permeability and leakage (Jiawen et al., 2019). Hence, in this area, acid compound fertilizer should be applied, and at the same time, the application of organic fertilizer should be increased to enhance soil fertility.

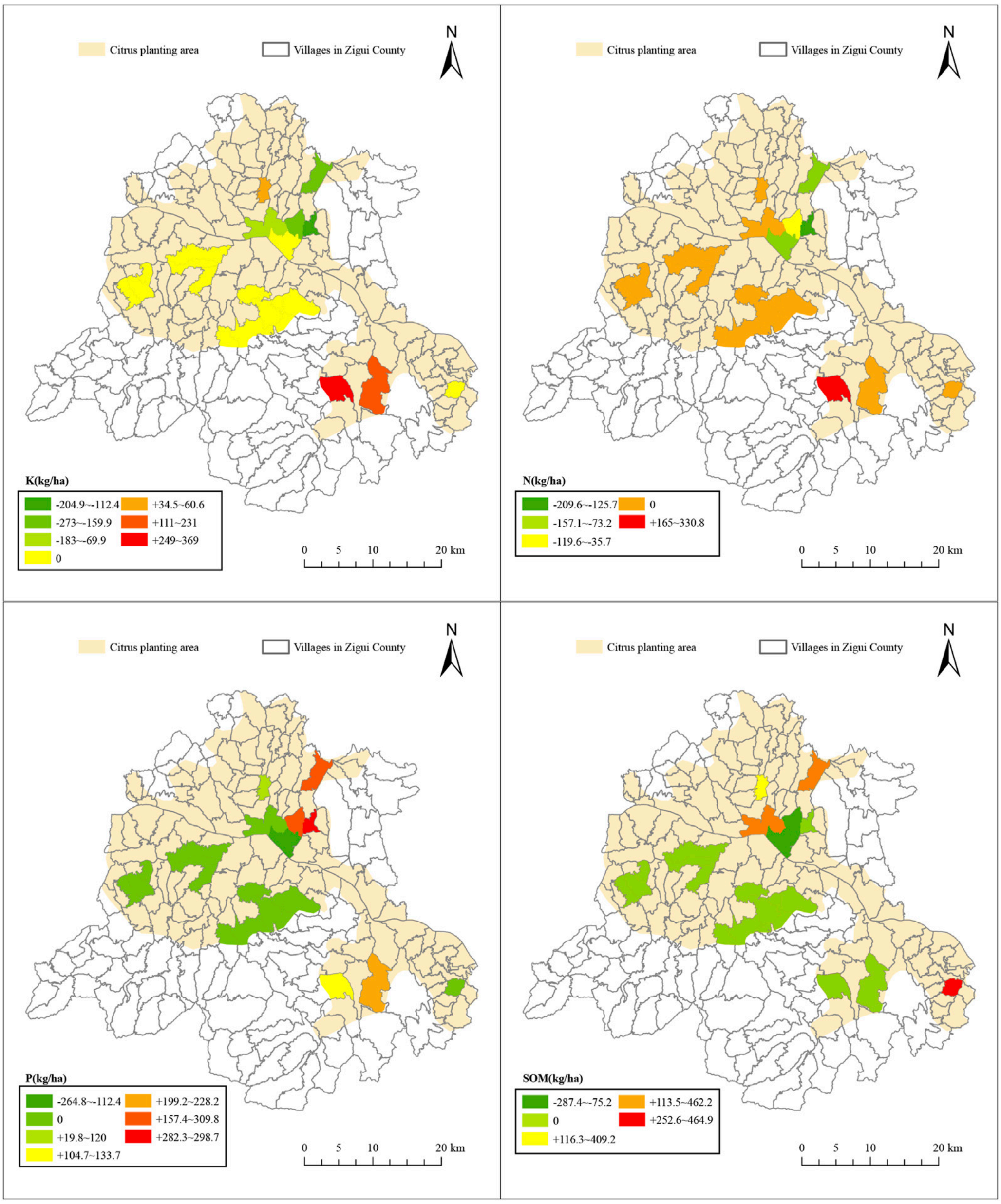

FIGURE 5
Optimized fertilization regimes for different towns. Note: + indicates increases; - indicates decreases.

Numerous studies and practices have demonstrated that fertilization is a critical factor in citrus orchard management and the basis for the high yields of orchards (Jae et al., 2014). Previous field experiments have shown that compared with a conventional fertilization pattern, an optimized fertilization management pattern could improve the yield by 18.9% and 15.5%, the Vc content by 0.69% and 7.66%, and decrease the titratable acid by 1.2% and 13.75% of citrus fruit in two consecutive years, respectively, resulting in a higher solid acid ratio and stronger flavor of the citrus fruit.

Optimization of the fertilization regime

The optimized fertilization regimes for the different towns were obtained based on the relationship between fertilizer application and soil nutrients with an artificial neural network (2019–2020). The results are presented in Figure 5. Excessive amounts of N and K fertilizers are applied in Guizhou town, and therefore, the application amount should be reduced to some extent. In addition, the application of N, P, and K fertilizer is inadequate in the orchards in Xietan, Meijiahe, and Jiuwanxi towns. The fertilization regimes should be optimized to provide more N, P, and K. In Guojiaba town, inadequate application of N fertilizer is prevalent in the orchards. However, the application of K fertilizer is excessive in some orchards. Excessive fertilization will inhibit the yield and quality of citrus fruit and greatly increase the cost of production. Hence, an optimized fertilization regime should be formulated to achieve high-quality, high-yield, and high-efficiency citrus production.

Conclusion

From 2018 to 2027, the overall suitability of the citrus producing area shows a gradually rising trend, with the "suitable" land area increasing from 4.5% to 20.16% and the "slightly suitable" and "moderately suitable" areas increasing from 37.15% to 9.92%–43.86% and 18.83%, respectively. This trend is due to the strong support of the local government for the citrus industry and the increased scientifically based management and maintenance of the citrus orchards by local farmers.

By 2027, there will still substantial room to improve the suitability of citrus orchards in Zigui County. Only by improving the suitability of citrus-producing areas can the yield and quality of citrus be improved. The environmental suitability for citrus cultivation in Maoping town may be promoted by applying biochar plus calcium silicate to increase the soil pH and the application ratio of phosphorus fertilizer. The conservation capacity of water and nutrients in Shazhenxi town should be enhanced through activities such as planting green manure, applying composite decomposed organic fertilizer, and integrating water and fertilizer to improve the fertility of the soil. In the joint area of Guojiaba and Guizhou towns, acid compound fertilizer should be applied. Moreover, the application of organic fertilizer should be increased to enhance soil fertility.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

ZW: Conceptualization, Investigation, Formal analysis, Visualization, Writing—original Draft. SZ: Resources, Supervision. YY: Resources, Investigation. XY: Resources, Investigation. QH: Resources, Investigation. CC: Writing—Review and Editing. MW: Writing—Review and Editing, Funding acquisition.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.985952/full#supplementary-material

References

Bei, Z., and Yong, Y. (2017). Spatiotemporal modeling and prediction of soil heavy metals based on spatiotemporal cokriging. *Sci. Rep.* 7 (1), 16750. doi:10.1038/s41598-017-17018-5

Belén, M-A., Mary-Rus, M-C., Almudena, B., Francisco, L., and Ana, Q. (2016). Liquid organic fertilizers for sustainable agriculture: Nutrient uptake of organic versus mineral fertilizers in citrus trees. *PLoS ONE* 11 (10), e0161619. doi:10.1371/journal.pone.0161619

Bouma, D. (1956). Studies in citrus nutrition. 2. Phosphorus deficiency and fruit quality. *Aust. J. Agric. Res.* 7 (4), 261. doi:10.1071/AR9560261

Dangui, H., Hong, S., Hongda, H., and Jianhui, X. (2017). Spatiotemporal regression Kriging to predict precipitation using time-series MODIS data. *Clust. Comput.* 20 (1), 347–357. doi:10.1007/s10586-016-0708-0

David, T., Kenneth, G. C., Pamela, A. M., Rosamond, N., and Stephen, P. (2002). Agricultural sustainability and intensive production practices. *Nature* 418 (6898), 671–677. doi:10.1038/nature01014

Eddie, W. L., Heng, L., and Danny, C. K. H. (2002). Analytic hierarchy process(AHP). *Meas. Bus. Excell.* 6 (4), 33–37. doi:10.1108/13683040210451697

Edward, C., Adams, S., Gideon, A., and Mandela, A. (2019). GIS-Based analysis of indigenous and technical knowledge of soil suitability evaluation of cocoa, citrus and oil palm in ejisu-juabeng district, ashanti region, Ghana. *Int. J. Plant Soil Sci.* 29 (2), 1–8. doi:10.9734/ijpss/2019/v29i230139

Emre, T., and Mehmet, A. D. (2020). Development of a land suitability model for citrus cultivation using GIS and multi-criteria assessment techniques in Antalya province of Turkey. *Ecol. Indic.* 117, 106549. doi:10.1016/j.ecolind.2020.106549

Hafeez, U., Ghulam, N., Ijaz, A., Tauseef, T., and Mukhtar, A. (2012). Growth and yield of Kinnow (Citrus reticulata Blanco) and soil physical properties as affected by orchard floor management practices in Punjab, Pakistan. *Soil & Environ.* 31, 163–170.

Hasan, Z., Anuar, A., Iris, V., Mohamad, Nor. S., Morteza, G., Behrouz, G., et al. (2015). Land suitability procedure for sustainable citrus planning using the application of the analytical network process approach and GIS. *Comput. Electron. Agric.* 117, 114–126. doi:10.1016/j.compag.2015.07.014

Jae, H. J., Hang, Y. W., Hae, N. H., Young, C. J., and Sang, W. K. (2014). Effect of long-term different fertilization on bacterial community structures and diversity in citrus orchard soil of volcanic ash. *J. Microbiol.* 52 (12), 995–1001. doi:10.1007/s12275-014-4129-6

Jenkins, D., Hall, D. G., and Goenaga, R. (2015). Diaphorina citri (Hemiptera: Liviidae) abundance in Puerto Rico declines with elevation. *J. Econ. Entomology* 108 (1), 252–258. doi:10.1093/jee/tou050

Jiawen, Z., Jinqiu, H., Zhihui, W., and Xun, W. (2019). Effects of nitrogen fertilizer on soil chemical property in citrus orchard. *IOP Conf. Ser. Earth Environ. Sci.* 310 (4), 042066. doi:10.1088/1755-1315/310/4/042066

Li, D., Li, X., Han, Q., Zhou, Y., Dong, J., and Duan, Z. (2020). Phosphorus application improved the yield of citrus plants grown for three years in an acid soil in the Three Gorges Reservoir Area. *Sci. Hortic.* 273, 109596. doi:10.1016/j.scienta.2020.109596

Li, Y., Han, M. Q., Lin, F., Ten, Y., Lin, J., Zhu, D. H., et al. (2015). Soil chemical properties, 'Guanximiyou' pummelo leaf mineral nutrient status and fruit quality in the southern region of Fujian province, China. *J. Soil Sci. Plant Nutr.* 15 (3), 0–628. doi:10.4067/S0718-95162015005000029

Ling, L., Tiantian, D., Xia, Q., Yi, R., Zhihui, W., and Jin, Z. (2019). Nitrogen nutrition is a key modulator of the sugar and organic acid content in citrus fruit. *PLoS ONE* 14 (10), e0223356. doi:10.1371/journal.pone.0223356

Liu, X., Wu, Y., Sun, R., Hu, S., Qiao, Z., Wang, S., et al. (2020). NH4+-N/NO3−-N ratio controlling nitrogen transformation accompanied with NO2−-N accumulation in the oxic-anoxic transition zone. *Environ. Res.* 189, 109962. doi:10.1016/j.envres.2020.109962

Marzieh, M., and Abbas, M. (2018). Using Fuzzy-AHP and order weight average (OWA) methods for land suitability determination for citrus cultivation in ArcGIS (Case study: Fars province, Iran). *Phys. A Stat. Mech. its Appl.* 508, 506–518. doi:10.1016/j.physa.2018.05.062

Orhan, O. (2021). Land suitability determination for citrus cultivation using a GIS-based multi-criteria analysis in Mersin, Turkey. *Comput. Electron. Agric.* 190, 106433. doi:10.1016/j.compag.2021.106433

Oyatokun, O., Okafor, B., Oluwasemire, K., and Adeoye, G. (2017). Properties of some soils developed from basement complex parent material in a savanna zone of Nigeria and their effect on soybean (Glycine max) production. *American-Eurasian J. Agric. Environ. Sci.* 17, 280–283.

Peina, L., Luke, D., Bin, M., and Jinghui, L. (2020). Bio-fertilizer and rotten straw amendments alter the rhizosphere bacterial community and increase oat productivity in a saline–alkaline environment. *Sci. Rep.* 10 (1), 19896. doi:10.1038/s41598-020-76978-3

Rafael, M., José, C., María, C. V., Luis, N., Patrick, O., and Pablo, A. (2019). Influence of temperature on the progamic phase in Citrus. *Environ. Exp. Bot.* 166, 103806. doi:10.1016/j.envexpbot.2019.103806

Ramana, K., Govindarajan, V., Ranganna, S., and Kefford, J. (1981). Citrus fruits — Varieties, chemistry, technology, and quality evaluation. Part I: Varieties, production, handling, and storage. *C R C Crit. Rev. Food Sci. Nutr.* 15, 353–431. doi:10.1080/10408398109527321

Raquel, C., Fahiem, E., and Larry, W. (2015). Modifying soil to enhance biological control of belowground dwelling insects in citrus groves under organic agriculture in Florida. *Biol. Control* 84, 53–63. doi:10.1016/j.biocontrol.2015.02.002

Satiprasad, S., Anirban, D., and Amlanjyoti, K. (2016). Environmental vulnerability assessment using Grey Analytic Hierarchy Process based model. *Environ. Impact Assess. Rev.* 56, 145–154. doi:10.1016/j.eiar.2015.10.002

Srivastava, A. K., Shyam, S., and Marathe, R. A. (2002). Organic citrus: Soil fertility and plant nutrition. *J. Sustain. Agric.* 19 (3), 5–29. doi:10.1300/J064v19n03_03

Syvertsen, J. P., Smith, M. L., and Boman, B. J. (1993). Tree growth, mineral nutrition and nutrient leaching losses from soil of salinized citrus. *Agric. Ecosyst. Environ.* 45 (3-4), 319–334. doi:10.1016/0167-8809(93)90080-9

Traboulsi, M. R. (2013). *Effect of climate change on supply response of Florida citrus crops 1980-2010. 2013 annual meeting*. Orlando: Florida Southern Agricultural Economics Association. February 2-5, 2013.

Xin, Y., Huiyu, H., Fenglin, W., Liya, C., Ningwei, L., Chongling, D., et al. (2021). Molecular mechanisms for magnesium-deficiency-induced leaf vein lignification, enlargement and cracking in Citrus sinensis revealed by RNA-Seq. *Tree Physiol.* 41 (2), 280–301. doi:10.1093/treephys/tpaa128

Xu, Q. X., Wang, T. W., Cai, C. F., Li, Z. X., and Shi, Z. H. (2012). Effects of soil conservation on soil properties of citrus orchards in the Three-Gorges Area, China. *Land Degrad. Dev.* 23 (1), 34–42. doi:10.1002/ldr.1045

Yong, Y., George, C., Xue, Y., and Junyu, H. (2018). Spatiotemporal characterization and mapping of PM2.5 concentrations in southern Jiangsu Province, China. *Environ. Pollut.* 234, 794–803. doi:10.1016/j.envpol.2017.11.077

Yong, Y., Jiaping, W., and George, C. (2015). Prediction of soil heavy metal distribution using Spatiotemporal Kriging with trend model. *Ecol. Indic.* 56, 125–133. doi:10.1016/j.ecolind.2015.03.034

Yuheng, W., Quan, L., Yueyue, L., Kang, F., Fan, Z., Xiong, H., et al. (2022). Mitigating magnesium deficiency for sustainable citrus production: A case study in southwest China. *Sci. Hortic.* 295, 110832. doi:10.1016/j.scienta.2021.110832

Yusuf, E., Rao, B. H., and Singh, D. N. (2008). Artificial neural network models for predicting soil thermal resistivity. *Int. J. Therm. Sci.* 47 (10), 1347–1358. doi:10.1016/j.ijthermalsci.2007.11.001

Zhiguo, L., Chiming, G., Runhua, Z., Mohamed, I., Guoshi, Z., Li, W., et al. (2017). The benefic effect induced by biochar on soil erosion and nutrient loss of slopping land under natural rainfall conditions in central China. *Agric. Water Manag.* 185, 145–150. doi:10.1016/j.agwat.2017.02.018

Zwieten, L., Kimber, S., Morris, S., Chan, K., Downie, A., Rust, J., et al. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant Soil* 327 (1-2), 235–246. doi:10.1007/s11104-009-0050-x