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Mapping Key Soil Properties of Cropland in a Mountainous Region of Southwestern China

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Abstract: Soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and total potassium (TK) are important indicators for evaluating soil fertility. Exploring the content and spatial distribution of these indicators is of great significance for optimizing cropland management measures and developing sustainable agriculture. Yunnan Province is one of the most important agricultural regions in southwestern China, characterized by large variations in the topography and an uneven distribution of soil fertility. In this study, the data of 8571 topsoil (0–20 cm) samples selected from Yunnan Province and a portion of related spatial data were used to carry out electronic mapping of the spatial distribution of soil sand content, clay content, silt content, SOC, TN, TP, TK content, and C:N ratio at 1 km resolution using the Random Forest (RF) model. The results indicated that the average measured contents of SOC, TN, TP, TK, and C:N ratio in the topsoil of Yunnan Province were 18.78 ± 0.09 g/kg, 1.78 ± 0.01 g/kg, 0.98 ± 0.01 g/kg, 13.89 ± 0.08 g/kg, and 10.56 ± 0.02, respectively. The spatial analysis showed that higher SOC was mainly distributed in northern and eastern Yunnan, and the spatial distribution pattern of TN and TP was similar to that of SOC. While higher TK was mainly distributed in southwestern Yunnan Province. There was a significant positive correlation between SOC and TN and TP contents with correlation coefficients of 0.889 and 0.463, however, there was a significant negative correlation between SOC and TK content with correlation coefficients of −0.060. It was also indicated that elevation, temperature, precipitation, clay content, sand content, and silt content were the most important factors affecting SOC, TN, TP, and TK content. The present study provided an understanding of soil nutrients characteristics and their affecting factors, which is helpful to optimize agricultural management practices and develop sustainable agriculture according to soil fertility.

Keywords: spatial pattern; soil nutrient content; random forest model; surface soil; cropland; mountainous area

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1. Introduction

Yunnan Province, a highly mountainous region located in southwest China, is one of the world's biodiversity hotspots. Sustainable crop production and management are crucial in this region, especially for the synergistic development of the environment and the economy. The heterogeneous distribution of soil nutrients poses challenges for balanced, site-specific fertilizer management, which is essential for economically sustainable agricultural production. Therefore, understanding the spatial distribution of soil nutrients is necessary to address this issue and promote regional agricultural green development.

Soil is a precious and non-renewable resource with a spatiotemporal continuum but high variability [1]. Soil fertility is an essential feature of soil to reflect the ability of soil to support and regulate crop growth based on soil nutrients and environmental conditions [2]. However, due to the highly intensive food production practices globally, there is increasing environmental pollution, degradation, and depletion of natural and non-renewable resources [3]. Managing and utilizing the soil efficiently is the key to a future sustainable intensification path. The spatial variations of soil nutrients in a certain region are influenced by natural factors such as parent material and topography, as well as anthropogenic activities, including land-use practices. The reasonable and objective assessment of the current state and the spatial change of soil fertility is a primary step to informing sustainable management [4], e.g., assisting reasonable crop layout, precise soil fertilization, nutrient management, and prevention of soil degradation [5–8]. This information is essential for various stakeholders, including local farmers, agricultural extension services, and local policymakers.

Soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and total potassium (TK) are the fundamental soil nutrients and important indicators of soil fertility [9,10], supporting the basic growth of crops and also affecting agricultural production efficiency [11–14]. Meanwhile, the spatial distribution of SOC, TN, TP, and TK can guide a search for nutrient deficit areas and inform the rational spatial allocation of cropping systems and management measures accordingly [15], especially in mountainous regions with elevation differences. The TN, TP, and TK content of soils is not only an essential nutrient for photosynthesis in plants but also plays a vital role in maintaining ecological stability and promoting geochemical cycles [16]. In addition, the geochemical cycling of C and N constantly influences global greenhouse gas emissions, further affecting global climate change [17,18]. A well-balanced carbon-to-nitrogen C:N ratio is also a key indicator of good soil health conditions and microbial activity. The C:N ratio in soil affects the decomposition of soil organic matter. A reasonable soil C:N ratio (from 10:1 to 20:1) is conducive to the transformation of soil nutrients, accelerating nutrient cycling, and playing an important role in maintaining the stability of farmland ecosystems [19].

Previous studies have investigated the factors affecting soil nutrients and further explained the interrelationships between external environmental factors and land nutrients [20,21]. For example, the soil SOC, TN, TP, and TK contents change under the influence of a combination of factors such as elevation, temperature, and precipitation [22]. Under suitable environmental conditions of temperature and humidity as well as pH, soil enzyme activity is greatly increased, microbial activity is higher, SOC decomposition is faster, and denitrification is intensified, which could alter the soil C:N ratio [23,24]. Elevation determines the distribution of soil moisture and thermal energy and affects the sequestration and transformation of SOC [25]. Soil nitrogen content is linearly related to organic matter content [26], so elevation also affects SOC and TN content. Complex topography can certainly control the weathering of soils, but soil parent material and its mineralogical composition are also important factors that determine particle sizes and relative nutrient availability. However, it is still not clear how the combination of the environmental factors influences multiple soil fertility indicators or which factors are more important.

The spatial distribution of soil fertility indicators and their influencing factors have not been adequately evaluated due to the lack of soil sampling in previous studies [27,28]. Solely relying on soil sampling and measuring may not cover the overall study region and the fine-scale soil variation due to the limitations of cost and labor. Thus, prediction modeling may help generate the spatial distribution of soil fertility on a fine scale. The random forest (RF) model is a classification tree-based algorithm that improves the model's prediction accuracy by aggregating numerous classification trees and performs well when dealing with large datasets due to its fast computing speed [29,30]. Moreover, the RF model can calculate the non-linear relationship of variables very well and reflect the importance of different variables in response variables [31]. Meanwhile, the RF model is also a powerful tool to interpret the importance of different variables to response variables.

This information can help identify the most influential factors driving soil fertility variability across the region, guiding further investigations and management decisions [32,33].

Yunnan Province is one of the most important mountainous areas for agricultural production in China, with highly varied elevations [34]. Though the complex topography of the region largely determines the distribution of soil nutrients, anthropogenic activities (e.g., cropping systems, intensive agricultural inputs) also result in spatial and temporal differences in soil nutrients. Previous studies have mapped the spatiotemporal variation of single soil fertility indicators in this region [35,36]. The spatial distribution of soil fertility indicators and their influencing factors have not been adequately evaluated due to the lack of soil sampling in previous studies. Therefore, the present study aims to have a more elaborate assessment of soil fertility indicators, which further advances the understanding of the soil fertility condition and helps synergistic management of soil fertility in this region. The following issues will be explored by using the random forest model: (1) to determine the contents of SOC, TN, TP, TK, and C:N ratios and their spatial distributions in the cropland of Yunnan Province; (2) to explore the importance of environmental factors affecting the spatial distributions of soil SOC, TN, TP, and TK; and (3) to clarify the relationship between these soil nutrients parameters.

2. Materials and Methods

2.1. Overview of the Study Area

The study was carried out in Yunnan Province, located in southwestern China, between 21°08′32″ and 29°15′8″ N and 97°31′39″ and 106°11′47″ E (Figure 1A). The region is predominantly mountainous (84% of the total area), with a wide range of undulations, including plateaus, hills, basins, and valleys (Figure 1B). The elevation ranges from 120 m to 5929 m.

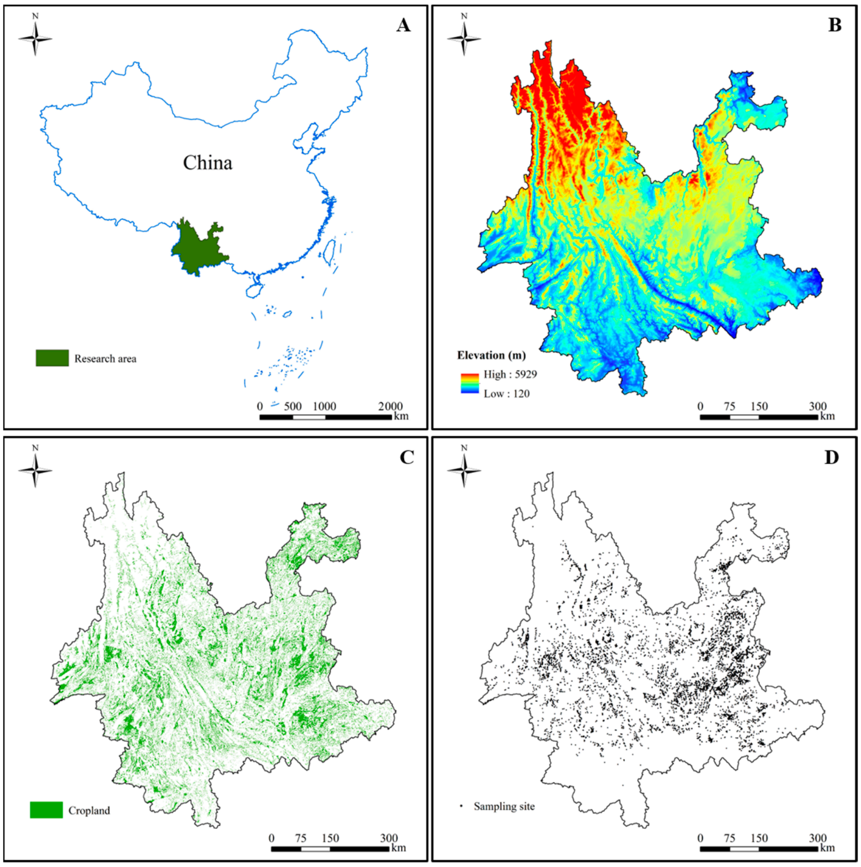

Figure 1. Location of the study area in China (**A**) and the distribution of elevation (**B**), cropland (**C**), and soil sampling site (**D**) in Yunnan Province.

The climate of Yunnan Province belongs to the subtropical highland monsoon climate type. There are many climate types; differences in annual temperatures are in the range of small to great differences in daily temperatures, and the dry and wet seasons are distinct. The average temperature of the province's hottest month (July) is 19–22 °C, and the average temperature of the coldest month (January) is 6–8 °C. Precipitation seasons are distinct, with the rainy season being May to October, concentrating 85% of the precipitation, and the dry season being November to April, with only 15% of the year's precipitation, ranging from 2200 to 2700 mm at the most to 580 mm at the least. According to Figure 1C, the area of cropland in Yunnan Province is about 6.8 × 104 km^2, accounting for 17.3% of the total area of Yunnan Province. The dominant cropping system in the region is double cropping (with two crops per year).

2.2. Access to Spatial Data

A series of spatial datasets were collected to investigate the distribution of cropland, elevation, soil particle size, and meteorological parameters and their relationship with soil nutrients (i.e., SOC, TN, TP, and TK). Using the Standard Map Service and the National Earth System Science Data Sharing Infrastructure, we obtained digital maps of national boundaries, provincial boundaries and soil physical properties at a scale of 1:1,000,000, which depict the elevation range, soil particle size distribution, and spatial distribution of soil sampling sites in Yunnan Province. The digital map of cropland distribution in 2016 at 30 m spatial resolution was obtained from the Geographical Information Monitoring Cloud Platform. The digital elevation model (DEM) with a 1 km resolution of Yunnan Province was obtained from the National Qinghai-Tibet Plateau Data Centre and used to calculate topographic parameters. Meteorological data, including annual mean temperature and annual precipitation from 1970 to 2020, was obtained from the WorldClim dataset with a 1 km resolution. The sources of these datasets are listed in Table 1.

Table 1. Sources of data used in the present study.

Item	Scale or Resolution	Source
A digital map of Chinese and provincial boundaries	1:1,000,000	http://bzdt.ch.mnr.gov.cn (accessed on 1 April 2020)
Soil dataset	1:1,000,000	http://www.geodata.cn (accessed on 3 March 2021)
Cropland distribution	30 m	http://www.dsac.cn/ (accessed on 27 April 2020)
Digital elevation model (DEM) data	1 km	http://www.tpdc.ac.cn/ (accessed on 12 April 2020)
Meteorological data	1 km	http://worldclim.org (accessed on 19 April 2021)

2.3. Soil Sampling and Analysis

Given Yunnan's complex and diverse topography and high spatial variability of environmental factors, 8571 soil samples were collected to minimize experimental error (Figure 1D). 3556, 4090, and 925 soil samples were taken from May to August in 2011, 2012, and 2013, respectively. For each sampling site, the geographical coordinates, altitude, cropping system, and planted crops were recorded in detail. The soil sampling follows the principles below. Firstly, a cropland with an area of 13.3 ha was selected as a sampling site. Secondly, a stainless-steel auger was used to collect a bulk soil sample to a depth of 20 cm from the soil surface. Thirdly, five sub-samples were collected and mixed with a soil sample to minimize experimental error. Fourthly, only one soil sample was collected for each site from 2011 to 2013. The collected soil samples were air-dried. The large particles in the soil, such as stones and crop residues, were picked out and removed, then mixed thoroughly. The crushed soil samples were passed through a 2 mm sieve, and finally, about 10 g of the samples were weighed out and stored in Ziplock bags pending further determination of soil nutrients. The content of SOC was determined by the potassium dichromate-concentrated sulfuric acid heating method, TN by Kjeldahl, TP by the molybdenum antimony colorimetric method, and TK by the flame photometric method [37]. The sand (>0.02 mm), clay (0.002–0.02 mm), and silt (<0.002 mm) content determinations were based on the references [38,39].

2.4. Digital Mapping and Importance Analysis

Soil particle size content, topography, and climate were selected as environmental parameters in the present study. The distribution of soil particle size contents, including sand, clay, and silt, was extracted from the soil dataset (Table 1). Based on the DEM of Yunnan Province (Figure 1B), the spatial distribution of topographic parameters including slope, aspect, profile curvature (PC), and topographic wetness index (TWI) with 1 km resolution was generated. The distribution of annual mean temperature and annual precipitation from 1970 to 2020 were generated based on the WorldClim dataset (Table 1). All digital map data extraction in this study was done using ArcGIS 10.8 software (Environmental Systems Research Institute, Redland, CA, USA).

The RF modeling approach was used to determine the distribution of soil nutrients and the importance of their affecting factors, according to the reference [40]. The RF model has been better calibrated and validated in previous studies to further optimize its accuracy [36]. In brief, 6860 soil samples, which account for more than 80% of total soil samples, were randomly selected as training data to model the relationship between SOC, TN, TP, TK, and C:N ratio observations and the predictors. Then RF algorithms were used for developing predictive models. The rest of the soil samples (1711) were used for validation. After being calibrated and validated, the RF model was applied to (1) predict the spatial distribution of SOC, TN, TP, TK, and the C:N ratio in the study region. The RF modeling predicted spatial distribution of SOC, TN, TP, and TK contents and soil texture was visualized by ArcGIS 10.8 software and (2) explained the importance of environmental factors influencing soil fertility.

2.5. Statistical Analysis

The data were statistically analyzed using SPSS 25 software (IBM Software, Chicago, IL, USA). The descriptive statistics, including mean, median, maximum, minimum, standard deviation (SD), coefficient of variation (CV), skewness, kurtosis, and frequency distribution for SOC, TN, TP, and TK content, and C:N ratio, were calculated, respectively. The pearson correlation coefficient was used to determine the relationships among SOC, TN, TP, and TK content.

3. Results

3.1. Changes in Annual Mean Temperature and Annual Precipitation

The averages of annual mean temperature and annual precipitation from 1970 to 2020 are shown in Figure 2. It was indicated that both annual mean temperature and annual precipitation decreased sequentially from the south to the north of Yunnan Province. Across the region, the annual mean temperature was 15.7 °C, and the annual precipitation was 1027 mm. Moreover, the annual mean temperature in the southwest of Yunnan Province was significantly higher than that in the northwest, with a maximum annual temperature of 24.0 °C and a minimum annual temperature of 0.0 °C (Figure 2A). The annual precipitation also shows a similar trend compared to the distribution of the annual mean temperature, with a maximum of 2150 mm and a minimum of 550 mm (Figure 2B). Concerning the effects of elevation on meteorological parameters, higher elevation resulted in lower annual mean temperature and annual precipitation (Figures 1 and 2).

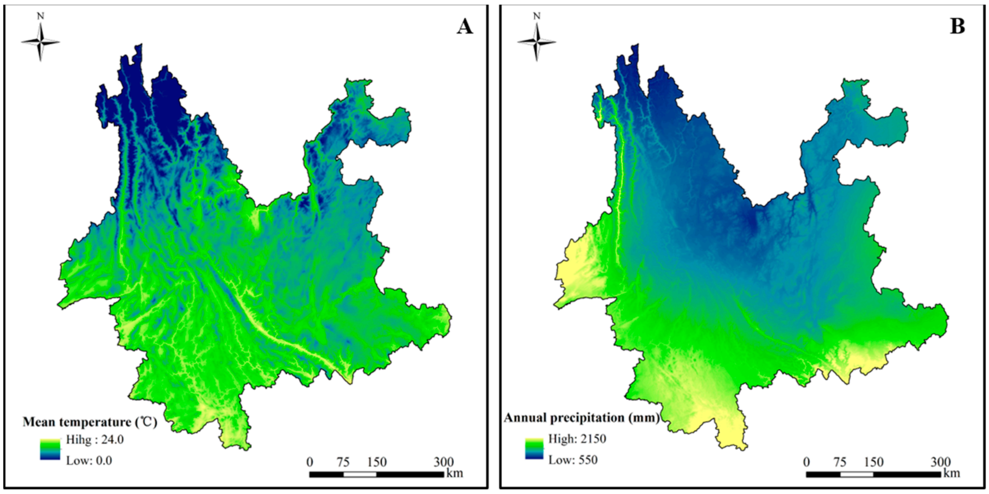

Figure 2. Distribution of annual mean temperature (**A**) and annual precipitation (**B**) of Yunnan Province from 1970 to 2020.

3.2. Spatial Distribution of Soil Sand, Clay, and Silt Content

The particle size distribution (i.e., sand, clay, and silt content) is one of the most important physical properties of soils, which not only affects soil structure but also has a great impact on soil fertility. According to Figure 3A, the sand content shows a spatially variable pattern of high northwestern to low southwestern, with the highest sand content being 74% and the lowest 20%, with an average content of 36%. Higher clay content is found in the southwestern and southeastern parts of Yunnan Province at lower elevations, with clay content ranging from 11% to 56% across the region (Figure 3B). The silt content ranged from 14% to 41%, with a lower distribution trend compared to sand and clay content (Figure 3C). It is also indicated that most of the soils in Yunnan Province belong to clay loam, loam, and sandy loam.

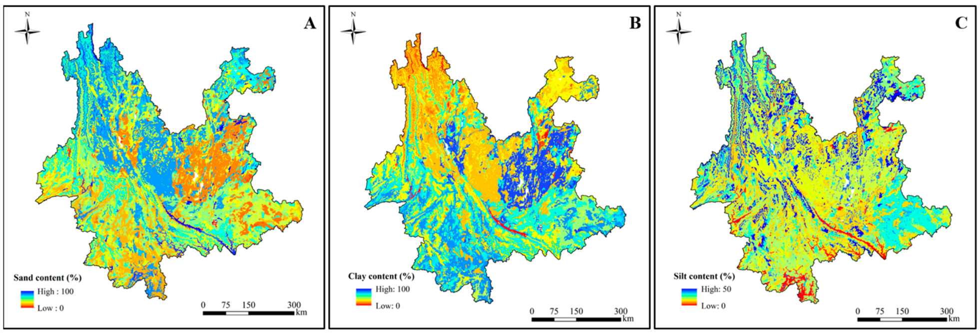

Figure 3. Distribution of sand (**A**), clay (**B**), and silt (**C**) content in 0–20 cm soil depth of Yunnan Province.

3.3. Soil Nutrient Contents, Carbon-to-Nitrogen Ratio, and Their Predicted Spatial Distributions

The frequency distribution and statistical parameters of measured SOC, TN, TP, TK, and C:N ratio in cropland of Yunnan Province is shown in Figure 4 and Table 2. It is indicated that the SOC content varied from 1.24 g/kg to 60.63 g/kg, with a mean value of 18.78 g/kg (Figure 4A). TN content ranged from 0.04 g/kg to 7.42 g/kg, with a mean value of 1.78 g/kg (Figure 4B). The mean values of TP and TK contents are 0.98 g/kg and 13.89 g/kg, respectively, with TP content varying from 0.12 g/kg to 3.95 g/kg and TK content ranging from 0.81 g/kg to 51.88 g/kg (Figure 4C,D). The measured soil C:N ratio is distributed from 1.85 to 53.54, with a mean value of 10.56 (Figure 4E). Among these soil properties, the C:N ratio showed a more concentrated distribution with a CV of 0.21, followed by TN content with CV of 0.40 (Table 2). However, TK and TP contents are highly uneven, with a higher CV of 0.53 and 0.52, respectively (Table 2).

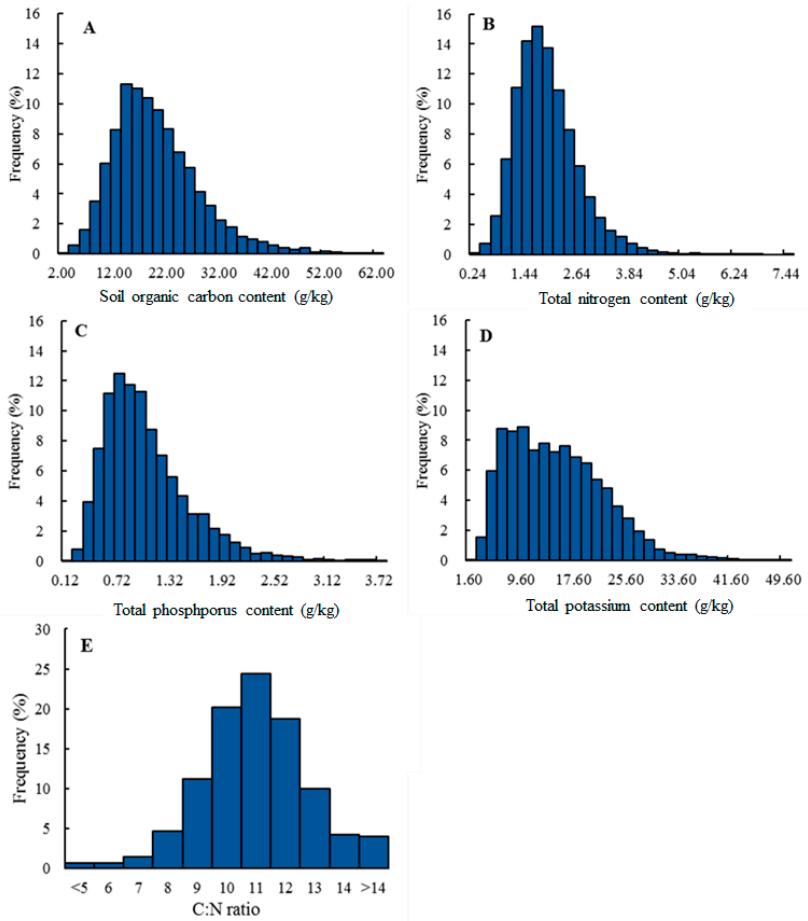

Figure 4. The frequency distribution of measured soil organic carbon (**A**), total nitrogen (**B**), total phosphorus (**C**), total potassium (**D**) content, and C:N ratio (**E**) in the topsoil of Yunnan Province. $n = 8571$.

Table 2. Statistical parameters of measured soil nutrients in cropland in Yunnan Province.

Soil Properties	Mean (g/kg)	Median (g/kg)	Max. (g/kg)	Min. (g/kg)	SD (g/kg)	CV	Skewness	Kurtosis
SOC	18.78	17.44	60.63	1.24	8.36	0.45	1.04	1.69
TN	1.78	1.68	7.42	0.04	0.72	0.40	1.07	2.63
TP	1.98	0.87	3.95	0.12	0.51	0.53	1.55	3.77
TK	13.98	13.09	51.88	0.81	7.24	0.52	0.74	0.52
C:N ratio	10.56	10.48	53.54	1.85	2.19	0.21	3.08	4.46

SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; TK, total potassium; C:N ratio, carbon: nitrogen ratio. SD, standard deviation; CV, coefficient of variation.

The digital maps in Figure 5 show the predicted spatial distribution of the contents of SOC, TN, TP, TK, and the C:N ratio in 0–20 cm of soil. The SOC content is found to be higher in the northern part of Yunnan Province compared to the southern part (Figure 5A). The predicted average SOC content is 22.9 g/kg, which is higher than the measured SOC content. The spatial distribution of TN content is similar to the distribution pattern of SOC content, which is also characterized by more in the north and less in the south (Figure 5B). The TN content is higher at high elevations than at lower elevations, and the highest TN content is found in the northwest and northeast of Yunnan Province, while it is lower in the southwest and southeast of Yunnan Province, ranging from 0.9 g/kg to 3.2 g/kg overall (Figure 5B). The spatial distribution of TP content is slightly different from the spatial distribution of SOC and TN content (Figure 5C). On a spatial scale, the areas with the highest TP content are in the northwest and northeast parts of Yunnan Province. Especially in the eastern part of Yunnan Province, where the elevations are higher, TP content in cropland is up to 2.3 g/kg. Furthermore, the southeast part of Yunnan Province has a lower content of TP. For Yunnan Province as a whole, the TK content varies between 0.3 g/kg and 28.8 g/kg (Figure 5D). The spatial distribution of TK content is opposite to the spatial distribution of SOC and TN content, characterized by high levels in the southwest and low levels in the southeast, northeast, and northwest regions of Yunnan Province. As shown in Figure 5E, the predicted spatial distribution of the soil C:N ratio in the cropland of Yunnan Province is extremely uneven. It is indicated that the spatial distribution of soil C:N ratio is relatively variable, with higher values concentrated in the northern part of Yunnan Province, where the highest value is 13.5, and lower values in the southwestern part of the province, with the lowest value of 8.1. The C:N ratio of soils in high-elevation areas of Yunnan Province is higher, and the C:N ratio of soils in the northern part of Yunnan Province is higher than in the southern part of the province.

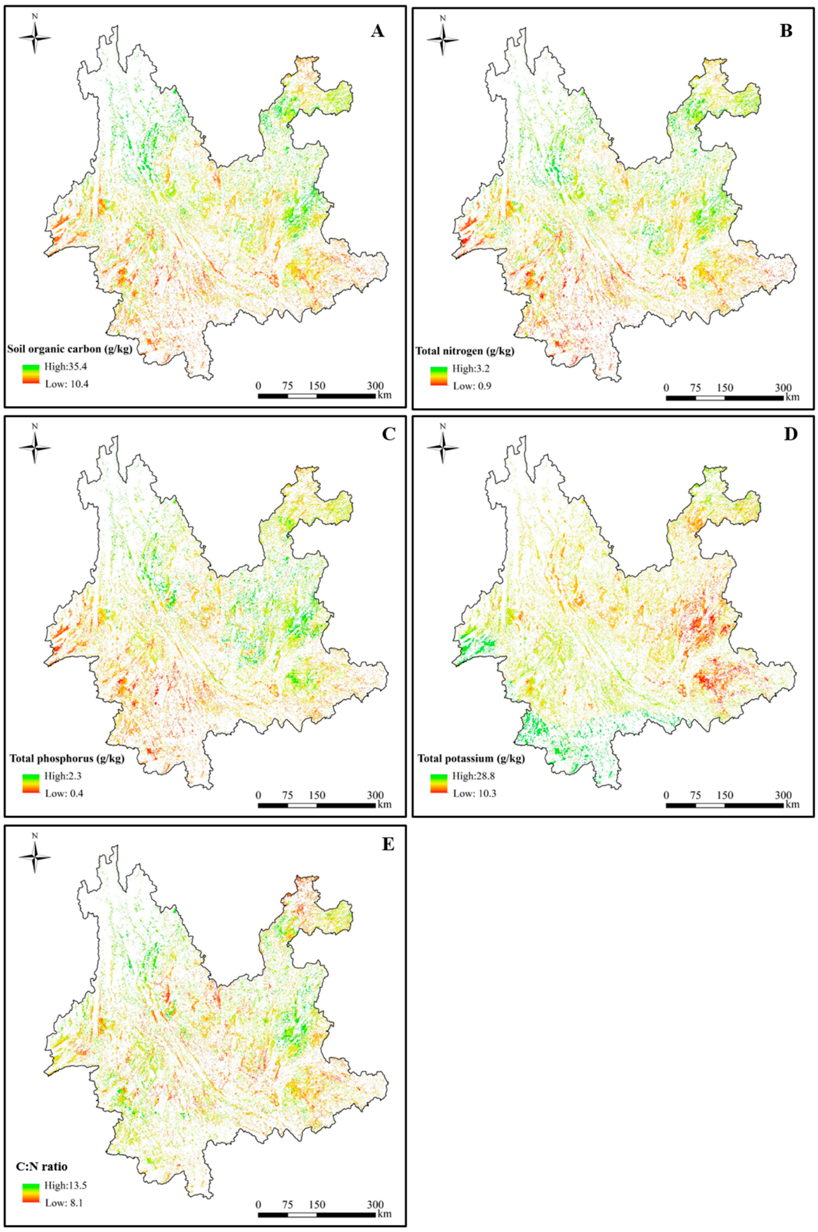

Figure 5. Distribution of soil organic carbon (**A**), total nitrogen (**B**), total phosphorus (**C**), total potassium (**D**), and C:N ratio (**E**) in cropland of Yunnan Province.

Furthermore, the correlations among the predicted SOC, TN, TP, and TK in 0–20 cm depth of soils was calculated using Pearson's correlation coefficient. The results show that there is a significant positive correlation between SOC and TN, TP contents at the level of $p < 0.01$, whereas there is significant negative correlation between SOC and TK content (Table 3). Similarly, TN content and TP and TK contents also shows the significant positive correlation with the correlation coefficients of 0.436 and 0.058, respectively. Moreover, TP content and TK content were significantly negatively correlated ($p < 0.01$) with a correlation coefficient of −0.176.

Table 3. Relationship between soil organic carbon, total nitrogen, total phosphorus, and total potassium in 0–20 cm soil depth of Yunnan Province.

Soil Properties	SOC	TN	TP	TK
SOC	1	0.889 **	0.463 **	−0.060 **
TN		1	0.436 **	0.058 **
TP			1	−0.176 **
TK				1

SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; TK, total potassium. ** indicates a significant correlation at $p < 0.01$.

3.4. Variable Importance Based on a Random Forest (RF) Model

Figure 6 shows the importance of environmental factors on the content of SOC, TN, TP, and TK in the topsoil of Yunnan Province. The higher importance variable means more influence on those soil fertility indicators. Elevation, temperature, and precipitation are the top three important environmental variables influencing soil SOC content (Figure 6A) and TN content (Figure 6B). Elevation, temperature, precipitation, sand, and clay were of equal importance (19%) for the predicted importance of TP content (Figure 6C). Elevation (25%), precipitation (25%), slope (25%), and temperature (17%) were of high importance for TK contents (Figure 6D). In general, elevation, precipitation, and temperature are important factors influencing the geographical distribution of soil SOC, TN, TP, and TK content, further influencing the spatial distribution of soil fertility.

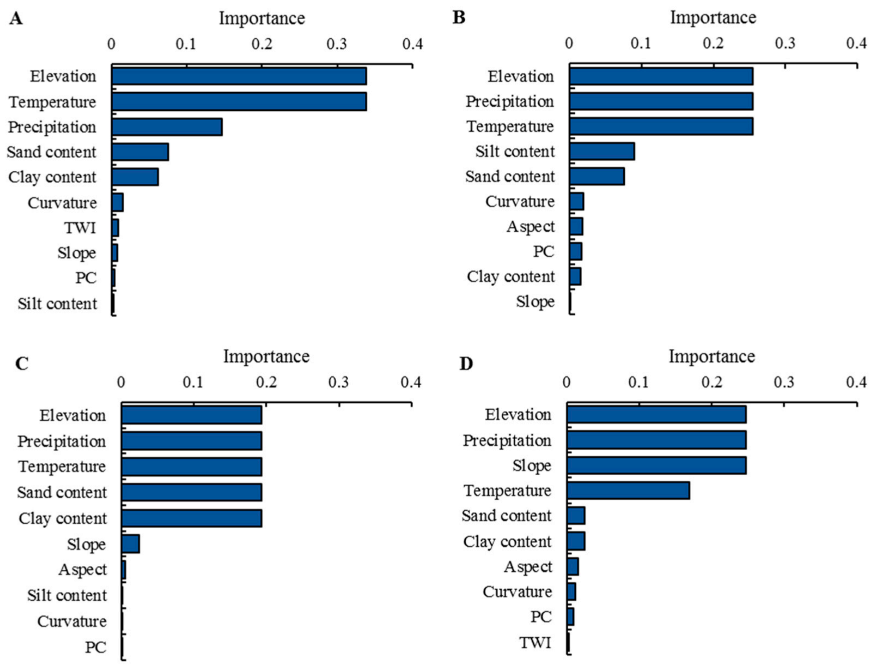

Figure 6. The predictive importance of soil and environmental variables relative to soil organic carbon (**A**), total nitrogen (**B**), total phosphorus (**C**), and total potassium (**D**) in the topsoil of Yunnan Province. PC, Profile Curvature; TWI, Topographic Wetness Index.

4. Discussion

4.1. Impact of Environmental Factors on Soil Nutrients

The complex nature of the environment has an important influence on the distribution of soil nutrients [41]. In this study, it was found that elevation has the most importance for predicting TN, TP, TK, and SOC contents in the cropland of Yunnan Province. SOC, TN, and TP are more widely distributed in higher elevation areas, including in northwestern and eastern Yunnan Province (Figure 4). For example, SOC tends to be retained more readily in cooler, more humid environments, which is similar to the previous study [42]. The reason might be that elevation will determine the distribution of precipitation and temperature patterns in an area, which significantly impacts the distribution of local vegetation characteristics [43,44]. Precipitation and temperature affect soil nutrient transformation by influencing the activities of soil microorganisms [45,46]. High temperatures and humidity may exacerbate the decomposition of soil organic matter, with adverse effects on soil nutrient accumulation. Furthermore, higher precipitation results in prolonged maceration; consequently, denitrification is enhanced, and nitrogen losses increase due to poor aeration [47]. The C:N ratio in the northern part of Yunnan Province is higher than in the southern part of the province, which may be related to temperature, precipitation, and human activities. Especially, agronomic management might change the SOC and TN content by the application of nitrogen fertilizer and soil tillage practices [36]. It is also important to mention that the dense network of rivers can have a significant impact on the mean annual temperature. Rivers also play a role in regulating local temperature changes. Precipitation is significantly lower in the mountains than in the plains, which are relatively warmer and more suitable for agricultural production.

The soil texture indicators, i.e., sand, clay, and silt content, reflect the soil's ability to store water and retain fertilizer [48,49]. In general, sandy soils have a superior fertilizer supply and poor fertilizer retention, whereas clay soils have the opposite performance and, in contrast, have a longer-lasting fertilizer retention capacity [50–52]. Due to clay soil's excellent water and fertilizer retention properties, an appropriate proportion of clay content is extremely beneficial for agricultural development. Areas with high soil silt content are mainly found in northern Yunnan Province and are particularly widespread in the northwestern part of the province due to a combination of precipitation and elevation factors.

4.2. The Total Assessment of Soil Properties in Yunnan Province and Other Ecoregions

Similar to the previous study, we found that the spatial distribution of key soil fertility indicators in Yunnan Province is extremely uneven due to its geographical characteristics, such as high northwest and low southeast, a decreasing terrain gradient, and large elevation differences [53,54]. In this study, the average contents of SOC are 18.78 g/kg, TN is 1.78 g/kg, TP is 0.98 g/kg, and TK is 13.89 g/kg (Figure 4). It showed that SOC, TN, and TK contents increased except for TP content compared to previous studies [55], which has declined in the last decade or so. The possible reasons for this difference may be the sampling strategies and the change in farm management. The extent of sampling, the number of samples taken, the type of soil at the sampling site, as well as the timing of sampling decisions, will cause a difference in soil measuring results. Long-term tillage measures degrade soil fertility and pose a threat to agricultural production [56]. However, with the application and promotion of advanced agronomic techniques and scientific as well as rational fertilization measures, soil fertility also improves from year to year [57]. For example, straw return to the field, less tillage, no-tillage, application of organic fertilizer, etc. can increase the content of soil organic matter, improve soil fertility, and promote the formation of soil aggregates to a certain extent, thereby improving the ability of the soil to store water and retain fertilizers [58,59].

There are also other studies in other ecoregions in China and worldwide that are based on RF models to map the soil properties, as we did. For example, a study in the subtropical monsoon region of southern Jiangxi Province found that soil TN content ranged from 0.42 to 2.52 g/kg, with a mean value of 1.21 g/kg, which was lower than the average of this study and the national average [60]. In saline semi-arid areas, the predicted range of SOC is 1–2.8%, which is narrower than our study, and a variable importance analysis indicated that salinity indices and NDV were dominant in the spatial prediction of soil parameters [61]. There are also other soil properties that have been studied by the RF model but have not been investigated in our study. For example, in the hilly farmland areas of China, soil available iron content ranged from 3.00 to 276.97 mg/kg, and significant factors negatively correlated with soil available iron content included slope, horizontal curvature, profile curvature, convergence index, and relative position index [62]. The study in Northwest China shows that the predicted soil organic matter is 15.9–25.8 g/kg by the RF model, and the main factors affecting the soil organic matter in the study area were elevation and rainfall [63]. All those studies found RF to be a sound method for digital soil mapping, but the factors influencing the soil properties are site-specific and depend on the research questions.

4.3. Limitations and Implications

In the present study, environmental variables (e.g., soil particle size, air temperature, precipitation, elevation, and slope) were used to predict the importance of soil nutrients. However, soil parent material always has a decisive influence on soil nutrients. Soil parent material is the foundation for soil formation, which directly determines the types and content of nutrients in the soil [64]. On the other hand, soil parent material also influences soil particle size composition, which indirectly results in the distribution and availability of nutrients in the soil [65]. Though the spatial variation in soil nutrients may become less pronounced due to changes in environmental conditions and agronomic practices, the influence of soil parent material remains a crucial factor. In Yunnan Province, the dominant soil types are Haplic Alisols, Calcaric Regosols, and Fluvisols, which account for ~60% of cropland in the region [36]. However, the soil parent material of these soil types is not clear by far, which restricts further investigation. Therefore, future studies should incorporate soil parent material to achieve a more comprehensive understanding of the factors affecting soil properties, leading to more accurate predictions and better-informed agricultural practices.

Due to budget and time constraints, our study did not include crop patterns and other anthropogenic factors that could play significant roles in soil fertility. Including these factors could provide a more comprehensive understanding of their relative importance. Moreover, this study only considers the surface soil (0–20 cm), whereas agricultural productivity is influenced by both surface and subsoil properties. Future research should aim to incorporate subsoil data to provide a more complete picture of soil fertility and its impact on crop growth.

Although the RF model has the power to predict the spatial distribution of soil fertility indicators, more attention should be paid when using the RF model. Firstly, the sampling and measured data used for calibrating and validating the model should encompass the diverse landscapes of the region, particularly accounting for the elevation differences in such mountainous areas. This ensures the model's predictions are robust and applicable across varied terrains. Secondly, the RF model is not suitable as a dynamic model like other process-based crop or environment models. It cannot capture the soil and environmental dynamics over time. This limitation means that while RF can provide a snapshot of soil fertility indicators, it cannot model changes in these indicators due to temporal environmental variations or soil processes.

5. Conclusions

The present study contributes to the body of knowledge by highlighting the importance of understanding the spatial distribution of key soil nutrients for sustainable agriculture. In this study, we employed the Random Forest (RF) model to accurately predict soil nutrient distribution in Yunnan Province using data from 8571 topsoil samples. Our findings revealed the average soil nutrient contents as follows: SOC (18.78 g/kg), TN

(1.78 g/kg), TP (0.98 g/kg), TK (13.89 g/kg), and C:N ratio (10.56). Elevation, temperature, and precipitation emerged as significant environmental factors influencing soil properties. While the RF model shows promise in predicting soil fertility indicators, its effectiveness hinges on comprehensive landscape coverage during data calibration and validation. Although there are limitations in capturing soil processes and dynamics, the model's insights into the spatial distribution of key soil fertility indicators can inform tailored crop choices and agricultural practices. These insights have the potential to aid soil testing and fertilizer recommendation programs. Future researchers should focus on improving model accuracy by incorporating more diverse environmental, topographical, and geological variables and longer-term soil data. This approach could enhance the predictive power of the RF model and further support the development of precise, site-specific agricultural sustainable practices.

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