



Geographic information system–assisted site quality assessment for hazelnut cultivation using multi-criteria decision analysis in the Black Sea region, Turkey

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Abstract

Developing land suitability models for strategically critical agricultural products to expand sustainable agricultural policies and sensitive agriculture management has become a significant trend. This study aims to improve a unique land suitability model for hazelnut cultivation by applying the criteria set (7 main criteria, 35 sub-criteria) including qualitative and quantitative reasons, integrated fuzzy analytic hierarchy process, inverse distance weighting, multi-criteria decision analysis, geographic information system, and weighted linear combination approaches. The model developed in the present study was applied and tested in Ünye District of Ordu Province, where hazelnut production in the Eastern Black Sea region of Turkey is an important economic activity. While 71.17% of the study area is classified as very highly suitable, highly suitable, and moderately suitable, 28.83% of the study area has marginally suitable and unsuitable properties for hazelnut cultivation. Generally, it was determined that the coastal parts of the study area were the most suitable areas for hazelnut growing. The hazelnut land suitability model's two main criteria impacting the final score values are climatic and topographic conditions, respectively. Heavy metal pollution and physical, chemical, and fertility conditions related to soil properties followed these, respectively. The first ten sub-criteria with the highest weight value were determined as elevation, annual average temperature, annual average precipitation, aspect, annual average relative humidity, nickel (pollution), slope, annual average maximum temperature, lead (pollution), and soil depth, respectively. Existing hazelnut cultivation areas were used to test the model. Of the existing cultivation areas, 75.59% coincided with the very highly suitable, highly suitable, and moderately suitable classes presented in this study, while 17.15% were in marginally suitable and 7.26% in unsuitable classes. The study results reveal that the hazelnut land suitability model developed is suitable in mild climate conditions. Using this model as a general transition model will be beneficial to test it in areas containing similar climatic conditions and various soil properties. This study will create a rational background in ensuring the sustainable food production system and security, agricultural land use planning, strategic planning and management of the hazelnut plant, increasing agricultural productivity and income, and the ecosystem.

Keywords Hazelnut · Land suitability · GIS · Multi-criteria decision analysis · Remote sensing · Soil sampling · Environmental conservation · Sustainable agriculture

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Introduction

The rapid increase of the global population, unplanned urban sprawl, industrialization, erroneous local, regional, and national planning strategies and misuse of agricultural lands are increasing day by day due to haphazard site selection decisions without using multi-criteria decision analysis methods. On the other hand, agricultural lands are at serious risk due to pesticide and excess fertilizer application, heavy metal pollution, mining activities, and improper waste management policies (Zhu et al. 2018; Jiang et al. 2020). This situation has irreversible consequences for food security, biodiversity, sustainable agricultural production, and public health (Özkan et al. 2020; Dereumeaux et al. 2020). For this reason, sustainable and rational use of lands, determination of suitability and quality of lands, and integrated evaluation of information such as climatic, topographic, and soil characteristics are of great importance in terms of transferring natural resources/heritage to future generations. In addition, today, people are becoming more environmentally conscious, which gives more momentum to adopt the sustainable use of the world's natural resources.

To develop sustainable and effective agricultural policies and ensure self-sufficiency in agricultural production, it is essential to evaluate land suitability for agricultural activities and significantly develop product-based evaluation indexes/models (Dedeoğlu and Dengiz 2019; Tercan and Dereli 2020). Product-based land evaluation approaches are of additional importance, especially for products of strategic importance for developing countries. In this context, land-use strategies that will support rural development should be designed to ensure the sustainable production of hazelnuts, which has strategic importance for Turkey and strengthens competition in the global market.

Hazelnut (*Corylus avellana* L.) is one of the most critical nut plants in the world due to its role in the nutrition, human health, cosmetics, and pharmaceutical industries (Pannico et al. 2017; Ortega Farias et al. 2020; Alidust et al. 2020). It is grown in temperate marine climates, particularly in Turkey, Italy, the USA, Azerbaijan, Georgia, Spain, and China. Despite their wide range of natural distribution, commercial orchards are concentrated in a few locations worldwide. Turkey is the leading hazelnut-producing country contributing more than half of the global production of shelled hazelnuts, followed by Italy, the USA, and Azerbaijan (FAO 2019; Jha et al. 2021).

Hazelnut has continually ranked first among agricultural products in Turkey as an export product. It has social and economic importance for the producers in the hazelnut-growing areas. Hazelnut production is the primary source of income for most farmers, especially in the provinces on

Turkey's Eastern Black Sea coast. Most of the hazelnut fields in the Eastern Black Sea region have a more than 20% slope. They are not very suitable for other agricultural applications. Hazelnut gardens in Turkey have an average area of 0.4 to 1.0 hectares and are generally located on sloping lands. In general, areas with a soil pH between 6.0 and 7.0 and receiving approximately 1000 mm of rainfall are suitable ecological conditions for growing hazelnuts. The production area is mainly harvested for commercial purposes. The hazelnut has been extensively spreading over approximately 540,000 hectares in 13 provinces in the Black Sea region of Turkey for the last 2500 years (Sarioğlu et al. 2013). In addition to that, Doğanay (2012) reported that at the growing hazelnut areas in the Eastern Black Sea region, commercial hazelnut cultivation was started in the fourteenth century or at the beginning of the sixteenth century. Thus, it is crucial to carry out product-based assessment studies and develop a land suitability model for hazelnuts, notably in areas where hazelnut production is intense in Turkey since hazelnut production has an essential place in agricultural income.

The development of methodologies that facilitate land suitability assessment has been the primary goal of land appraisal studies. In general, land assessment methods are divided into qualitative methods based on expert knowledge and quantitative models based on simulation models. Quantitative models are highly detailed for field performance and often require a lot of data, time, and costs. On the other hand, in determining the suitability of agricultural lands with qualitative approaches, land and soil properties are expressed with mathematical formulas (Özkan et al. 2020). In this context, land suitability assessment for agricultural activities is naturally accepted as a complex problem with more than one criterion. In other words, an evaluation approach that covers more than one criterion would be more appropriate for land assessment analysis studies. In this case, especially potential agricultural lands should be determined. By applying today's technologies, land suitability studies should be carried out to rationalize and evaluate fast, accurate, and sufficient information and data regarding soil and land resources.

The process of evaluating land suitability and developing product-based evaluation models requires the evaluation of many interrelated and conflicting criteria such as climatic, topographic, and geological conditions and soil properties in line with expert opinions and, therefore, a multi-criteria approach. Multi-criteria decision analysis (MCDA) methods are used to solve problems with many conflicting evaluation criteria. The analytic hierarchy process (AHP) method is one of the MCDA methods that can quickly solve complex decision problems with a hierarchical structure consisting alternative and evaluation criteria (Türkeş et al. 2020; Tercan et al. 2021). However, the traditional AHP method is insufficient to solve real-life problems with uncertainty and where

data are uncertain. In such cases, the fuzzy logic theory is employed to strengthen the solution to the problem (Deng 1999). In determining the weights of the evaluation criteria in this study, the fuzzy AHP (FAHP) method frequently preferred for resolving spatial location problems in the literature (Tercan et al. 2020; Karaca et al. 2021) was used. In addition, these difficulties can be overcome more easily, thanks to current technologies such as remote sensing (RS) and geographic information system (GIS) and approaches such as MCDA to make rational analyses and evaluations. GIS creates a solid and integrated background for experts in storing, analyzing, and visualizing spatial data sets required for land suitability assessment for various purposes. Numerous scientific research studies have been conducted in the literature that combine the capabilities of the GIS environment with MCDA approaches for the presentation and development of product-based evaluation models (Zhang et al. 2015; Dengiz et al. 2015; Kazemi et al. 2016; Maleki et al. 2017; Özkan et al. 2019; Ostovari et al. 2019; Dedeoğlu and Dengiz 2019; Pilevar et al. 2020; Nguyen et al. 2020; Nabati et al. 2020; Fekadu and Negese 2020; Tercan and Dereli 2020). On the other hand, as far as the authors of this article know, a land suitability model has not been developed for hazelnut, which is economically and strategically important for Turkey. To find a solution to this necessity, climatic (temperature, precipitation, and relative humidity) and topographic (elevation, aspect, and slope) factors and many characteristics of the soil (physical, chemical, productivity, heavy metal pollution) were considered. A unique GIS-MCDA-based land suitability model was developed for the hazelnut plant in the Black Sea region of Turkey, which has semi-humid and humid terrestrial ecosystems. In this study, FAHP, inverse distance weighting (IDW), weighted linear combination (WLC), and GIS approaches were used. In addition, the model developed in the study was used and tested in Ünye District of Ordu Province located in the Black Sea region. In this context, the main contributions and prominent aspects of the research are as follows:

- It will contribute to evaluating current planning decisions by comparing the existing hazelnut cultivation areas and the appropriate fields obtained due to the model developed in this study.
- It will provide essential background for the sustainable and rational use and management of lands with the integrated evaluation of many criteria sets.
- This land suitability model developed for hazelnut, which is economically valuable for Turkey and has strategic importance worldwide, will create an essential and beneficial hazelnut strategic planning framework for agricultural land use planning, land planning, and management of hazelnut plant, food security, and humanity.

- Considering and applying this model at the country level will provide serious advantages in product quality and efficiency in the global market.
- This study can help farmers, hazelnut growers, and regional planners make better hazelnut plantation decisions.
- The model developed in this study can be a planning tool for hazelnut cultivation in different study regions.
- This study will significantly contribute to the literature, as it is the most comprehensive GIS-MCDA-based land suitability model developed for the hazelnut plant.

The rest of this study is organized as follows: The general description of the study area, definition of the modeling approach and its stages, current land use/land cover of the study area, soil sampling and analysis, criteria definition and suitability scores of sub-criteria, and Fuzzy AHP approach are given in the “**Materials and methods**” section. Some physicochemical properties and heavy metal concentration, and land suitability for hazelnut and validation are given in the “**Results and discussion**” section. In the last section, “**Conclusions**” are presented.

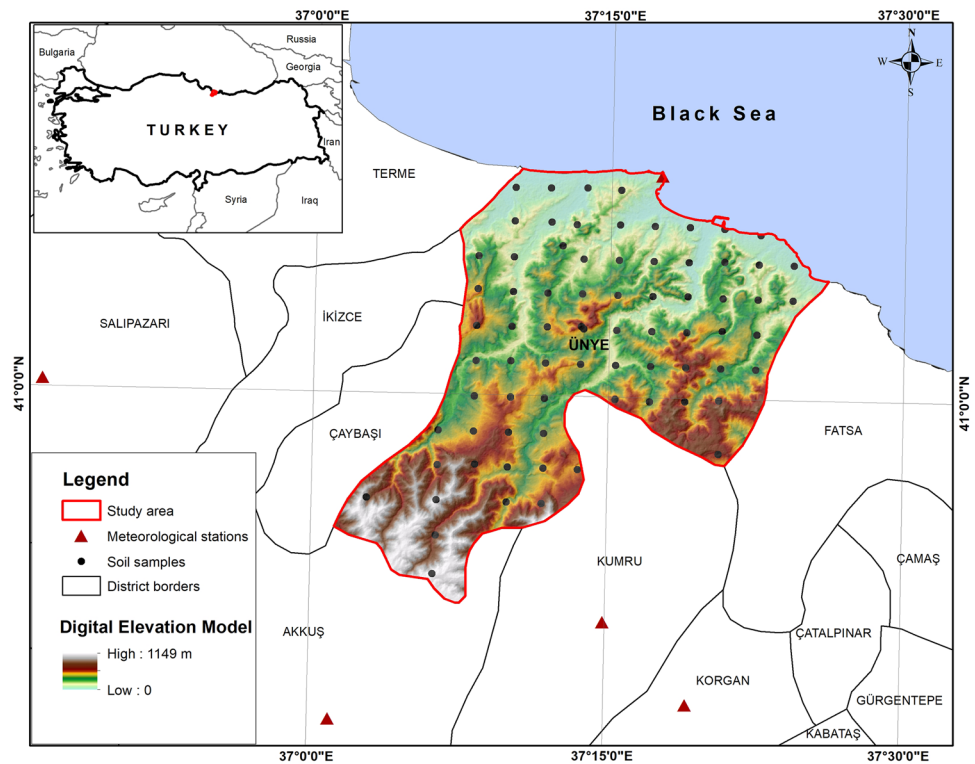
Materials and methods

General description of the study area

The study area is Ünye District, one of the 19 districts of Ordu Province located in Eastern Black Sea region of Turkey. The study area is situated between 37°0′39.51″–37°26′37.03″ east longitudes and 41°8′40.1″–40°52′17.16″ north latitudes and has a surface area of 510.6 km². The minimum and maximum elevation of the study area is 0 m and 1149 m, respectively (Fig. 1).

The Black Sea is located north of the district and the North Anatolian Mountains to the south. The Black Sea climate is effective in Ünye and its vicinity. According to the meteorological observation data for the 1960–2016 period, the annual average temperature in the study area is 14.3 °C, the annual average relative humidity is 75.2%, and the yearly average total precipitation is 1044 mm. Humidity is high due to its low altitude compared to its surroundings and close distance to the sea. Due to the precipitation in every season, the number of cloudy days and annual precipitation is high. The precipitation decreases towards the south, and the Black Sea climate leaves its place in the continental climate. In Ünye, which has a warm and temperate climate, rainfall can be seen even in the driest months. It has a soil diversity of the gray-brown podzolic, brown forest, and alluvial soils. In addition, according to WRB (2015), the study area’s soils were classified as Alisol and

Fig. 1 Location map of the study area



Acrisol-Podzols by Özcan et al. (2017). Considering the geological pattern of the study area, basalt, trachyandesite, dacite, tuff, and pyroclastic rocks dominate as volcanic and volcanoclastic rocks of the Late Cretaceous and Eocene age. In addition, marine and fluvial sediments, alluvial deposits, and late Cretaceous-Paleocene sedimentary rocks, which are accepted as early Quaternary-Pleistocene, exist in the area sandstone-mudstone, claystone, mudstone-limestone, sandstone, and limestone (Ersoy et al. 2006). In terms of economic activities, the most critical income-generating agricultural product in agricultural activities is hazelnut. Ünye District was chosen for the hazelnut land suitability model due to the suitability of the climatic conditions, fertile agricultural lands, the soil characteristics, geographical location, and the fact that hazelnut production is an important agricultural economic activity.

Definition of the modeling approach and its stages

This study was conducted to determine ecologically and economically suitable areas for hazelnut agriculture. Various methodologies such as MCDA, Fuzzy-AHP, and Geo-statistics were adopted concerning GIS and RS techniques to overcome the complex ecological structure of nature. Consequently, the modeling architecture was developed to reveal the relationships between the methods presented in Fig. 2. Determining the hazelnut suitability areas consists 4 main steps. In the first step, satellite image analysis was

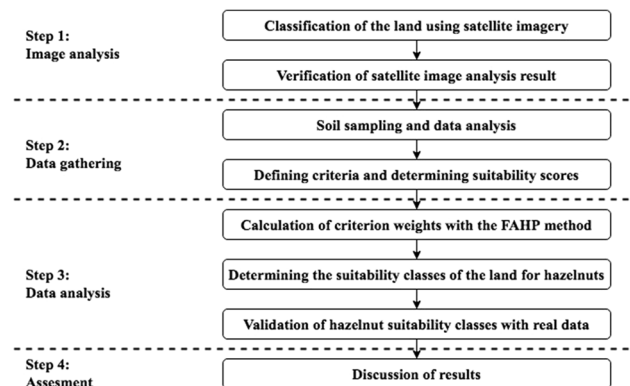


Fig. 2 Schematic chart

conducted to determine the study area’s current land use and cover types. In the second step, the analysis of soil samples belonging to the site, the indicators’ determination, and the primary database’s creation was performed. In the third step, data analysis was performed to determine the hazelnut suitability areas and test the obtained results’ accuracy. In the last step, the findings were evaluated.

Current land use/land cover of the study area

Sentinel satellite image covering the study area was used to determine the study area’s current land use and land cover

spatial distributions. The satellite image was produced on 29 July 2020. The resolution of the bands (Band 8, Band 4, Band 3, Band 2) used was given as 10 m, and the cloudiness ratio as 0.7025. Corine land cover/use classification system (Kosztra et al. 2017) was applied to define the land use classes and slightly modified for the study area. Five land use classes were determined in this study. These classes are artificial surfaces, agricultural areas, hazelnut cultivation areas, forest, semi-natural areas, and water bodies. The maximum likelihood approach (Kogo et al. 2021; Hishe et al. 2021), the controlled classification method frequently used in the literature for land cover/use classification, was used in the image classification. Local knowledge of the study area was used to develop a training data set. Training samples represent five land use classes. The number of training samples differs for different classes depending on the variability of each class and ease of identification. Envi 5.3v software was employed to perform these operations.

Of the study area, 9.63% (49.55 km²) was determined as artificial surfaces, 9.83% (50.62 km²) as agricultural areas, 57.94% (298.19 km²) as hazelnut cultivation areas, 22.60% (116.30 km²) as forest and semi-natural areas, and 0.001% (0.0036 km²) as water bodies (Fig. 3). As can be seen from the results of the land use map obtained, most agricultural areas are used as hazelnut orchards. In this study, random sampling points were created for each cell to evaluate the classification performance. Then, accuracy analysis was performed by evaluating whether these points are in the real

land use class or not. For accuracy analysis, it was ensured that the sample size of each class or region of interest (ROI) was precisely the same. Error matrices were generated as a result of evaluating the randomly generated points. Evaluations of the produced test and control points were carried out using visual interpretation and past Google Earth satellite images based on local information of the study area. Overall accuracy and kappa coefficient were used to evaluate the classification accuracy. The overall accuracy was 91.94%, and the kappa coefficient was 0.88.

Soil sampling and analysis

Fieldwork was carried out in 2019. Seventy-five soil samples were collected from a depth of 0–30 cm from the hazelnut orchards distributed within the study area that met the specified criteria (Fig. 1). Sampling was conducted following the autumn harvest period to minimize the effects of agricultural activities during the previous growing season, such as field traffic and fertilization. Soil sampled gardens had been used for hazelnut production for a long time (more than 30 years). Sampling points were recorded using a portable Global Positioning System (GPS) device (Garmin eTrex 30× Magellan). After soil samples were brought to the laboratory, they were separated from the roots and coarse particles; after being made air-dry at room temperature, they were sieved through a 2-mm sieve and made ready for physical and chemical analysis. The methods adopted in the physical and chemical

Fig. 3 Current land use and land cover map of the study area

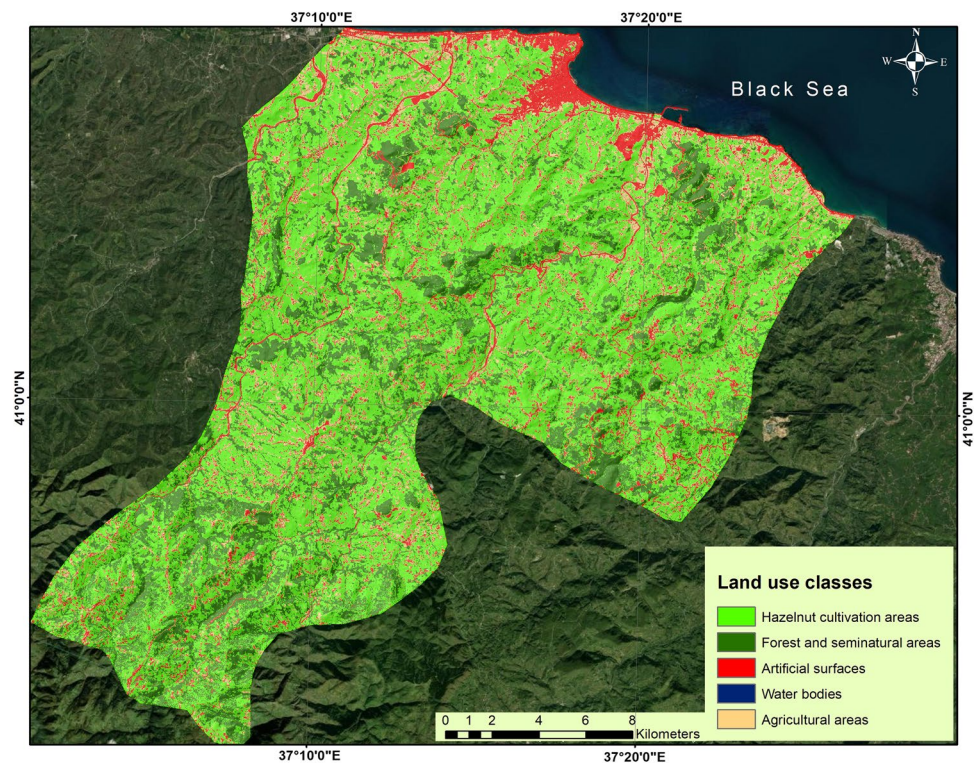


Table 1 Methods applied for the analysis of soil physical and chemical properties

Parameter	Unit	Procedure	Reference
Texture (clay, silt and sand)	%	Hydrometer method	Bouyoucos 1951
pH	1:1	Soil–water suspension (w:v)	Soil Survey Staff 1992
EC	dS m ⁻¹	Soil–water suspension (w:v)	Soil Survey Staff 1992
CaCO ₃	%	Calcimetric method	Soil Survey Staff 1992
Organic matter	%	Walkley–Black method	Nelson and Sommers 1982
Available P	mg kg ⁻¹	Bray–Kurtz and Olsen method	Bray and Kurtz 1945; Olsen et al. 1954
Total N	%	Kjeldahl method	Bremner and Mulvaney 1982
Exchangeable cations Ca, Mg, Na, K	mg kg ⁻¹	Ammonium acetate extraction method	Soil Survey Staff 1992
Microelements Fe, Cu, Zn, Mn	mg kg ⁻¹	DTPA extraction method	Lindsay and Norvell 1978
Available B	mg kg ⁻¹	Azomethine-H method	Cottenie et al. 1982
Total heavy metals Cu, Cd, Cr, Pb, Co, Ni, Zn	mg kg ⁻¹	According to EPA 3051 ICP-OES detection	Kloke 1980

studies of soils were determined according to the methodologies in the literature shown in Table 1.

Criteria definition and suitability scores of sub-criteria

Determining the land's suitability and quality is essential in assessing land use according to its potential and protecting natural resources for future generations (Özkan et al. 2020). Land use types are defined by land quality parameters or land use requirements, the land conditions necessary for successful agriculture. In contrast, land mapping units are defined as a set of land and soil characteristics that affect the suitability of specific land use types (Dengiz 2013). The land use type in this study is hazelnut. In this context, the most crucial step in determining suitable areas for the sustainable use of hazelnut fields is selecting eligibility indicators. It is undoubtedly impossible to use many features affecting eligibility areas at various levels. Consequently, it is vital to select the appropriate indicators to establish the land suitability assessment model. Karaca et al. (2021) stated that it is commonly accepted that land and soil suitability indicators can be separated naturally or dynamically. While natural factors may be, for instance, soil texture or mineralogical composition, dynamic property indicates that soil management decisions (fertilization, irrigation, tillage, etc.) are considered to assess how they affect soil properties. Some researchers (Qi et al. 2009; Doran and Parkin 1996) suggest that when determining the land suitability assessment of the land use type, as few as possible but effective parameters should be used by considering ecological conditions. In developing the spatial land suitability model for hazelnuts, seven main criteria and 35 sub-criteria were employed. The rationale for all criteria determined by considering the literature and

expert opinions is explained in the paragraphs below. Point values between 0 and 3 (0 unsuitable, 1 marginally suitable, 2 moderately suitable, 3 highly suitable) is given to the value ranges created for each sub-criterion.

Climatic conditions (C₁)

The fact that hazelnut is a sensitive product in terms of climatic conditions, and that it blooms during the winter months in humid and temperate climates, is one of the primary conditions that limit and determine hazelnut cultivation. During the vegetative period (October, November, December) (*from dormancy to flowering*) and the heat, especially in the winter months, affects the flowering time and the flowering duration of the male and female hazelnut flowers (Beyhan and Odabaş, 1996). An increase in minimum temperature during the cold season may limit the accumulation of cooling hours required to break the dormancy of vegetative buds and trigger pollen shedding and female anesthesia (Mehlenbacher et al. 1991; Jha et al. 2021). The minimum temperature should not fall below 0 °C too frequently in the period called *bud break and fully flowering* corresponding to January, February, March, and April (Beyhan and Odabaş, 1996; An et al. 2020). During this period, environmental factors such as temperature, humidity, and wind can reduce the germination power of flower powders. The vegetative buds of hazelnuts are highly vulnerable to low temperatures in the spring. Spring frosts damage especially varieties whose buds awaken early. In addition, failure to meet the total temperature required for ovarian tissue development and fertilization during this period causes castings and fruit failure (Beyhan and Odabaş, 1996). During the fertilization/ripening period of the hazelnut (*grain filling season: from flowering to maturity*) (May–June–July–August),

wind and high summer temperatures and drought adversely affect annual shoot development, flower bud formation, and internal development of fruits (Beyhan and Odabaş, 1996). Particularly throughout this period, the increase in the number of days when the maximum temperature is higher than 35 °C and the relative humidity is below 70% causes severe water stress that leads to a decrease in the seed filling and a shortened vegetative growth (Thompson 1981; Tombesi 1994; Bignami and Natali 1996; Luciani et al. 2019; Jha et al. 2021). On the other hand, the total annual precipitation should be above 750 mm, and the relative humidity should not fall below 60%, mainly in June and July (Köksal 2002; Ustaoglu 2012).

In summary, in the suitability location selection model presented in this study, factors such as annual average temperature, annual average precipitation (mm), annual average relative humidity (%), annual average maximum temperature (°C), and annual average minimum temperature (°C) were considered as climatic conditions. Data on meteorological observation stations that form the base of the data set on climatic conditions were obtained from the Turkish Meteorology General Directorate. In this study, 15 meteorology observation stations were used. IDW interpolation method, which is one of the deterministic spatial interpolation methods that is commonly preferred in GIS-based location selection applications in the literature (Mokarram and Mirsoleimani 2018; Ostovari et al. 2019; Tercan and Dereli 2020; Radočaj et al. 2021), was used in generating distribution maps regarding climatic conditions. While the value ranges and scores of these criteria are presented in Table 2, the classified thematic maps are shown in Fig. 4.

Topographical conditions (C₂)

The elevation is one of the most critical topographic conditions due to the increased risk of hazelnut cultivation in parallel with the increase in elevation. Therefore, it was accepted as an evaluation criterion. In this study, elevations above 750 m (Sarioğlu et al. 2013) were considered unsuitable for hazelnut yield and quality areas. The most critical factor limiting hazelnut production with the increase in elevation in inland areas far from the coast is the very low winter temperatures. Another important topographic feature is the aspect. Aspect plays an active role in the plant's development, yield, and quality along with the parameters such as exposure to sunlight, wind direction, and precipitation (Aydinoglu 2010; Akıncı et al. 2013; Dedeoğlu and Dengiz 2019). Therefore, it was accepted as an evaluation criterion. In addition, the slope factor takes its place among the topographical features in terms of protecting the soils in place and affecting the land management systems. Lacko-Bartošova and Buday (2013) stated that the slope degree frequently indicates the land's capability and suitability for agricultural activities. Therefore, lands with low slope values should be preferred as much as possible to reduce erosion risk, reduce organic matter and nutrient loss, reduce irrigation and mechanization costs, and reduce maintenance and transportation costs (Sauer et al. 2010; Begum et al. 2013; Dedeoğlu and Dengiz 2019). Thus, the slope was accepted as an evaluation criterion.

In the location selection model presented in this study, elevation, aspect, and slope factors were considered topographic conditions. ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), global digital

Table 2 Value ranges and scores of climatic and topographical conditions

ID	Sub-Criteria	Value ranges and suitability scores			
		Highly (3)	Moderately (2)	Marginally (1)	Unsuitable (0)
C ₁	Climatic conditions				
C ₁₁	Annual average temperature (°C)	12.66–13.74 13.74–14.33	11.58–12.66	10.50–11.58	9.73–10.50
C ₁₂	Annual average precipitation (mm)	996.50–1044.00	901.50–949.00 949.00–996.50	854.70–901.50	-
C ₁₃	Annual average relative humidity (%)	74.45–75.56	72.25–73.35 73.35–74.45	71.15–72.25	-
C ₁₄	Annual average maximum temperature (°C)	16.67–17.47 17.47–17.72	15.87–16.67	15.07–15.87	14.10–14.27 14.27–15.07
C ₁₅	Annual average minimum temperature (°C)	9.27–10.63 10.63–11.53	7.92–9.27	6.56–7.92	5.89–6.56
C ₂	Topographical conditions				
C ₂₁	Elevation (m)	0–250	250–550	550–750	750–1149
C ₂₂	Aspect	North, Northeast, Flat	Northwest, West, South, Southwest	East, Southeast	-
C ₂₃	Slope (%)	0–10	10–20	20–40	40–61

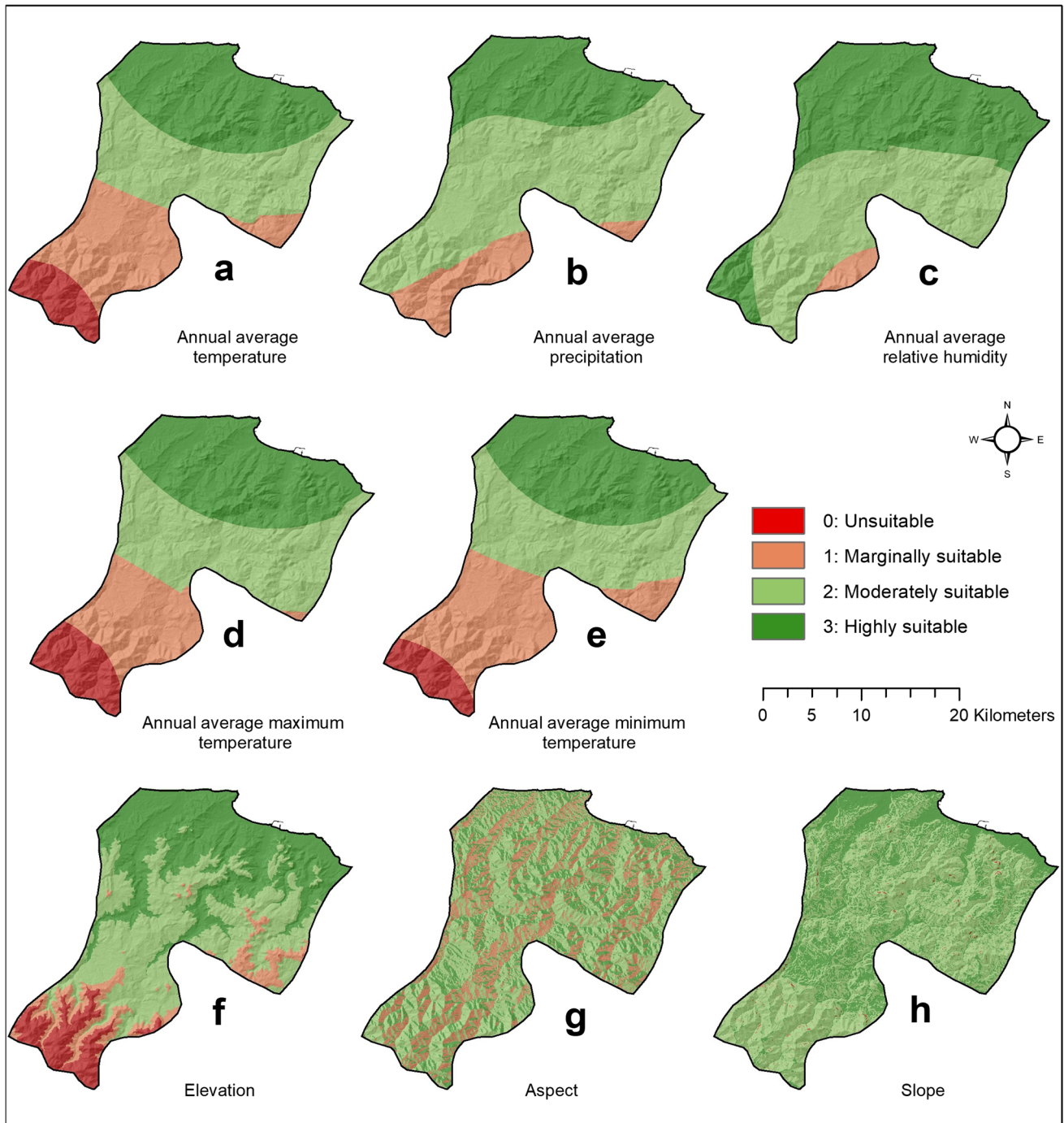


Fig. 4 Thematic maps for the climatic and topographic factors: **a** annual average temperature, **b** annual average precipitation, **c** annual average relative humidity, **d** annual average maximum temperature, **e** annual average minimum temperature, **f** elevation, **g** aspect, **h** slope

elevation model (GDEM) (Earth Data 2021) obtained from NASA (The National Aeronautics and Space Administration) Earth Data, was used as a database to produce the elevation, aspect, and slope maps. While the value ranges and scores of these criteria are presented in Table 2, the classified thematic maps are shown in Fig. 4.

Heavy metal pollution conditions (C_3)

Agricultural lands are under pressure due to geogenic pollution and anthropogenic pollution sources such as excessive fertilizers and pesticides, fossil fuels, mining activities, rapid population growth and urban sprawl, and improper waste

management policies. As a result of these pressures, heavy metal pollution in agricultural land has become a field of research that requires severe and rational planning in recent years due to its adverse effects on food safety, flora, and fauna. These heavy metals cause a decrease in microbial activity, soil fertility, biodiversity, and yield and can also cause poisoning in animals and humans through the food chain (Bayraklı and Dengiz 2019, 2020). Therefore, the evaluation of heavy metal pollution in agricultural lands is highly critical.

In this study, heavy metals (Cd, Cr, Pb, Ni, Zn, Fe, and Cu), which are commonly used in the literature concerning the hazards and occurrences that may occur in contaminated soils, were used as sub-criteria under the heavy metal loading conditions (Akoto et al. 2008; Bayraklı ve Dengiz 2019). In the location selection model presented in this study, the value ranges and scores of these criteria are shown in Table 3. In contrast, the classified thematic maps created using the IDW interpolation approach are presented in Fig. 5.

Physical conditions of soil (C₄)

Soil depth, which significantly affects the storage of plant nutrients and water and soil depth as well as plant root development, is one of the most critical criteria of many agricultural classification systems in terms of soil classification and soil quality (Calviño and Sadrás 1999; Bregaglio et al. 2016; Dedeoğlu and Dengiz 2019). In this study, it was considered as a factor for the land suitability model for hazelnut. The ratios of clay, silt, and sand in the soil have effects on parameters such as soil water permeability, water holding capacity, pore size, aggregate stability, aeration, root spread, and nutrient (Pilevar et al. 2020; Abuzaid et al. 2021; Özkan et al. 2020; Kumar et al. 2021), and they were evaluated as

a set of criteria in the land suitability model for hazelnut. The parent material determines both the soil's formation rate and the original supply of nutrients which are released after decomposition depending on its ecological conditions and affects the balance between nutrient loss and retention. Consequently, it is an essential factor determining the soil's fundamental physical and chemical properties (Anderson 1988; Ulrich and Becker 2006; Lacoste et al. 2011; Wilson 2019). It was accepted as a factor for the land suitability model for hazelnut. In the location selection model presented in this study, soil depth, clay, sand, and parent material factors were considered the physical conditions of the soil. While the value ranges and scores of these criteria are presented in Table 4, the classified thematic maps are shown in Fig. 6.

Chemical conditions of soil (C₅)

This study considered OM, EC, pH, and CaCO₃ as chemical soil parameters. Many authors have recommended these factors due to their significant effects on properties such as plant root development, soil fertility, the efficiency of nutrients, soil pore size, soil structure, and aggregate stability (Jiang et al. 2017; Nabiollahi et al. 2017; Dedeoğlu and Dengiz 2019). Soil organic matter content is an essential indicator for agricultural functions (i.e., production and economy) and environmental functions (i.e., carbon sequestration and air quality). The organic matter content of the soil affects the product performance due to its positive effects on soil properties and is an essential parameter in terms of the quality, yield, and sustainable use of the soil (Bauer and Black 1994; Turan et al. 2019). Due to its multi-functional feature, it was accepted as the evaluation criteria for the land suitability model for hazelnut. Soil reaction (pH) is among the main soil variables that directly or indirectly affect many biological, chemical, and physical events and processes occurring in the soil (Minasny et al. 2016; Neina 2019), and therefore, it was accepted as an evaluation criterion. Although the lime content (CaCO₃) of the soil in the cultivated area does not directly affect the plant growth, it was accepted as an evaluation criterion because the present nutrients direct the functional behavior of plants and affect the soil reaction (Turan et al. 2019). In addition, electrical conductivity (EC) was chosen as another chemical soil factor. EC is considered a measure of the ion concentration of the soil solution (Richards 1954). If the EC value exceeds the critical values for plants, it causes a decrease in vegetation and inhibits plant growth in later periods (Bresler 1972). Due to high concentrations of Na⁺ and Cl⁻ under saline conditions, nutrient imbalance causes a reduction in food intake, including P, and ion toxicity (Miransari and Smith 2007; Dedeoğlu and Dengiz 2019). Thus, it was accepted as an evaluation criterion in this study.

In the location selection model presented in this study, organic matter, reaction, CaCO₃, and electrical conductivity

Table 3 Value ranges and scores for heavy metal pollution conditions

ID	Sub-factors	Value ranges	Description	Score
C ₃₁	Nickel (Ni) (mg kg ⁻¹)	> 50	Risk	0
		< 50	No risk	3
C ₃₂	Lead (Pb) (mg kg ⁻¹)	> 100	Risk	0
		< 100	No risk	3
C ₃₃	Copper (Cu) (mg kg ⁻¹)	> 100	Risk	0
		< 100	No risk	3
C ₃₄	Cadmium (Cd) (mg kg ⁻¹)	> 3	Risk	0
		< 3	No risk	3
C ₃₅	Cobalt (Co) (mg kg ⁻¹)	> 50	Risk	0
		< 50	No risk	3
C ₃₆	Zinc (Zn) (mg kg ⁻¹)	> 300	Risk	0
		< 300	No risk	3
C ₃₇	Chrome (Cr) (mg kg ⁻¹)	> 100	Risk	0
		< 100	No risk	3

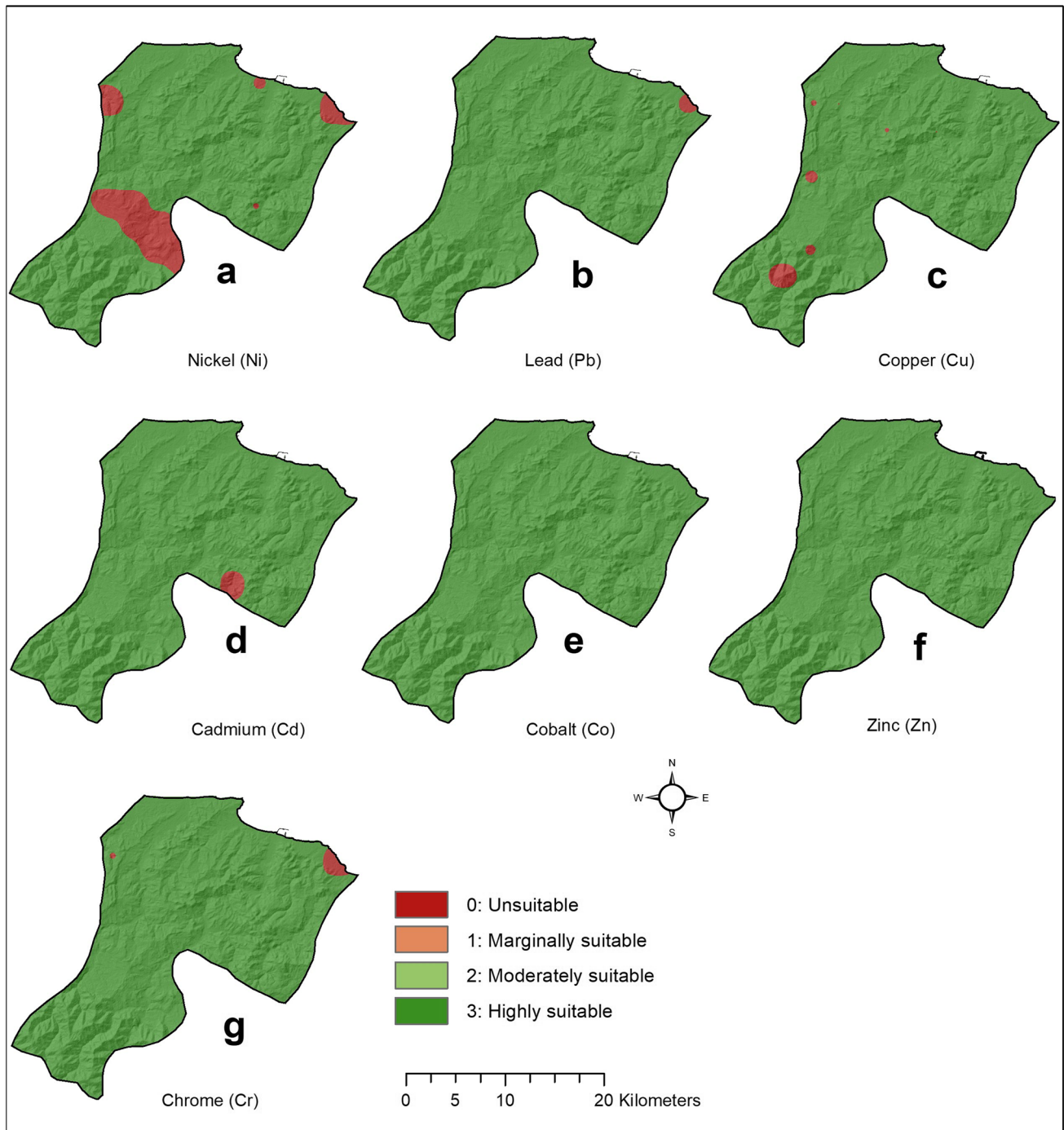


Fig. 5 Thematic maps of the heavy metal indicators: **a** nickel, **b** lead, **c** copper, **d** cadmium, **e** cobalt, **f** zinc, **g** chrome

factors were considered as the chemical conditions of the soil due to their effects on root development, soil fertility, availability of nutrients, soil pore size, soil structure, and aggregate stability. While the value ranges and scores of these criteria are presented in Table 5, the classified thematic maps created using the IDW interpolation approach are shown in Fig. 6.

Fertility conditions of soil (macroelements) (C_6) and (microelements) (C_7)

Plant nutrients are chemical elements that are vital for plant growth. For an element to be necessary, it must be essential for a plant to complete its life cycle, and no other nutrients can fully replace this requirement. Accordingly, soil fertility

Table 4 Value ranges of physical conditions of soil

ID	Sub-factors	Value ranges	Description	Score
C ₄₁	Soil depth (cm)	0–20	Very shallow	0
		20–50	Shallow	1
		50–90	Moderate	2
		> 90	Deep	3
C ₄₂	Clay (%)	> 45	Very heavy	1
		35–45	Heavy	3
		10–30	Moderate	2
		< 10	Slight	0
C ₄₃	Silty (%)	> 55	Very coarse	0
		35–55	Coarse	2
		15–35	Moderate	3
		< 15	Fine	1
C ₄₄	Sand (%)	> 70	Very coarse	0
		40–70	Coarse	2
		15–40	Moderate	3
		< 15	Fine	1
C ₄₅	Parent material	Sandstone, granite, agglomerate, andesite, trachyte, gabbro, melange, ophiolitic, serpentine, metamorphic rocks such as shale, schist, phyllite		1
		Marine coastal strip dune, travertine, conglomerate, limestone, dolomite, marble		1
		Terrestrial dune, volcanic ash, tuff, marl, claystone, mudstone and siltstone, gypsum, evaporates		2
		Basaltic vulcanite, ultra-basic magmatic and eruptive rocks, alluvial sediments, old alluvial sediments and deposits		3

characteristics, considered micro- and macronutrient contents, are also affected by management practices, such as fertilization, irrigation, and/or organic waste or animal or green manure application (Franzluubbers and Stuedemann 2009; Bhogal et al. 2011). These characteristics are essential in determining yield, plant health, and animal and human health (Gugino et al. 2009). Therefore, fertilizer use and management are critical in crop production systems. For instance, NPK fertilizers, which constitute the highest fertilizer input in wheat cultivation, are one of them (Liakas et al. 2001; Dedeoğlu and Dengiz 2019). In addition, the presence of boron in soil and irrigation water is an essential determinant of agricultural production (Tanaka ve Fujiwara 2008; Camacho-Cristóbal et al. 2008). In addition, boron, a macronutrient element, has an essential effect on the growth and productivity of the hazelnut plant. Shorrocks (1997) reported that in 132 plant species, including hazelnut plants, B fertilization positively affects yield in crop production. In boron deficiency, some physiological processes occurring in plants slow down, or these processes stop completely (Camacho-Cristóbal et al. 2008). Boron deficiency causes a decrease in the fruit set in hazelnuts and the formation of empty fruit. Long-term preservation of soil fertility is a prerequisite for sustainable productivity. For sustained soil fertility, it is essential to compensate for the nutrients removed during harvest or production through regular fertilization so that

the soil's nutrient balance is not negative in the long term. However, intensive agricultural practice or monoculture agriculture may cause depletion of nutrients and deterioration of soil quality, and even soil erosion (Karaca et al. 2021). In this study, soil fertility indicators called macronutrients (N, P, K, B, Ca, Mg, Na) and micronutrients (Cu, Zn, Fe, Mn) were used to reflect the main effects a result of land management. While the value ranges and scores of these criteria are presented in Table 6, the classified thematic maps created using the IDW interpolation approach are also shown in Fig. 7.

Fuzzy AHP

Zadeh (1965) firstly presented the fuzzy logic theory. In a classical set theory, an element is either the element of the set or not. An object cannot partially belong to a set. Fuzzy set theory performs graded data modeling using linguistic variables such as low, frequent, medium, low, high, and many. A fuzzy set is a valuable technique for identifying and solving uncertainty and uncertain real-life issues. Fuzzy logic sets are described by membership functions (Van Laarhoven and Pedrycz 1983). Finding various membership sets in fuzzy logic applications, triangular and trapezoidal membership functions are often used in MCDA-based approaches. TFNs are used in this study. The operational

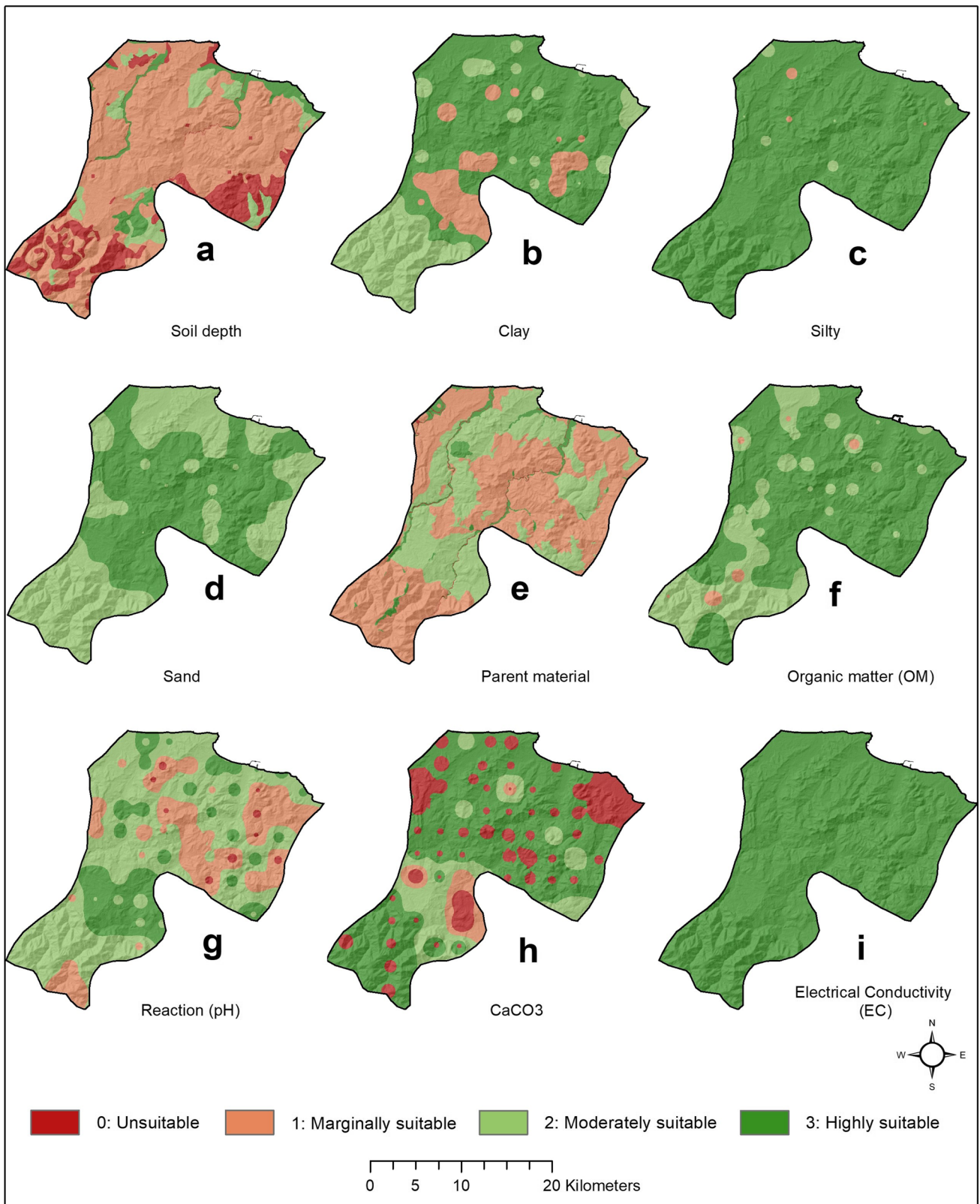


Fig. 6 Thematic maps of the soil physical and chemical indicators: **a** soil depth, **b** clay, **c** silty, **d** sand, **e** parent material, **f** organic matter, **g** reaction, **h** CaCO₃, **i** electrical conductivity

Table 5 Value ranges of chemical conditions of soil

ID	Sub-factors	Value ranges	Description	Score
C ₅₁	Organic matter (OM) (%) (Ülgen and Yurtsever 1984)	< 1.0	Very low	0
		1.0–2.0	Low	1
		2.0–3.0	Moderate	2
		3.0–4.0	High	3
		> 4.0	Very high	3
C ₅₂	Soil reaction (pH) (Ülgen and Yurtsever 1984)	< 4.5	Strongly acid	0
		4.5–5.5	Moderately acid	1
		5.5–6.5	Slightly acid	2
		6.5–7.5	Neutral	3
		7.5–8.5	Slightly alkaline	2
C ₅₃	Lime content-CaCO ₃ (%) (Ülgen and Yurtsever 1984)	< 1.0	Low lime	0
		1.0–5.0	Limey	3
		5.0–15.0	Moderately lime	2
		15.0–25.0	Highly lime	1
		> 25.0	Very highly lime	0
C ₅₄	Electrical conductivity (EC) (dS m ⁻¹) (Richards 1954)	0–4	Non saline	3
		4–8	Slightly saline	2
		8–15	Moderately saline	1
		> 15	Very highly saline	0

laws are used to calculate with TFNs (Hsieh et al. 2004). The AHP method proposed by Saaty (1980) is one of the MCDA methods used in organizing and analyzing complex decisions with many conflicting criteria. In the traditional AHP method, exact numbers represent people's judgments. However, traditional MCDA methods tend to be less effective when dealing with linguistic evaluations' imprecise or ambiguous nature (Kahraman et al. 2003). Thus, the fuzzy set theory proposed by Zadeh (1965) was adapted to these methods to overcome this uncertainty that occurs in the use of the traditional AHP method and solve the problem. The FAHP method can be seen as an advanced analytical method developed from conventional AHP. Various researchers in the literature put forward many different FAHP approaches (Özkan et al. 2020). In this study, based on the method developed by Buckley (1985), the FAHP method proposed by Sun (2010) was used.

The process for determining the weightings of the assessment criteria with FAHP can be summed up briefly as follows (Sun 2010):

Step 1: construct the pairwise comparison matrix

Pairwise comparison matrices are constructed between all criteria in the hierarchical structure. Allocated linguistic terms to the pairwise comparisons by asking which is the more important of each two criteria are as in Eq. (1).

Table 6 Value ranges of fertility conditions of soil (macroelements and microelements)

ID	Sub-factors	Value ranges	Description	Score
C ₆ Macroelements				
C ₆₁	Nitrogen (N) (%)	< 0.070	Very low	0
		0.070–0.090	Low	1
		0.091–0.110	Sufficient	2
		0.111–0.130	High	3
		> 0.130	Very high	3
C ₆₂	Phosphorous (P) (mg kg ⁻¹)	< 4	Very low	0
		4–8	Low	1
		8–16	Sufficient	2
		16–24	High	3
		> 24	Very high	3
C ₆₃	Potassium (K) (mg kg ⁻¹) (Pizer 1967)	< 100	Very low	0
		100–150	Low	1
		150–250	Sufficient	2
		250–320	High	3
		> 320	Very high	3
C ₆₄	Boron (B) (mg kg ⁻¹) (Wolf 1971)	< 0.5	Very low	0
		0.5–0.99	Low	1
		1.0–2.49	Sufficient	3
		2.5–4.99	High	1
		> 5.0	Very high	0
C ₆₅	Calcium (Ca) (mg kg ⁻¹) (Loue 1968)	< 714	Very low	0
		714–1430	Low	1
		1430–2860	Sufficient	2
		> 2860	High	3
		> 2860	High	3
C ₆₆	Magnesium (Mg) (mg kg ⁻¹) (Loue 1968)	< 54	Low	0
		54–115	Sufficient	2
		> 115	High	3
C ₆₇	Sodium (Na) (mg kg ⁻¹) (Loue 1968)	< 34	Very low	3
		34–68	Low	2
		68–230	Sufficient	1
		230–460	High	0
		> 460	Very high	0
C ₇ Microelements				
C ₇₁	Iron (Fe) (mg kg ⁻¹) (Lindsay ve Norvell 1978)	< 2.5	Low	0
		2.5–4.5	Sufficient	2
		> 4.5	High	3
C ₇₂	Zinc (Zn) (mg kg ⁻¹) (Lindsay ve Norvell 1978)	< 0.2	Very low	0
		0.2–0.7	Low	1
		0.7–2.4	Sufficient	2
		2.4–8.0	High	3
		> 8.0	Very high	3
C ₇₃	Manganese (Mn) (mg kg ⁻¹) (Lindsay ve Norvell 1978)	< 1	Nonsufficient	0
		> 1	Sufficient	3
C ₇₄	Copper (Cu) (mg kg ⁻¹) (Lindsay ve Norvell 1978)	< 0.2	Nonsufficient	0
		> 0.2	Sufficient	3

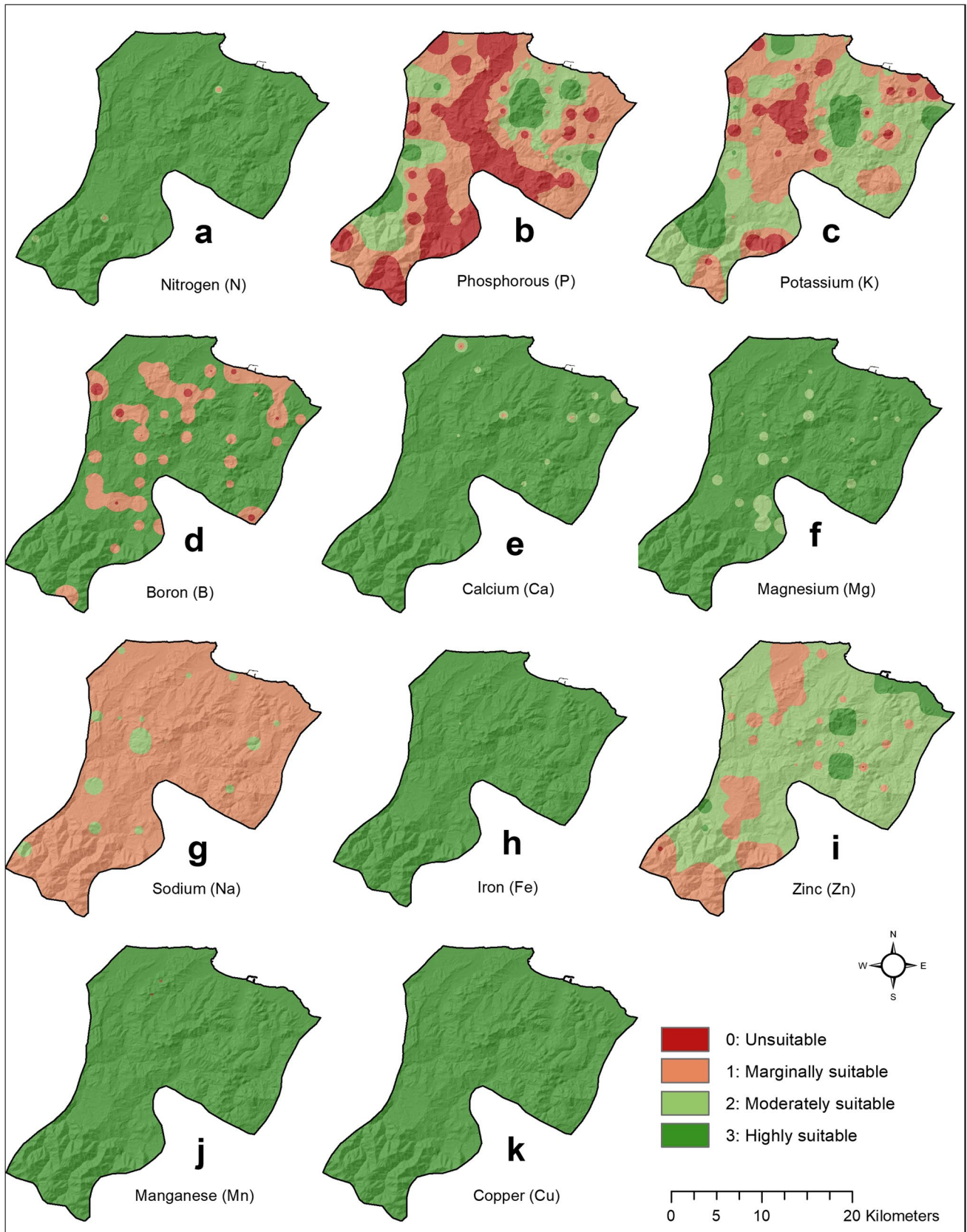


Fig. 7 Thematic maps of the soil fertility indicators: **a** nitrogen, **b** phosphorous, **c** potassium, **d** boron, **e** calcium, **f** magnesium, **g** sodium, **h** iron, **i** zinc, **j** manganese, **k** copper

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \dots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} \quad (1)$$

where \tilde{a}_{ij} measure denotes, let \tilde{I} be (1,1,1) when i equals j (i.e., $i=j$); if criterion i has one of the above linguistic variables assigned to it when compared with criterion j , then j has the reciprocal value when compared with i . If criterion i has one of the above linguistic variables assigned to it compared with criterion j , then j has the reciprocal value when compared with i . If criterion i is relatively essential to criterion j , then criterion j is relatively crucial to criterion i . If $\tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}, \tilde{5}, \tilde{6}, \tilde{7}, \tilde{8}, \tilde{9}$ measure that criterion i is relatively important to criterion j , then $\tilde{1}^{-1}, \tilde{2}^{-1}, \tilde{3}^{-1}, \tilde{4}^{-1}, \tilde{5}^{-1}, \tilde{6}^{-1}, \tilde{7}^{-1}, \tilde{8}^{-1}, \tilde{9}^{-1}$ measure that criterion j is relatively important to criterion i . The linguistic comparison terms and their equivalent TFNs used in this study are given in Table 7.

Step 2: compute the fuzzy geometric mean for each criterion

The use of the geometric mean to define the fuzzy geometric mean and the fuzzy weighting of each criterion was described by Buckley (1985). The geometric mean of each row of $\tilde{A} = [\tilde{a}_{ij}]$ is calculated as in Eq. (2).

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{1/n} \quad (2)$$

where \tilde{a}_{in} is the fuzzy value of criterion i compared to criterion n ; thus, \tilde{r}_i is the geometric mean of the fuzzy comparison values of criterion i for each criterion.

Step 3: compute the fuzzy weight for each criterion

The fuzzy weight of the i th criterion is calculated as in Eq. (3).

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \otimes \dots \otimes \tilde{r}_n)^{-1} \quad (3)$$

where \tilde{w}_i is the fuzzy weighting of the i th criterion and can be indicated by a TFN, $\tilde{w}_i = (lw_i, mw_i, uw_i)$, with lw_i , mw_i and uw_i representing the lower, middle, and upper values, respectively, of the fuzzy weighting of the i th criterion.

Step 4: convert fuzzy weight to crisp value

The result of the fuzzy synthetic decision reached for each alternative is a fuzzy number. Defuzzification is a mathematical process performed to convert the fuzzy output into a crisp value. The center of area (COA) method is a practical and straightforward method, and there is no need to introduce the preferences of any evaluators (Sun 2010). The best non-fuzzy performance (BNP) value of the fuzzy number, \tilde{w}_i , which is equal to (lw_i, mw_i, uw_i) , can be determined as in Eq. (4).

$$BNP_i = lw_i + \frac{(uw_i - lw_i) + (mw_i - lw_i)}{3}, \forall i. \quad (4)$$

Step 5: the crisp weights of criteria are normalized

Results and discussion

Some physicochemical properties and heavy metal concentration

The physicochemical characteristics and heavy metal properties of the 75 soil samples from the hazelnut plantations of Ünye District vary due to the natural environmental factors, the degree of decomposition during soil formation or the soil science process, the leaching process, and the dynamic interactions between human activities (soil cultivation, fertilization, etc.). The soils were generally light-heavy, acidic reaction, moderate organic matter level, low nitrogen levels, low phosphorus, and low potassium content. In addition, most of the soils are not calcareous or salty. Values for exchangeable sodium, calcium, and magnesium concentrations are very low, very high, and high, respectively. The basic descriptive statistics of some physicochemical properties and heavy metal content of the soils belonging to the study area, such as minimum, maximum, average value, standard deviation, are given in Table 8. The pH values of the soil samples vary between strong acid (3.98) and slightly alkaline (7.92). Minimum and maximum EC values are 0.16 and 1.37 dS m⁻¹. In addition, while the minimum and maximum CaCO₃ values vary from 0.23 to 43.84%, OM values range between 1.06 and 6.14%. In addition to these, the clay content of the soils is between 14.14 and 68.81%, and the silt content varies from 10.63 to 41.19%, while the amount of sand varies between 19.12 and 69.90%. The physical, chemical, and

Table 7 Linguistic variables for importance of criteria (Gumus 2009)

Fuzzy number	Linguistic	Scale of triangular fuzzy number	Scale of triangular reciprocal fuzzy number
1	Equal	(1,1,1)	(1,1,1)
2	Weak advantage	(1,2,3)	(1/3,1/2,1)
3	Not bad	(2,3,4)	(1/4,1/3,1/2)
4	Preferable	(3,4,5)	(1/5,1/4,1/3)
5	Good	(4,5,6)	(1/6,1/5,1/4)
6	Fairly good	(5,6,7)	(1/7,1/6,1/5)
7	Very good	(6,7,8)	(1/8,1/7,1/6)
8	Absolute	(7,8,9)	(1/9,1/8,1/7)
9	Perfect	(8,9,10)	(1/10,1/9,1/8)

Table 8 Descriptive statistics of some heavy metal, physical, chemical, and fertility properties of soil samples ($n = 75$)

ID	Parameter	Min	Max	Mean	SD	Variance	CV	Skewness	Kurtosis
C ₃	Heavy metal factors								
C ₃₁	Ni (mg kg ⁻¹)	3.35	143.27	30.53	25.77	664.07	84	1.82	4.65
C ₃₂	Pb (mg kg ⁻¹)	12.44	159.09	30.31	18.68	348.78	62	5.01	31.81
C ₃₃	Cu (mg kg ⁻¹)	2.60	152.08	39.39	30.72	943.77	78	1.58	2.36
C ₃₄	Cd (mg kg ⁻¹)	0.08	7.70	0.79	0.93	0.87	117	5.72	41.16
C ₃₅	Co (mg kg ⁻¹)	3.01	46.12	24.67	9.03	81.48	37	-0.48	0.21
C ₃₆	Zn (mg kg ⁻¹)	10.90	182.08	50.65	25.34	641.91	50	1.85	8.62
C ₃₇	Cr (mg kg ⁻¹)	1.45	266.43	27.05	32.18	1035.65	119	5.92	42.39
C ₄	Physical factors								
C ₄₂	Clay (%)	14.14	60.81	36.21	12.26	150.26	34	0.19	-0.94
C ₄₃	Silty (%)	10.63	41.19	23.85	6.12	37.47	26	0.81	1.04
C ₄₄	Sand (%)	19.12	69.90	39.94	12.62	159.20	32	0.29	-0.85
C ₅	Chemical factors								
C ₅₁	OM (%)	1.06	6.14	3.49	1.28	1.64	37	0.40	-0.65
C ₅₂	pH	3.98	7.92	5.96	1.19	1.42	20	0.03	-1.40
C ₅₃	CaCO ₃ (%)	0.23	43.84	4.29	9.62	92.48	224	3.00	8.75
C ₅₄	EC (dS m ⁻¹)	0.16	1.37	0.44	0.21	0.05	48	1.57	3.93
C ₆	Fertility factors (macroelements)								
C ₆₁	N (%)	0.07	0.48	0.21	0.07	0.01	36	1.37	2.53
C ₆₂	P (mg kg ⁻¹)	0.30	106.51	7.94	15.21	231.33	192	4.68	26.10
C ₆₃	K (mg kg ⁻¹)	38.00	1038.00	174.77	153.23	23,480.58	88	3.25	13.98
C ₆₄	B (mg kg ⁻¹)	0.20	5.80	1.57	1.13	1.28	72	1.66	2.95
C ₆₅	Ca (mg kg ⁻¹)	672	17,240.00	6992.74	4020.49	164,364.06	57	0.56	-0.61
C ₆₆	Mg (mg kg ⁻¹)	53.63	920.97	224.52	145.85	21,273.51	65	1.82	5.77
C ₆₇	Na (mg kg ⁻¹)	42.00	185.00	88.61	30.10	906.06	34	1.74	3.04
C ₇	Fertility factors (microelements)								
C ₇₁	Fe (mg kg ⁻¹)	3.58	152.28	36.43	28.19	794.84	77	1.80	4.10
C ₇₂	Zn (mg kg ⁻¹)	0.17	10.17	1.29	1.82	3.30	141	3.60	13.33
C ₇₃	Mn (mg kg ⁻¹)	2.27	176.28	32.14	30.68	941.00	95	2.30	7.40
C ₇₄	Cu (mg kg ⁻¹)	0.16	29.31	2.32	3.59	12.91	155	6.11	44.08

fertility properties and heavy metal (except Co) contents of soils have a normal distribution. Heavy metal values in soils are determined as 2.60 to 152.08 mg kg⁻¹ for Cu, 3.35 to 143.27 mg kg⁻¹ for Ni, 12.44 to 159.09 mg kg⁻¹ for Pb, 0.08 to 7.70 mg kg⁻¹ for Cd, 3.01 to 46.12 for Co, between 10.90 and 182.08 mg kg⁻¹ for Zn, and between 1.45 and 266.43 mg kg⁻¹ for Cr. Some researchers classify the coefficient of variation, which is considered to be an essential indicator in explaining the changes in soil properties, as low (< 15%), medium (15–35%), and high (> 35%) according to the values taken (Wilding et al. 1994; Mulla et al. 2000; Zhou et al. 2010; Dengiz 2020). As can be seen in this study, the soil properties observed have medium and high variability. While CaCO₃ has the highest variability, pH shows the lowest variability. Sağlam et al. (2015) stated that static properties such as soil structure, mineralogy, soil color, or thickness generally have low or medium variability. In contrast, the dynamic properties of soils, such as water content,

changeable cations, or plant nutrients, organic matter, and biological activities, etc., might show higher variability.

The most important reason for the high variability of CaCO₃ content is the distribution of volcanic rocks, which do not produce carbonate, and of calcareous carbonate in the geological pattern of the study area, as well as the decalcification event that occurs as a result of leaching in coarse-textured soils with the effect of heavy precipitation. A similar situation was valid for heavy metal distributions, and all heavy metal elements showed high variability.

Prioritization of the criteria

After determining the criteria to be used for the classification of land suitability for the hazelnut plant, the priorities of the criteria should be determined. For this purpose, firstly, pairwise comparisons are completed for each main criterion and sub-criterion by using Table 7. In the FAHP method, the calculation of weights for only one sub-criteria group

Table 9 Pairwise comparisons matrix for climatic conditions criteria

Criteria	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₁₅
C ₁₁	1	2	3	3	3
C ₁₂	1/2	1	2	3	3
C ₁₃	1/3	1/2	1	2	2
C ₁₄	1/3	1/3	1/2	1	2
C ₁₅	1/3	1/3	1/2	1/2	1

is given in the application section since the calculations include long and repetitive operations. All pairwise comparison matrices are presented in the “Appendix”. Pairwise comparison matrix performed for sub-criteria determined for climatic conditions is given in Table 9.

After determining the pairwise comparison matrix, the linguistic terms are converted into TFNs (Table 10) using the scale given in Table 7.

After the pairwise comparison matrix was converted into TFNs by using the geometric mean method suggested by Buckley (1985) in Eq. (2), firstly \tilde{r}_i value was calculated by using Eq. (2) to calculate the fuzzy weights of criteria. For $\tilde{r}_{1,1}$ as example:

$$\tilde{r}_{1,1} = ((1 \times 1 \times 2 \times 2 \times 2)^{1/5}, (1 \times 2 \times 3 \times 3 \times 3)^{1/5}, (1 \times 3 \times 4 \times 4 \times 4)^{1/5}) = (1.516, 2.221, 2.862)$$

Similarly, the remaining \tilde{r}_i values were calculated; these are:

$$\tilde{r}_{1,2} = (1.059, 1.552, 2.169), \tilde{r}_{1,3} = (0.608, 0.922, 1.351), \tilde{r}_{1,4} = (0.461, 0.644, 0.944), \tilde{r}_{1,5} = (0.370, 0.488, 0.758)$$

Then, \tilde{w}_i values were calculated using Eq. (3). For $\tilde{w}_{1,1}$ as example:

$$\tilde{w}_{1,1} = (1.516, 2.221, 2.862) \otimes (1/(2.862 + 2.169 + 1.351 + 0.944 + 0.758), 1/(2.221 + 1.552 + 0.922 + 0.644 + 0.488), 1/(1.516 + 1.059 + 0.608 + 0.461 + 0.370)) = (0.188, 0.381, 0.713)$$

Similarly, the remaining \tilde{w}_i values were calculated; these are:

$$\tilde{w}_{1,2} = (0.131, 0.266, 0.540), \tilde{w}_{1,3} = (0.075, 0.158, 0.337), \tilde{w}_{1,4} = (0.057, 0.111, 0.235), \tilde{w}_{1,5} = (0.046, 0.084, 0.189)$$

Thus, the weights of the criteria consisting of TFNs are calculated. The COA defuzzification method was used to calculate BNP weights of criteria. For $BNP_{1,1}$ as example:

$$BNP_{1,1} = 0.188 + [(0.713 - 0.188) + (0.713 - 0.381)]/3 = 0.427$$

Similarly, the remaining BNP weights of criteria were calculated, there are:

Table 10 Pairwise comparison matrix with TFNs for climatic conditions criteria

Criteria	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₁₅
C ₁₁	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)	(2,3,4)
C ₁₂	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)
C ₁₃	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1,2,3)
C ₁₄	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1,2,3)
C ₁₅	(1/4,1/3,1/2)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1/3,1/2,1)	(1,1,1)

$$BNP_{1,2} = 0.313, BNP_{1,3} = 0.190, BNP_{1,4} = 0.134, BNP_{1,5} = 0.106$$

After the BNP values are calculated, the criterion weights are normalized so that the sum is equal to 1. The steps described above are repeated for the main criteria and all other sub-criteria, and local weights are calculated for all criteria. Then, the global weights of the criteria are calculated by multiplying each sub-criterion by the weight of the main criterion to which it belongs (Table 11).

When weighting the main criteria using the FAHP method, climatic conditions (34.05%) ranked first in terms of importance, followed by topographical conditions (24.50%),

heavy metal pollution (16.29%), soil physical indicators (10.70%), chemical indicators (6.99%), soil macroelements

(4.62%), and microelement content (3.15%), respectively. In terms of evaluating the main criteria, it has also been

reported in previous scientific research studies on the assessment of land suitability for different agricultural products

that climatic conditions are respectively the most effective and dominant criteria (Zhang et al. 2015; Kazemi et al. 2016; Maleki et al. 2017; Tercan and Dereli 2020). In terms of climatic conditions, as a result of weighting the sub-criteria of climatic conditions with the FAHP method, the weight values in order of importance were determined as annual average temperature (12.43%), annual average precipitation (9.10%), annual average relative humidity (5.53%), annual

Table 11 Main and sub-criteria weights

Main criteria	Sub-criteria	Local	Global
C ₁		0.341	
	C ₁₁	0.365	0.124
	C ₁₂	0.267	0.091
	C ₁₃	0.162	0.055
	C ₁₄	0.115	0.039
C ₂		0.242	
	C ₂₁	0.519	0.126
	C ₂₂	0.308	0.075
C ₃	C ₂₃	0.173	0.042
		0.163	
	C ₃₁	0.266	0.043
	C ₃₂	0.225	0.037
	C ₃₃	0.167	0.027
	C ₃₄	0.141	0.023
	C ₃₅	0.091	0.015
	C ₃₆	0.060	0.010
C ₄	C ₃₇	0.050	0.008
		0.107	
	C ₄₁	0.349	0.037
	C ₄₂	0.256	0.027
	C ₄₃	0.159	0.017
C ₅	C ₄₄	0.142	0.015
	C ₄₅	0.094	0.010
		0.070	
	C ₅₁	0.395	0.028
	C ₅₂	0.294	0.021
C ₆	C ₅₃	0.199	0.014
	C ₅₄	0.112	0.008
		0.046	
	C ₆₁	0.262	0.012
	C ₆₂	0.203	0.009
	C ₆₃	0.163	0.008
	C ₆₄	0.137	0.006
C ₇	C ₆₅	0.102	0.005
	C ₆₆	0.079	0.004
	C ₆₇	0.054	0.003
		0.032	
	C ₇₁	0.398	0.013
	C ₇₂	0.270	0.009
	C ₇₃	0.201	0.006
	0.130	0.004	

average maximum temperature (3.91%), and annual average minimum temperature (3.09%), respectively. In this study, topographic conditions were established as the second main criterion because the elevation factor plays a vital role in the cultivation of agricultural products; the aspect factor plays an influential role in crop development, yield, and quality;

and the risk of erosion affects the reduction of organic matter and the loss of nutrients. The slope factor influences the cost of maintenance and transportation. Begum et al. (2013) asserted that due to the relationship between root and shoot development of the plant with flowering, fertilization, photosynthesis, and respiration, the total yield and quality are directly affected by both elevation and exposure to the sun. As a result of weighting the sub-criteria of topographic conditions with the FAHP method, the weight values were determined in order of importance as elevation (12.56%), aspect (7.45%), and slope (4.19%), respectively.

Many scientific studies have highlighted that the high heavy metal content of soils should be considered as an influential factor in land suitability assessment due to its negative impact on human health, food safety, biodiversity, and soil fertility (Safari and Delavar 2019; Bayraklı and Dengiz 2019, 2020). As a result of weighting the sub-criteria of heavy metal pollution conditions with the FAHP method, the weight values in order of importance were nickel (4.33%), lead (3.66%), copper (2.72%), cadmium (2.30%), cobalt (1.49%), zinc (0.97%), and chrome (0.82%), respectively. No severe risk was identified in the study area regarding heavy metal pollution of both anthropogenic and geological origins. It is critical in society and habitat that urgent measures should be taken in high-risk areas identified as risky in heavy metal conditions.

As the physical conditions (10.70%) and chemical conditions (6.99%) of the soil are natural and intrinsic factors affected by soil formation and environmental conditions, they were ranked as the fourth and fifth main factors in this study, respectively. As a result of weighting the sub-criteria of the physical conditions of the soil with the FAHP method, the weight values in order of importance were determined as soil depth (3.74%), clay (2.74%), silt (1.70%), and sand (1.52%), respectively. Turan et al. (2019) stated that the soil depth, defined as the root area and soil volume, where the plants meet their water and nutrient requirements, is a crucial land quality indicator in the land suitability assessment for plants.

In addition, grain size distribution (clay, silt, and sand content) has been considered the most critical physical indicator of physical soil conditions. It significantly affects water holding capacity, soil drainage, air and temperature circulation, soil erosion, soil fertility, and crop productivity. On the other hand, the parent material was determined at the level of 1% as a significant criterion in terms of being directly or indirectly a factor on the physical properties of the soil as well as its chemical properties (such as pH and lime amount) and providing the original supply of nutrients.

As a result of weighting the sub-criteria of the chemical conditions of the soil with the FAHP method, organic matter with the highest value (2.76%) was determined. It is well known that organic matter is an essential indicator for soil

quality due to its storage and supply of nutrients, improving soil fertility, minimizing erosion risks, and its impact on biological and physicochemical soil properties. Thus, it was determined as the most critical criterion in terms of the chemical conditions of the soil. pH was determined to be the second most important criterion with 2.05% in terms of the chemical conditions of the soil, as it is one of the main soil variables due to its effect on biological, chemical, and physical events as a result of the chemical reaction occurring in the soil. Among the chemical indicators of soils, CaCO₃ content with 1.39% was determined in third place in weighting; it was determined as the third important criterion in terms of chemical conditions of the soil because it forms the basis of the current nutrient behavior and affects the soil reaction. Finally, EC (0.79%) was determined as the lowest parameter in weighting. In general, salinity is not a problem in soils present within the study area, and EC values are below 2 dSm⁻¹.

On the other hand, in the context of soil fertility conditions, which can be called a dynamic factor, the lowest weight values were 4.62% and 3.15% for the densities of macroelements and microelements, respectively. When macronutrients were evaluated within themselves, the highest weight values were found in total nitrogen (1.21%), available phosphorus (0.94%), and potassium (0.75%) elements, respectively. They were followed by boron (0.63%), calcium (0.47%), magnesium (0.37%), and sodium (0.25%). When microelements were evaluated within themselves, the highest weight values were found in iron (1.25%) and zinc (0.85%) elements. Manganese (0.63%) and copper (0.41%) followed them. In general, there is no deficiency or excessive excess of macro- and micronutrients in the study area. There is some deficiency in terms of the elements of phosphorus, potassium, and sodium. It will be possible to improve sound and sustainable land management practices in areas with deficiencies and surpluses in all macro- and micronutrients, especially phosphorus, potassium, and sodium elements.

Land suitability for hazelnut and validation

Hazelnut suitability index (HSI) was calculated similarly to those used in linear combination models using Eq. (5) (Dedeoğlu and Dengiz 2019; Tercan and Dereli 2020):

$$HSI = \sum_{k=1}^1 w_k a_{ik} \quad (5)$$

Here, *HSI* refers to the hazelnut land suitability index; *W_k* is the weight value of parameter *k*; *a_{ik}* refers to the sub-criterion score of *i* for parameter *k*; and *k* represents the total number of parameters considered.

In this method, the criteria affecting the land use for hazelnut cultivation areas and weighted by FAHP are

multiplied by the lower value of the factor they belong to, and score values between 0 and 3 are generated. Because the sub-class scores of the selected criterion get a minimum of 0 and a maximum of 3 points. The final suitability map for the hazelnut plantations was obtained through weighted overlay analysis in the ArcGIS spatial data analysis tool, based on the weight values of 7 main criteria and 35 sub-criteria and the value ranges and scores of the requirements. Thematic compliance map produced as a result of HSI classification is presented in Fig. 8. This study's suitability classification was based on minor modifications of the FAO framework (FAO 1977). Thus, while coding with S1 shows that the land is very suitable for hazelnut production without any restrictions, the symbol S2 indicates that it is very suitable with very few restrictions. The symbol S3, on the other hand, suggests that it is moderately appropriate with some restrictions. S4 indicates marginally suitable with severe limitations, while the symbol N suggests that the land is not suitable for hazelnut production. Suitability assessment was made in 5 classes using the natural breaks Jenks method (Jenks 1967), considering the frequency distribution of the values and statistical information. This method is mainly used when the data is not evenly distributed. The values between the classifications that need to be presented are made more specific. Index values for HSI are shown in Table 12.

According to the results obtained, it was determined that 11.14% (56.84 km²) of the study area is not suitable for sustainable hazelnut farming, and 17.69% (90.33 km²) had marginal suitability. While these areas are primarily distributed in the southwestern parts of the study area, highly suitable and very highly suitable areas constitute almost half of the study area (47.57%). They are distributed in the north, north-west, and northeast parts of the study area and near the sea. Of the study area, 23.60% is moderately suitable (S3) areas (Table 12). In addition, the distribution map of the suitability classes created for hazelnut agriculture is given in Fig. 8.

Reis and Yomralıoğlu (2006) carried out a research in the province of Trabzon to create a methodology for determining existing potential hazelnut areas just using GIS and RS techniques regarding to support hazelnut policy developers and economists. Landsat ETM+ image was used to generate a current land cover classification. Using the supervised classification method, overall accuracy was determined to be 84.7%. Suitable hazelnut areas were determined according to criteria settled by government regulations. In addition, researchers suggested that not only more information on existing land cover but also other ecological criteria are required to determine ideal potential hazelnut areas.

In the present study, existing hazelnut-growing areas were also used to validate the developed model. The existing hazelnut-growing areas obtained from the Ministry of Agriculture and Forestry (LPIS-Land Parcel Identification System) and the suitability classes obtained as a result of the

Fig. 8 Hazelnut suitability map of the study area

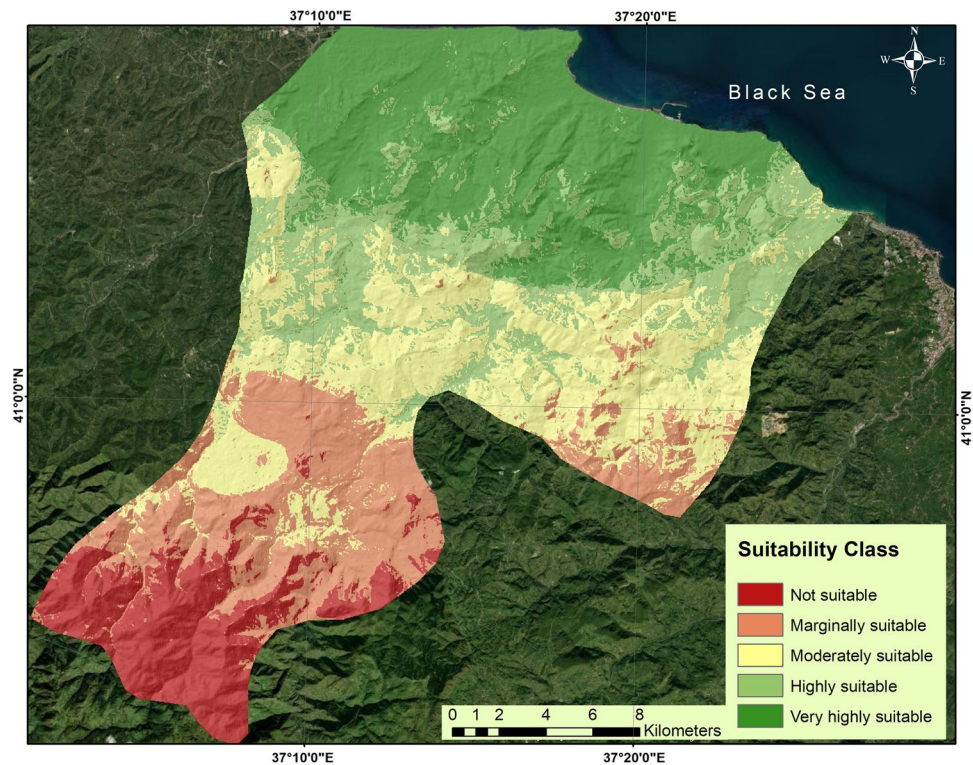


Table 12 Land suitability classes for hazelnut and their distribution and index values

Suitability classes	Symbol	Area (km ²)	Ratio (%)	Suitability index
Very highly suitable	(S1)	145.03	28.40	2.58–2.97
Highly suitable	(S2)	97.85	19.17	2.31–2.58
Moderately suitable	(S3)	120.50	23.60	2.03–2.31
Marginally suitable	(S4)	90.33	17.69	1.70–2.03
Not suitable	(N)	56.84	11.14	1.27–1.70

model developed in this study were compared, and high parallelism was achieved. The results obtained show that of the existing hazelnut-growing areas, 29.47% (91.86 km²) overlap with very highly suitable areas, 20.46% (63.79 km²) with highly suitable areas, 25.66% (79.98 km²) with moderately suitable areas, 17.15% (53.48 km²) with marginally suitable areas (Fig. 9). In summary, it was determined that 92.74% of the existing hazelnut-growing areas of 311.76 km² are in the suitable classes presented in this study, which is an essential indicator of the accuracy of the proposed hazelnut land suitability model.

On the other hand, in the land suitability model presented in this study, there are existing hazelnut-growing areas with an area of 22.65 km² (7.26%) that fall within problematic

areas. The predominant parameters limiting the suitability of these areas are climatic and topographic conditions. These areas have severe limitations, especially climatic factors such as annual average minimum and maximum temperature and average temperature. In addition, the elevation of most of these areas is over 750 m. In terms of soil conditions, there are limitations in terms of soil depth and parent material properties, which are physical indicators of the soil, and pH, which are chemical indicators of the soil, as well as limitations in terms of phosphorus and potassium, which are the macro-soil nutrients. In such areas, it will be necessary to review the planning decisions by considering hazelnuts' efficiency and quality characteristics of hazelnuts and the economy.

Conclusions

In most cases, farmers or decision-makers follow traditional land management practices that are not recommended for the sustainability of natural environmental conditions. However, optimum use of natural resources should be ensured by considering future needs with a new strategic approach. For this purpose, land suitability assessment studies are essential in land use planning where natural resources are limited.

The research was conducted to create a hazelnut suitability index model in the Eastern Black Sea region with semi-humid-humid ecological conditions and in Ordu Province

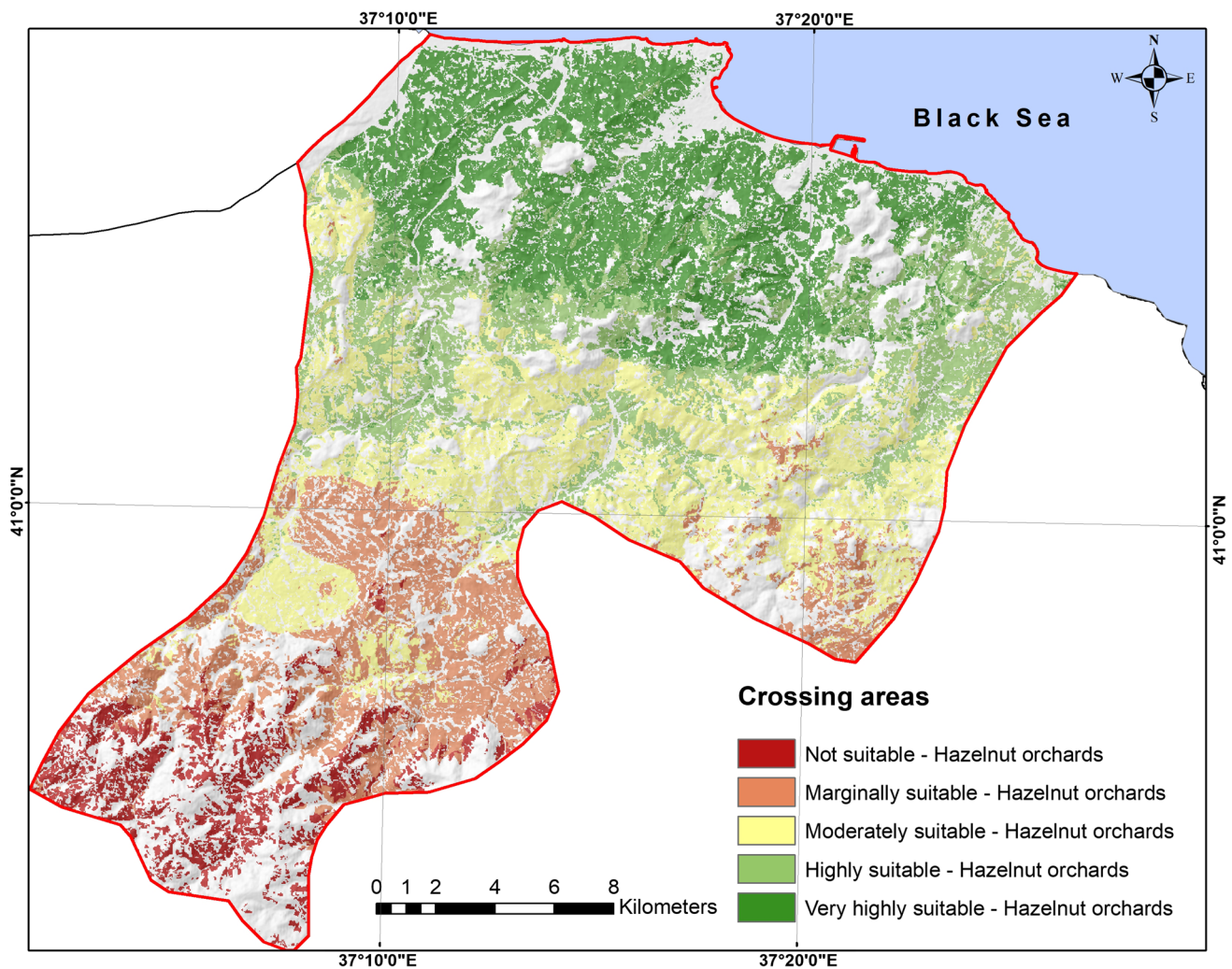


Fig. 9 Thematic map of the overlay analysis of existing hazelnut growing areas and the eligibility classes presented in this study

Ünye District, which is essential in Turkey's hazelnut production. In the study, a unique land suitability model for hazelnut cultivation was constructed using the set of criteria (7 main criteria, 35 sub-criteria) including qualitative and quantitative reasons and fuzzy analytic hierarchy process, inverse distance weighting, weighted linear combination, and GIS approaches. According to the model result, 71.16% of the study area was classified as very highly suitable, highly suitable, and moderately suitable, while 28.82% had marginally suitable and not suitable properties for hazelnut cultivation. In addition, the existing hazelnut cultivation areas obtained from the parcel registration system (LPIS—land parcel identification system) and the relevant fields obtained as a result of the model were compared, and it was concluded that they were highly compatible.

As stated above, many data on environmental factors and ecological conditions were brought together to protect the terrestrial ecosystem and ensure its production continuity.

They played an essential role in the decision-making process by providing more accurate and more accessible information by using MCDA approaches with techniques and programs such as GIS-RS, which provide the spatial characteristics of the data to be analyzed, in dealing with all processes of the creation of the hazelnut suitability index model.

As a result, land suitability assessment studies are essential. However, planners and decision-makers have some obstacles and challenges in obtaining information and data from large areas. Accordingly, as in this study, the results for determining areas suitable for hazelnut agriculture for regions with similar ecology will indicate where the appropriate land is located in agricultural production and sustainable land use and positively affect the decision-making process. This study can not only serve as a guide for future studies but can also be further improved by including various biophysical indicators and socioeconomic factors.

Appendix

- Table 13
- Table 14
- Table 15
- Table 16
- Table 17
- Table 18
- Table 19

Table 13 Pairwise comparisons matrix for main-criteria

Criteria	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇
C ₁	1	2	3	4	5	6	7
C ₂	1/2	1	2	3	4	5	6
C ₃	1/3	1/2	1	2	3	4	5
C ₄	1/4	1/3	1/2	1	2	3	4
C ₅	1/5	1/4	1/3	1/2	1	2	3
C ₆	1/6	1/5	1/4	1/3	1/2	1	2
C ₇	1/7	1/6	1/5	1/4	1/3	1/2	1

Table 14 Pairwise comparisons matrix for topographical conditions criteria

Criteria	C ₂₁	C ₂₂	C ₂₃
C ₂₁	1	2	3
C ₂₂	1/2	1	2
C ₂₃	1/3	1/2	1

Table 15 Pairwise comparisons matrix for heavy metal pollution conditions criteria

Criteria	C ₃₁	C ₃₂	C ₃₃	C ₃₄	C ₃₅	C ₃₆	C ₃₇
C ₃₁	1	2	2	2	3	4	4
C ₃₂	1/2	1	2	2	3	4	4
C ₃₃	1/2	1/2	1	2	2	3	3
C ₃₄	1/2	1/2	1/2	1	2	3	3
C ₃₅	1/3	1/3	1/2	1	1	2	2
C ₃₆	1/4	1/4	1/3	1/2	1	1	2
C ₃₇	1/4	1/4	1/3	1/2	1	1/2	1

Table 16 Pairwise comparisons matrix for physical conditions of soil criteria

Criteria	C ₄₁	C ₄₂	C ₄₃	C ₄₄	C ₄₅
C ₄₁	1	2	2	3	3
C ₄₂	1/2	1	2	2	3
C ₄₃	1/2	1/2	1	1	2
C ₄₄	1/3	1/2	1	1	2
C ₄₅	1/3	1/3	1/2	1/2	1

Table 17 Pairwise comparisons matrix for chemical conditions of soil criteria

Criteria	C ₅₁	C ₅₂	C ₅₃	C ₅₄
C ₅₁	1	2	2	3
C ₅₂	1/2	1	2	3
C ₅₃	1/2	1/2	1	2
C ₅₄	1/3	1/3	1/2	1

Table 18 Pairwise comparisons matrix for fertility conditions of soil (macro)criteria

Criteria	C ₆₁	C ₆₂	C ₆₃	C ₆₄	C ₆₅	C ₆₆	C ₆₇
C ₆₁	1	2	2	2	3	3	4
C ₆₂	1/2	1	2	2	2	3	3
C ₆₃	1/2	1/2	1	2	2	2	3
C ₆₄	1/2	1/2	1/2	1	2	2	3
C ₆₅	1/3	1/2	1/2	1/2	1	2	2
C ₆₆	1/3	1/3	1/2	1/2	1/2	1	2
C ₆₇	1/4	1/3	1/3	1/3	1/2	1/2	1

Table 19 Pairwise comparisons matrix for fertility conditions of soil (micro) criteria

Criteria	C ₇₁	C ₇₂	C ₇₃	C ₇₄
C ₇₁	1	2	2	3
C ₇₂	1/2	1	2	2
C ₇₃	1/2	1/2	1	2
C ₇₄	1/3	1/2	1/2	1

Author contribution ET and OD conceived the ideas and designed methodology, and collected the data; ET, OD, BO, and MAD analyzed the data; ET, OD, and MAD developed figure presentations; ET and OD led the writing of the manuscript; all authors (ET, OD, BO, MAD, and YBO) edited and revised the paper and gave final approval for publication.

Data availability The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

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