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Viticulture Suitability in Western Slopes of Jabal Al-ArabAn Integration of Bioclimatic, Soil, and Topographic Indicators for Viticulture Suitability Using Multi-Criteria Evaluation: A Case Study in the Western Slopes of Jabal Al-Arab – Syria

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Abstract:

In the 21st century, Geographic Information Systems (GIS) have become one of the leading technologies in different sectors for development and planning, particularly in modern agricultural management. Moreover, recent advances in GIS tools and methods have helped decision-makers as well as farmers to find optimal sites for production of different crops. The cultivation of vineyards and grapes is one of the most important agricultural activities in the Al-Sweidaa governorate-Syria, which has been suffering from a decrease in annual productivity in conjunction with an increase in the annual demand for grapes and wine products, particularly in recent decades. Therefore, the aim of this research was to establish a new method for analysing the optimum regions for economic viticulture production in the Western Slopes of Jabal Al Arab in the Al-Sweidaa governorate by using Multi Criteria Evaluation (MCE). To this end, a field survey was conducted and a soil sample was collected for physical and chemically analysis, and a 1984-2014 MRm.30-meter resolution dataset of climatic variables for the Al-Sweidaa governorate was set up as well. The results show that suitable areas are concentrated in the higher part of the study area (the eastern part) where climate and soil are favourable, and did not show any relevant limitations. Conversely, the lower part of the study area (the western) has unfavourable climate and soil chemical and physical fertility; therefore grape production is only possible if irrigation is applied and the fertility properties of the soil are improved, particularly the percentage of organic matter and the soil texture.

Keywords: Multi Criteria Evaluation, Multivariate Regression Models, Climate-Viticulture Indices, Jabal Al Arab and Analytical Hierarchy Process.

1. Introduction

Suitability is a key function for assessing crop requirements, as well as the characteristics of land for a particular use; it measures the conformity of land unit characteristics to the requirements of a form of use (FAO 1976), and the capacity of a given type of land to support specific use (Duc 2006). Moreover, many systems-research methods and several tools relating to information technology have become available for modern agriculture, such as GIS and RS technologies and have become widely used in the management of multiple crops in several scales (Acharya and Yang 2015). In addition, Multi Criteria Evaluation (MCE) has been developed to enhance spatial decision-making when evaluating a range of alternatives based on conflicting and unequal criteria, such as the evaluation of several crops in a land unit to support sustainable development (Mustafa et al. 2011). Therefore, farmers can now select the best or most suitable site for the cultivation of their crops or modify a pattern of land use according to crop requirements and based on environmental criteria such as climate, soils and topography properties. Vineyards are one of the most common cultivations around the world, and due to their value in the production of grapes and wine, the suitability of vineyards has been one of the most frequently studied of all crops in many regions (Watkins et al. 1997; Jones 2005; Jones et al. 2009; Anderson et al. 2012; Köse 2014; Fraga et al. 2014; Acharya and Yang 2015; MacCracken and Houser 2016; Mills-Novoa et al.2016; Hunter and Bonnardot 2011; Stanchi et al. 2013). Some of this research has focused on analysis of climate-viticulture as an input processing of the evaluation of suitability, and some on environmental suitability in general (soils, topographic elements, land cover, climate and geology). Overall, local and regional climate is essential for determining vineyard site suitability (Winkler et al. 1974). Understanding climate variables, including temperature, humidity, precipitation, sunshine and wind, is important for determining suitability. Each of these variables has a different degree of influence on wine grape growth (MacCracken & Houser 2016). However, past studies have shown that temperature plays a dominant role. (Winkler et al. 1974; Jacob 1950; Barans et al. 1946; Amerine and Winkler, 1944; Tonietto and Carbonneau, 2004). As an example, cooler climates, with a mean pre-harvest temperature below 15°C have a significant impact on - and are a clear challenge for - wine grape growth and its maturity on appropriate dates; this climate condition produces grapes and wines with lower sugar, higher acid, high pH, and lower yields per land unit (Jackson 2000). Hotter climates with a mean temperature high than 35°C during grape growth also have a negative impact (Blanco-ward, et al. 2017). Due to the importance of temperature, a wide range of climate-viticulture indices have been proposed which use the temperature element as the most relevant variable for growing grapes and one essential for determining vineyard site suitability (Winkler et al. 1974; Huglin 1978; Gladstones 1992; Barans et al. 1946; Tonietto and Carbonneau 2004). Some of the indices which have been proposed use interaction between the number of actual sunlight hours, accumulated temperature, and the amount of precipitation in the growing season (Barans et al. 1974; Barans et al. 1946). These indices have been applied to define vinicultural regions on both a global and a local scale (Anderson et al. 2012; Mills-Novoa et al. 2016; Fraga et al. 2014; Jones et al. 2010; MacCracken and Houser, 2016; Köse 2014; Lorenzo et al. 2013; Mesterházy et al. 2013; Hunter and Bonnardot 2011; Blanco-ward, et al. 2017). This was the case with Jabal Al Arab in Syria, and was based on 1984-2014 MRm.30-meter resolution grids dataset of climatic variables for the Al-Sweidaa governorate (Alsafadi 2016), and showed elements such as the average of minimum and maximum temperature, precipitation, the number of actual sunlight hours, and the extreme temperature events through the vineyards' growing season.

In addition to the above, vineyards are often characterized by limited amounts of wines and grapes with steep slopes, low soil fertility, and dryness (Stanchi et al. 2013; Alganci el al. 2018). So climate and soil characteristics play an important role compared to other variables in the interaction with vineyards to produce wines and grapes in higher quality (Kumara and Sendanayake 2016; Kurtural et al. 2006; Ubalde et all. 2010).

Overall, the main aim of this research is to integrate the analysis of climate-viticulture indices with soil and topography criteria and consider them in terms of vineyard suitability. To our knowledge, this is the first study in which climate, soil, and topography have been jointly studied to analyse the viticultural western slopes of Jabal Al Arab.

2. Study Area

The study area is located in the western part of the Al-Sweidaa Governorate, in southern Syria, between 32°28′15"N, 36°24′18"E and 32°46′44"N, 36°45′15"E) (Fig.1a). This region has a Mediterranean wet climate (Csb) in higher areas with dry summers and temperate winters, while in the lower areas it has a cold semi-arid climate (Bsk) according to the Kopin classification; mean annual precipitation is between 250 and 550 mm, more than 80% of which falls from October to April (Alsafadi 2016). It covers an area of 523 km^2 (52300 hectares). Altitude ranges between 696 m in the west and 1795 m in the east (Tall Qeni). The agricultural area is around 83.66 % of the study area (Fig. 1b). The total viticultural area was around 10 125 ha in 2015, although it was 15 497 hectares in 1991, according to SMOAAR (2015). This area decreases annually, due to the frequency of cold and heat waves, and high production costs.

Fig. 1(a) Location of the study area from the Al-Sweidaa governorate and sites of soil profiles, (b) Land cover map.

3. Data and Methods

3.1. Climatic, Topographic and Soil Data

In order to accurately calculate and analyse temperature-based climate indices for this research, we used 1984-2014 MRm.30-meter (Multivariate Regression Models), high resolution grid datasets of climatic variables for the Al-Sweidaa governorate (Alsafadi 2016), which include details such as average minimum and maximum temperature (from April to October), seasonal precipitation, the number of actual sunlight hours and extreme temperature events through the vineyards' growing season. The grids were based on daily data collected from climate stations in the Al-Sweidaa governorate and other climate stations outside the study area such as Daraa, Alqunaytra, Damascus, and North of Jordan, for the period 1984-2014. Individual weather stations in the study area can only record information at their specific sites, but the grid data cover the entire study area and take into consideration the gradient of climate elements over a short distance caused by the complexity of the topography. The grids data were created with an analysis of the Multivariate Regression Model, using latitude, longitude, distance from coastal line, elevation, slops, and aspect as requested variables, and climatic variables as dependent variables, which means reproducing the equation of the regression fit using the raster matrices of the independent variables. The outcome of this procedure is a raster matrix map for each month with high resolution (30m by 30m) regular grids. The annual and seasonal temperature and precipitation grids have been shown to have Std. Error estimated at between 0.3 and 0.7 °C for temperature layers and 37mm for precipitation layers (Alsafadi 2016). These temperature grids, along with other climate parameter grids, have been used in developing climatic suitability maps for growing vine-grapes in the study area.

For the topographic analysis, elevation, geographical aspect and slopes were selected as the leading elements to be studied in suitability processing, due to their importance in viticulture. For this study, data were collected from available sources on the web. The main input data are from a DEM: a Digital Elevation Model of the study area (Fig. 3.a) which was clipped from NASA's Shuttle Radar Topography Mission (SRTM). These data grids have a 1°arc-sec global (approx. 30m) resolution (https://earthexplorer.usgs.gov). The DEM was later used to generate slope (Fig. 3.b), hill-shade (Fig. 3.c), and aspect (Fig. 3.d) maps.

Analysed soil data was obtained from soil survey and laboratory analysis conducted in the study area (Kiwan 2014; Hennawi and Habib 2013; Hennawi and Habib 2012; Habib 2006). Following this, the values of the soil characteristics were recalculated using a weight factor, and then the new data were converted to grid datasets by the Kriging method as a geostatistical surface high resolution of 30 by 30 m, and then classified for vineyard suitability.

The map of present land cover distribution has been elaborated from Bing Images high resolution 8m by 8m (www.giscloud.com), after rectification and geo-referencing using ArcMap 10.5 (Fig.1b).

3.2 Data Analysis

3.2.1 Climate-Viticulture Indices and Extreme Temperature Events

The Climate-viticulture indices are presented in Table1. Five climatic indices were calculated to evaluate the climate of the western slopes of Jabal Al Arab in terms of sunshine duration, precipitation and heat summation requirements for viticulture. *(1) Branes Heliothermic Index (BHI)*: developed by Branas et al. (1974), this index combines the number of actual sunshine hours and the temperature during the growing season. BHI is used to evaluate grape regions, cultivar adaptation, phenological development and ripening characteristics (Köse 2014). *(2)* The *Hydrothermal Coefficient (HTC)* which was developed by Branas et al. (1946) combines the effect of the amount of seasonal precipitation and temperature during the growing season; this is a characteristic number, which measures the water supply for vegetation, and determines the possibility of rainfed viticulture (Alsafadi 2016; Mesterházy et al. 2013). In regions where HTC values are below 0.5 mm/°C, grape production is only possible if the air humidity is high or if irrigation is applied. The maximum value of the HTC is 1.5−2.5 mm/°C, while the optimal value is 1.0 mm/°C (Mesterházy et al. 2013). *(3)* The *Winkler Index (WI-GDD)*: this makes use of the sum of the daily average temperatures between April and the end of October. WI-GDD provides information on the accumulation of heat during the growing season for vineyards with a base temperature of 10 °C (Amerine and Winkler 1944). *(4)* The *Huglin Index (HI)*: this was developed by Huglin (1978). HI values are computed similarly to WI-GDD but its processing calculation includes a high weighting for maximum temperature and an adjustment based on latitude; i.e. the coefficient length of the day (Huglin 1978). In addition, it provides better information regarding the sugar potential of given varieties, and thus provides qualitative information combined with the values of the CI cool night index (Tonietto and Carbonneau, 2004). Jones et al. (2009), and Hall and Jones (2010) have updated the HI formula for all latitudes, using the months from April to September (in the Northern Hemisphere), leaving out October, as they suggested that harvesting during that time made the values less important (Jones et al. 2010; Anderson et al. 2012). *(5)* The *Cool Night Index (CI):* this was developed by Tonietto and Carbonneau (2004) and is a night coolness variable which takes into consideration the mean minimum night temperatures during the month when ripening usually occurs (i.e. September). This climatic factor is also important as regards grape and wine colour and aromas; CI is recommended for improving the assessment of the qualitative situation of wine-gapes, in relation to secondary metabolites in grapes juice, such as aromas and polyphenols. (Kliewer and Torres 1972; Kliewer 1973). The calculation for the determination of CI is as follows: in the Northern Hemisphere: CI = minimum air temperature in the months of September (mean of the minima), in °C. In the Southern Hemisphere: CI = minimum air temperature in the months of March (mean of minima), in °C (Tonietto and Carbonneau, 2004). Thus, categorized climate-viticulture indices allow us to determine the optimum climatic suitability in terms of heat and water availability and phenological development during the growth season, as well as ripening conditions (Fraga et al. 2014).

Table 1 Climate-Viticulture Indices (bioclimatic), definitions and classified limits

Bearing in mind the discussion above regarding the complex climate influences on growing grapes and wine production, is there an ideal climate for vineyards? Jones (2015) suggested an optimum zone, where it is best to match the cultivars to the climate condition, as shown in Fig. 2. In the optimum zone a cultivated cultivar will produce higher quality grapes and wine as it provides an appropriate growth period and tends to balance the four ripeness clocks that are evolving simultaneously but at different averages — acid respiration, sugar accumulation, fruit character, and phenolic ripeness (Jones et al. 2005; Jones et al. 2010). Furthermore, any given grape cultivar has thresholds related to the climate; if it is being grown in very cool regions, this will lead to lower sugar levels, higher acid retention, unbalanced wines and unripe flavours. Conversely, if a given grape cultivar is being grown in a very warm region, this will lead to lower acid retention, higher sugar levels, unbalanced wines and overripe flavours (Jones 2015). According to the previous proposal, the current study has classified the values of HI and WI-GDD by dividing them into several limits as shown in Table 6. The very cold and the very warm limits were given little importance; on the other hand, the moderate zone was given great importance because it achieves a balanced growth.

Fig. 2 Relationship and thresholds between climate and wine production and quality metrics (Jones 2015)

In addition to the above five climate-viticulture indices, the heat waves and the cold waves (the number of days below 15°C during the flowering period (NDb15), and the number of days over 35°C during the ripening period (NDh35)) have been computed and estimated based on the daily minimum temperature of May for cold waves, and the daily maximum temperature of July and August for heat waves, using cubic equations and nonlinear regressions to estimate these climatic parameters for the study area, as shown in Table 2. The frequency of heat waves during the ripening stage has a negative effect on vineyard vegetation and grapes, and on wine production, particularly when the temperature is above 35 °C (Mesterházy et al. 2013; Alsafadi 2016; Blanco-ward, et al. 2017). In addition, the frequency of cold waves during the flowering stage has a direct effect (Alsafadi, 2016); when the mean daily temperature was 15°C or below, no inflorescences were produced (Vasconcelos 2009).

Table 2 Estimation of the frequency of heat waves and cold waves during ripening and flowering stages, based on daily temperature data from 1984 - 2014 at Alswuydaa and Ain Al-Arab stations

3.2.2 Soil Sampling and Indicators

To achieve the study goals a soil survey was conducted in the study area by dividing it into 10 zones according to climatic characteristics and geomorphological aspects. As a result, more than 56 soil profiles were dug till the bedrock was reached and were described according to the system outlined by the FAO (1990). Following this, 244 soil samples were transferred to the soil laboratory at the General Commission of Scientific Research, Damascus, Syria, to analyse the soil texture (Day 1965), the electrical conductivity (EC) of (1:5) the soil dS/m (Rhoades 1983), the soil reaction (pH) of (1:2.5) the soil (Melan 1982), the organic matter % (Nelson and Sommers 1982), and the CaCO3% (Nelson and Sommers 1982). Laboratory results were recalculated and modified for each characteristic and each profile by using a weighting factor (Sys et al. 1991) as shown (Table 3).

Table 3 Weighting factor classification

The six soil indicators were classified to evaluate a soil's suitability for vineyards on the western slopes of Jabal Al Arab, as follows: *(1) Organic Matter (OM):* organic matter contributes through structure, nutrients, moisture available in the soil, and porosity. The organic matter gives a pool of slowly available nitrogen to support vineyard growth. OM values greater than 5 percent are counter-productive because the excessive nitrogen released by OM decomposition may lead to excessive vegetative growth; the desired values for vineyard soils are 2-3 percent (Kurtura et al. 2008; Wolf and Boyer 2003). *(2) Soil Texture*: all soil texture classes show their properties in terms of agricultural use. Sandy soils have coarse particles and are usually excessively drained, with low water retention capacity. Conversely, clay soils have small particles and retain large amounts of water, but its discharge is poor and usually difficult to manage. With relatively even proportions between particles, loamy soils are typically well drained and provide sufficient nutrient retention and are thus usually preferable for agricultural use (Fraga et al. 2014; White 2009). Therefore, the relatively even proportion between particles has been calculated based on the total proportion of each sand and silt to clay, in order to evaluation the quantitative importance of these particles, especially the soil of the study area characterized by a high clay content, and to implement soil texture as a dataset layer. *(3) Soil pH:* soil pH gives an indication of nutrient balance and fertility; most studies have found that preferred values for vineyard growing are between 5.5 and 8.0; nutrients may become out of balance outside this range (Jones, 2004). Soil pH values from 6.0 to 6.8 provide the optimum availability of nutrients in vineyard soils (Kurtura et al. 2008; Wolf and Boyer 2003; White 2003). *(4) Electrical Conductivity (EC):* this is linked to or indicates the soil's salinity levels; vineyards are sensitive to high salinity levels, so vineyard damage and poor growth can occur as a result of an "osmotic effect" as roots strive to uptake salty water; the optimum value is >2 dS/m (Labay 2017: Cass et al. 1995; Lanyon et al. 2004), although, vine rootstock can tolerate EC up to 4 dS/m (White 2003). *(5) Soil Depth*: a deep soil (> 100 cm) offers a greater volume of potential soil moisture than does a shallow soil (< 40 cm). Vineyards can be grown on shallow soils; however, these vines will suffer from drought if supplementary water is not available by irrigation (Wolf and Boyer 2003). *(6) Calcium Carbonate (CaCO3):* generally, Ca+ plays a good role in the soil by improving soil structure and soil aggregation, but badly affects the mineralization rate of the soil organic matter (Virto et al. 2018), Lebrun (2016) mentioned that the soil Ca+ content could affect the wine's properties.

3.2.3 Topography

The terrain of a site is recognized as having an influence on grape-vine production by affecting its mesoclimate (Gladstones 1992). Slopes are important for soil water drainage, and are necessary and critical in the growing of vineyards. Slopes steeper than 15% are not recommended because of the risk of the downhill drift of towed equipment in the vineyard rows (Wolf & Boyer 2003). However, a geographical aspect refers to the predominant directional orientation of a slope, and this is important in terms of its effects on the total heat balance of a vineyard (Chen 2011). Aspect will affect the angle at which sunlight hits the vineyard and its total balance of heat. Vineyards should be exposed to direct sunlight for at least a part of the day; eastern aspects are probably optimal (Gladstones 1992). Therefore, aspect and slope data were calculated based on DEM data using surfaces analysis in ArcGIS software, as shown in (Fig. 3).

Fig. 3 Topographic characteristics (a) elevation (b) slope-percentage (C) hill-shade, (d) aspect

3.3. Multi-criteria Evaluation (MCE)

Evaluation of multi-criteria is an integrated process which selects better alternatives where a decision has to be taken considering several constraints and factors depending on their relative importance to the final objective, integrated with GIS tools and procedures (Malczewski 1999; Malczewski 2000; Carver 1991). Several practical techniques are used for land suitability analysis, for example, Weighted Linear Combination (WLC) or Sum, depending on the nature of the input layers (Kumara & Sendanayake 2016; Dengiz and Usul 2018). Many studies have set several criteria and factors for selecting the best sites for vineyards based on the soil and topography properties (Watkins et al. 1997; Jones et al. 2004; Ghosh 2005; Happ2014; Acharya and Yang 2015; Alganci el al. 2018), while others have focused on analysis of bioclimatic indices in suitability evaluation (Mills-Novoa et al. 2016; MacCracken and Houser 2016; Campbell 2013; Jones et al. 2010; Anderson et al. 2012; Koufos2017; Blanco-ward, et al. 2007; Santos et al. 2018). However, a few studies have integrated the analysis of climate-viticulture indices, with soil, topography and land cover criteria, for consideration of vineyard suitability (Kurtural et al. 2006; Stanchi et al. 2013; Fraga et al. 2014). This has been done in this research, which has applied vineyard suitability on two levels: the first level includes three main criteria (climate, soil, and topography) and the second includes many sub-criteria within the main criteria, as explained in Table. 6, and applied as shown in Fig.4.

Second level or sub-criterion ranks are computed for each layer. These values are combined with weight (calculated using the AHP method) to provide a suitability value for each layer. The formula is as follows:

$$S = [\sum_{i=1}^{n} Wi * Xi] \Pi cj \quad \text{...(Eq.1)}$$

S: Suitability index

wi Weight of criterion i

xi: Rank of criterion i

cj: Boolean value of limited criterion

The above formula is applied to each layer. Overall, a higher final S value indicates a higher suitability for viticulture. In our experiment, cj takes a value of 1 or 0. A value of 0 is applied to a land cover mapping unit which is not suitable due to its natural conditions, i.e. for water bodies, buildings and public facilities; 1 is for other types of land cover. Consequently, the Boolean value in our study is land cover pattern, by a value of 0 and 1, where urban areas were excluded from final suitability using the algebra calculator in GIS tools, as shown in Fig.4.

The land suitability system is divided into suitable (S) and not suitable (N). The suitable category is divided into a very suitable class (S1), a suitable class (S2) and a moderately suitable class (S3). The not suitable category is grouped into a temporarily not suitable class (N1) and a permanently not suitable class (N2) (FAO 1976). Before applying a weighted linear combination equation to calculate the suitability index, these calculated ranks are standardized to measure the scale, where 0 is permanently not suitable (N2), 1 is low or temporarily not suitable (N1), 5 is moderately suitable (S3), 7 is high (S2), and 9 is very high suitability (S1). The conversion is shown in Table 6.

3.4. Analytical Hierarchy Process (AHP)

Analysis of land suitability requires consideration of several criteria for specific land use as explained in this study which has integrated many criteria for analysis of vineyard suitability. Although GIS has emerged as a powerful tool and method to handle spatial data in land suitability evaluation, the application of these tools alone could not overcome the issue of inconsistency in experts' opinions when trying to assign relative importance or weight to each criteria and layer and considering it in a suitability analysis (Duc2006). To solve this issue, the AHP method is used in combination with the GIS tool (Feizizadeh and Blaschke 2012; Kumar et al. 2016; Dengiz and Usul 2018; Jhariya et al. 2018; Alganci el al. 2018). AHP is designed as a system to support the optimum decision, particularly for complex circumstances with a hierarchical structure (Saaty 2008, 1990, 1980). In the AHP method, criteria are compared with others to get a final relative preference expressed as a numeric value.

The relative importance of criteria and sub-criteria were derived from an exploratory study that was distributed to experts and farmers in the study area to determine their opinions in assessing soil properties and their effect on vineyards. As well as the relative importance of bioclimatic indicators, which were derived from measuring the quantitative correlation between these indices and yields from vineyards in the period from 1984 to 2015. Using a pair-wise comparison matrix, criteria weights were calculated by comparing two criteria together, as shown in Tables 4-5. This pair-wise comparison allowed for an independent evaluation of the contribution of each criterion, thereby simplifying the decision-making associated with the cultivation of economic vineyards.

AHP calculates the weighting for each criterion (w1) and sub-criterion (w2), and then the sum of the components, as shown in equation (2):

$$\sum_{i=1}^{n} Wi = 1 \qquad \text{(Eq.2)}$$

The importance scale is suggested for these comparisons on the basis of Saaty's scaling ratios 1- 9 (Saaty, 1980).

Normally, the weights taken from a comparison matrix are consistent, and this is an important part of the method used in AHP. Therefore, one of the capacities of AHP is that it allows for inconsistent judgments and relationships while, at the same time, providing a consistency ratio CR equation (3). It provides information about the compatibility of preferences between a pair-wise comparison matrix (Saaty, 2008, 1990, 1980) as an indicator of the degree of consistency, using the following equation.

$$CR = \frac{CI}{RI} \qquad \text{(Eq.3)}$$

The Randomness Index (RI), depending on the order number of the matrix given by Saaty (1980), and the consistency index (CI), can be expressed as (4):

$$CI = \frac{(\lambda max - n)}{n-1} \qquad \text{(Eq.4)}$$

In which λmax is the largest or principal eigenvalue of the matrix, and (n) is the number of the criteria used in each processing. A consistency ratio (CR) of 0.10 or less indicates a reasonable level of consistency (Saaty 1977).

For climatic suitability: $\mathrm{CI} = \frac{(7.369-7)}{7-1} = 0.0496$

A Randomness Index RI = 1.32 was used, since there were seven criteria.

$$\mathrm{CR} = \frac{0.0496}{1.32} = 0.049 < 0.10 \ \ consistent$$

For soil suitability: $\mathrm{CI} = \frac{(6.02-6)}{6-1} = 0.004$

A Randomness Index RI = 1.24 was used, since there were six criteria.

$$\mathrm{CR} = \frac{0.004}{1.24} = 0.0032 < 0.10 \ \ consistent$$

Table 4 Normalized pair wise comparison matrix of the AHP method for climatic criteria

Table 5 Normalized pair wise comparison matrix of the AHP method for soil criteria

Table 6 Bioclimatic, topographic, and soil requirements for viticulture suitability, and class, degree of limitation, criteria weights and rating scale for each criterion

Fig 4. Methodological flowchart: assessing viticulture suitability

4. Results and Discussion

4.1. Spatial Distribution of Climate-Viticulture Indices

According to the spatial distribution as shown in Fig. 5, there is a high variability of these indices' values, due to the non-uniformity of the topography (from 696 m to 1796m) in the study area. Therefore, the diversity of these climatic regions for vineyard cultivation has led to a variety of grape cultivars and has had a direct effect on the quantity and quality of production of wine-grapes and the maturity period of grapes.

Fig. 5 Distribution of climate-viticulture indices and heat waves and cold waves for viticulture suitability

The range in the BHI values (Fig. 6a) crossed 4 different classification limits (Table 6; Fig. 5); all values were between 2 and 4. Therefore, it was revealed that around 230.6 km^2 (44.47%) are very suitable areas for vineyards (S1). In addition, the range in the average HTC values were between >0.2 and 0.87 mm/°C (Fig. 6b), but around 155.4 km^2 (29.96%) of study areas were very suitable for vineyards (S1) (Table 4; Fig. 5). However, in areas where the HTC values were below 0.5 mm/°C (70 % of study area), grape production is only possible if the air humidity and soil moisture is high or if irrigation is applied, so HTC values in the study area have the highest weight in the vineyard suitability evaluation.

Fig. 6 Maps of Climate-Viticulture Indices: (a) Branas Heliothermic Index BHI; (b) Hydrothermal coefficient HTC; (c) Winkler Index WI-GDD; (d) Huglin Index HI; (e) Cool Night Index CI

The WI-GDD values between cold region (I) and hot region (V) (Fig. 6c) crossed 5 different classification limits, as shown in Table 1; Fig. 5. Furthermore, the optimum zone S1 (1671 -1940) made up around 188.44 km^2 (20.56 %) of the study area. Moreover, no portion of the study area was found to have heat summation values outside the suitable range for high quality wine and grape production. Also, HI values - somewhat similar to WI-GDD values - (Fig. 6d) presented 4 different classification limits (Table 1), which ranged between temperate HI-1 and very warm HI+3, but the optimum zone S1 (1950-2250) as classified in Table 6 constituted around 18.28% of study area. Conversely, the HI values outside the suitable range N1, as calculated and shown in Table 6; Fig. 5, were around 32.5% in western parts of study area.

In addition, the CI values (Fig. 6e) showed 4 different regions, as classified in Table 6; Fig. 5, where around 60.22% of study area was in the moderately suitable S3 category. The CI values play an important role during maturity (September), notably in relation to secondary metabolites (polyphenols, aromas, colour and flavour of grape juice) in grapes (Tonietto and Carbonneau, 2004), but a small area was found to have the preferred temperature at this stage, as shown in regions S1 and S2, which constituted 23.04% and 16.55 % of the study area, respectively.

Fig. 7 Maps of heat wave and cold wave frequency during the vineyard growing season: (a) NDb15 number of days below 15°C during the flowering period; (b) NDh35 number of days high than 35°C during the ripening period

4.2. Spatial Distribution of Soil Indicators

Spatial analysis of soil indicators (Fig. 9) showed a wide variety in the properties of the soil in the study area, which was related to soil gneisses and soil forming factors such as topography, parent material and climatic conditions. These indicators vary greatly from the upper part to the low western slopes, and the range is especially evident in the depth, soil texture, pH, and the percentage values of calcium carbonate (CaCo3).

According to the soil indicators related to the criteria for the ecological needs of a vineyard as classified in Table 6, the results shown in Figs. 8 and 9 for the soil texture value show that clay soil is dominant, although it is not preferred. On the other hand, loamy soil, which has typical properties suitable for vineyards, was limited in area and distribution; around 48.24 % of the study area was not suitable (N1), while the S1 class covered around 1.8 % of study area.

Fig. 8 Distribution of soil indicators for viticulture suitability

The pH values of the studied soil were between 6.5 and 8 (Fig. 9c) and were divided into moderately suitable S3 (around 40 % of the study area), and S2 which makes up about 54% of study area, as shown in Fig.8. However, no portion of the study area has pH values outside the suitable range. OM values are somewhat similar to pH values; in terms of relevance and distribution (Fig.9c) around 52 % of the study area is in the moderately suitable class S3, and the rest of the area lies within S1 and S2 regions

Fig. 9 Maps of soil indicators for viticulture suitability: (a) organic matter; (b) depth; (c) soil reactions (pH) of (1:2.5); (d) electrical conductivity; (e) soil's $CaCO_3$; (f) soil texture

4.3. Spatial Analysis of Topographic Suitability:

The slope value has two critical effects: (1) a positive effect through facing solar radiation and (2) limited mechanization where it becomes very steep (Stanchi et al. 2013). In the study area, we defined the following 3 classes according to economical sustainability criteria for viticulture (Acharya and Yang 2015; Chen 2011), as presented in Table 6. The results showed

(Fig. 10) about 74.24 % of the study area was highly favourable (S1), where terracing may be limited, and mechanization is widely applicable. In contrast, the aspect values were almost equal for S1, S2 and S3 respectively (Fig.10). However, aspects values carried less weight in the suitability evaluation, compared to the weights given to the climatic and soil indicators (Wolf & Boyer 2003).

Fig. 10 Topographic suitability for viticulture in the study area

4.4 Vineyard Suitability Analysis:

In this study, suitability evaluation for vineyards (Fig. 11) revealed that around 151.55 Km^2 (28.97%) of the study area is highly favourable (S1) for vineyard growing and can be divided into 3 subclasses; A, B and C. These areas have perfect conditions in terms of climate, soil, and topography. Around 168.8 km^2 (32.22 %) of the study area were suitable (S2) but of lower value than the previous region. Besides, the moderately suitable class S3 was 122.35 km^2 (23.4%) of the study area. As for the last region (N1), it was limited in area to around 0.01 %, with the rest of study area making up around 68.53 km^2 (15.4%).

The current study provides a model proposal and novel insights for site selection for economic viticulture, built up by a GIS approach and multi-criteria evaluation MCE, considering the climatic, soil and topographic conditions; this will be helpful for farmers in developing production, upgrading production efficiency, and moving away from areas that need intensive cultivation processes. Therefore, understanding the spatial variability of these factors provides the basis for a viable characterization of each viticulture region.

5. Conclusions

The main environmental variables as shown in the previous analysis play a critical role in the suitability of land for vineyard cultivation. The elevation factor has an important role in affecting climatic and soil variables.

Overall, highly suitable areas are concentrated in the higher portion (i.e. the eastern part of the study area) where favourable climate and soil are available, and did not show any relevant limitation. Conversely, the lower portion (i.e. the western part of the study area) has unfavourable climate and soil chemical and physical fertility; therefore, grape production is only possible if irrigation is applied and associated with fertilization. In addition, farmers' positive experiences in the S1 and S2 regions in the eastern portion in the study area confirm the results of this research, showing that good wine and grape production can be achieved in such specific environmental conditions.

Fig. 11 Final maps of vineyards suitability: (a) map of climatic suitability, (b)map of soil suitability, (c) map of topographic suitability, (d) map of agriculture area and excluded urban area

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Legend of tables

Table 1 Climate-Viticulture Indices (bioclimatic), definitions and classified limits

Table 2 Estimation of the frequency of heat waves and cold waves during ripening and flowering stages, based on daily temperature data from 1984 - 2014 at Alswuydaa and Ain Al-Arab stations.

Table 3 Weighting factor classification.

Table 4 Normalized pair wise comparison matrix of the AHP method for climatic criteria

Table 5 Normalized pair wise comparison matrix of the AHP method for soil criteria

Table 6 Bioclimatic, topographic, and soil requirements for viticulture suitability, and class, degree of limitation, criteria weights and rating scale for each criterion

Table 1 Climate-Viticulture Indices (bioclimatic), definitions and classified limits.

Climate-Viticulture Indices	Definition	Class of viticultural climateand class interval	Sources
(1) Branas Heliothermic Index (BHI)	$(T_{avg}\text{-}10^{\circ}C)*\sum I_e*10^{-6}\sum$ T_{avg}: Average temperature calculated for 1 April to 30 Sept; I_e: annual effective insolation	Not suitable below 2.6	(Branas, 1974)
(2) Hydrother-mal Coefficient (HTC)	$HTC = 10P / T_0$ P: the precipitation during the growing season in mm T_0: the sum of effective degree days above 10 °C	Not suitable below 0.5 Max 1.5- 2.5 optimal value = 1	(Branas, 1946)
(3) Winkler Index (WI-GDD)	$\sum_{1\ April}^{31\ October}\left(\frac{Tmax + Tmin}{2}\right) - 10$	To cold <850 Region I cold 850 to 1390 Region II moderately cold 1391 to 1670 Region III warm 1671 to 1940 Region IV moderately warm 1941 to 2220 Region V hot 2221 to 2700 To hot >2700	(Amerine and Winkler 1944)
(4) Huglin Index (HI)	$\sum_{1\ April}^{30\ september}\left(\frac{(Tmean - 10) + (Tmax -}{2}\right.$ d: The coefficient length of day (d) by latitude for the HI index: ≤40° = 1	Very cool (HI-3) <1500 Cool (HI-2) 1500 to 1800 Temperate (HI-1) 1800 to 2100 Temperate warm (HI+1) 2100 to2400 Warm (HI+2) 2400 to 2700 Very warm (HI+3) >2700	(Huglin 1978)
(5) Cool Night Index (CI)	In the Northern Hemisphere: CI = minimum air temperature in the month of September (mean of minima), in ◦C	Very cool nights (CI+2) ≤12 Cool nights (CI+1) >12 ≤ 14 Temperate night (CI-1) >14 ≤ 18 Warm nights (CI-2) >18	(Tonietto and Carbonneau 2004)

Table 2 Estimation of the frequency of heat waves and cold waves during ripening and flowering stages, based on daily temperature data from 1984 - 2014 at Alswuydaa and Ain Al-Arab stations**.**

Equation	R Square	Parameter Estimates				Sig.
		Constant	b1	b2	b3	
Number of days below 15°C (NDb15) during flowering period*	0.799	136.106	-12.570-	0.289	0.0001	<0.001
Number of days higher than 35°C (NDh35) during the ripening period**	0.751	76.042	0.0001	-0.324-	.0080	<0.001

Table3 Weighting factor classification

Depth	Section number	Weighting Factor
125-150	6	2-1.5-1-0.75-0.5-0.25
100-125	5	1.75-1.5-1-0.5-0.25
75-100	4	1.75-1.25-0.75-0.25
50-75	3	1.5-1-0.75
25-50	2	1.25-0.75
0-25	1	1

Table 4 Normalized pair wise comparison matrix of the AHP method for climatic criteria

criteria	BHI	Wink	HI	CI	HTC	NDh35	NDb15	wi	Consistancy Measure
BHI	0.141	0.190	0.120	0.144	0.121	0.205	0.245	0.167	7.666
WI-GDD	0.035	0.048	0.080	0.029	0.061	0.103	0.031	0.055	7.100
HI	0.047	0.024	0.040	0.024	0.061	0.026	0.020	0.034	7.296
CI	0.141	0.238	0.240	0.144	0.121	0.205	0.184	0.182	7.478
HTC	0.565	0.381	0.320	0.576	0.486	0.308	0.429	0.438	7.697
NDh35	0.035	0.024	0.080	0.036	0.081	0.051	0.031	0.048	7.098
NDb15	0.035	0.095	0.120	0.048	0.069	0.103	0.061	0.076	7.247

Table 5 Normalized pair wise comparison matrix of the AHP method for soil criteria

criteria	soil texture	soil depth	EC	pH	CaCo3	OM	wi	Consistancy Measure
soil texture	0.1587	0.1595	0.1606	0.1606	0.1587	0.1565	0.1591	6.0210
soil depth	0.1397	0.1403	0.1400	0.1399	0.1398	0.1419	0.1403	6.0212
EC	0.1365	0.1375	0.1363	0.1365	0.1374	0.1358	0.1367	6.0209
pH	0.1143	0.1137	0.1132	0.1137	0.1128	0.1217	0.1149	6.0218
CaCo3	0.2444	0.2441	0.2427	0.2445	0.2453	0.2413	0.2437	6.0209
OM	0.2063	0.2049	0.2072	0.2047	0.2060	0.2028	0.2053	6.0209

Level 1 Main Criteria	Level 1 Weight (w_1)	Level 2 sub-criteria	Attribute values of criteria					Sources	Level 2 weight (w_2)	Overall weight
		Ranks(x_i)	9	7	5	1	0			(W_i = w1*w_2)
		Suitability	S1	S2	S3	N1	N2			
Climatic Suitability	0.57	BHI	2.6-3.5	(2.6-2) (3.5-4)	>4 / <2	-		(Branas 1974)	0.167	0.0952
		HTC mm/°C	0.5-1	0.5-3	0.3-0.2	<0.2		(Branas 1946) (Mesterházy et al. 2013)	0.438	0.25
		WI-GDD °C	1671 - 1940	1941 - 2220 1391 - 1670	2221 - 2700 850 - 1390	>2700 <850		(Amerineand Winkler 1944) (Jones 2015)	0.055	0.0313
		HI °C	1950-2250	2250 - 2400 1950 - 1800	2400-2700 1800-1500	>2700 <1500		(Huglin 1978) (Jones 2015)	0.034	0.02
		CI °C	<12	14≥ 12<	18≥ 14<	≥18		(ToniettoandCarbonneau 2004)	0.182	0.108
		NDb15 / day May %	0 0%	0-5 0-16%	5-10 16 -33%	>10 >33%		(Vasconcelos2009)	0.076	0.043
		NDh35/day July& August %	0 0%	0-10 0-16%	10-20 16 -33%	>20 >33%		(Blanco-ward et al. 2017)	0.048	0.027
Soil Suitability	0.34	OM %	2-3	1-2	3-5 <1	>5		(Kurtura et al. 2008; Wolf & Boyer 2003)	0.205	0.0697
		Depth / Cm	>100	>75 and < 100	>40 and < 75	< 40		(Ghosh 2005)	0.141	0.048
		pH H_2O (1:2.5)	6-6.8	6.8-7.5 5.5-6	7.5-8 5.5-5	>8 and <9 <5		(Wolf and Boyer,2003; Ghosh 2005)	0.116	0.0394
		EC dS/m	<2	>2 and <4	>4 and <8	>8		(Ghosh 2005; Cass et al. 1995; Labay 2017)	0.136	0.0462
		$CaCo_3$ %	<2	>2 and <7.5	>7.5 and <15	>15		(Ghosh 2005)	0.245	0.0833
		Soil texture	Clay loam /Sandyloam/Loam	Sandy clay loam / Silty clay loam	Loamy sand/Sandy clay Silty clay/Silt Loam	Clay/Silt/Sand		(Fraga et al. 2014; Ghosh 2005)	0.156	0.05319
		(silt +sand/clay) %	>200	150-200	150-100	<100				
Topographic Suitability	0.09	Slope %	2-15	0-2 15-30	>30	-		(Acharya and Yang 2015; Chen 2011)	0.75	0.0675
		Aspects	S/SE	SW/E	Flat/W/NE	NW/N		(Chen 2011)	0.25	0.0225
Land cover Boolean value of limited criterion	Πcj	1; Agricultural land, forests, rocky land, mixed agricultural to building, mixed agricultural to rocky land Wasteland, Grazing land					0; water bodies, streets, building	-	-	0-1

Table 6 Bioclimatic, topographic, and soil requirements for viticulture suitability, and class, degree of limitation, criteria weights and rating scale for each criterion.

Figure captions:

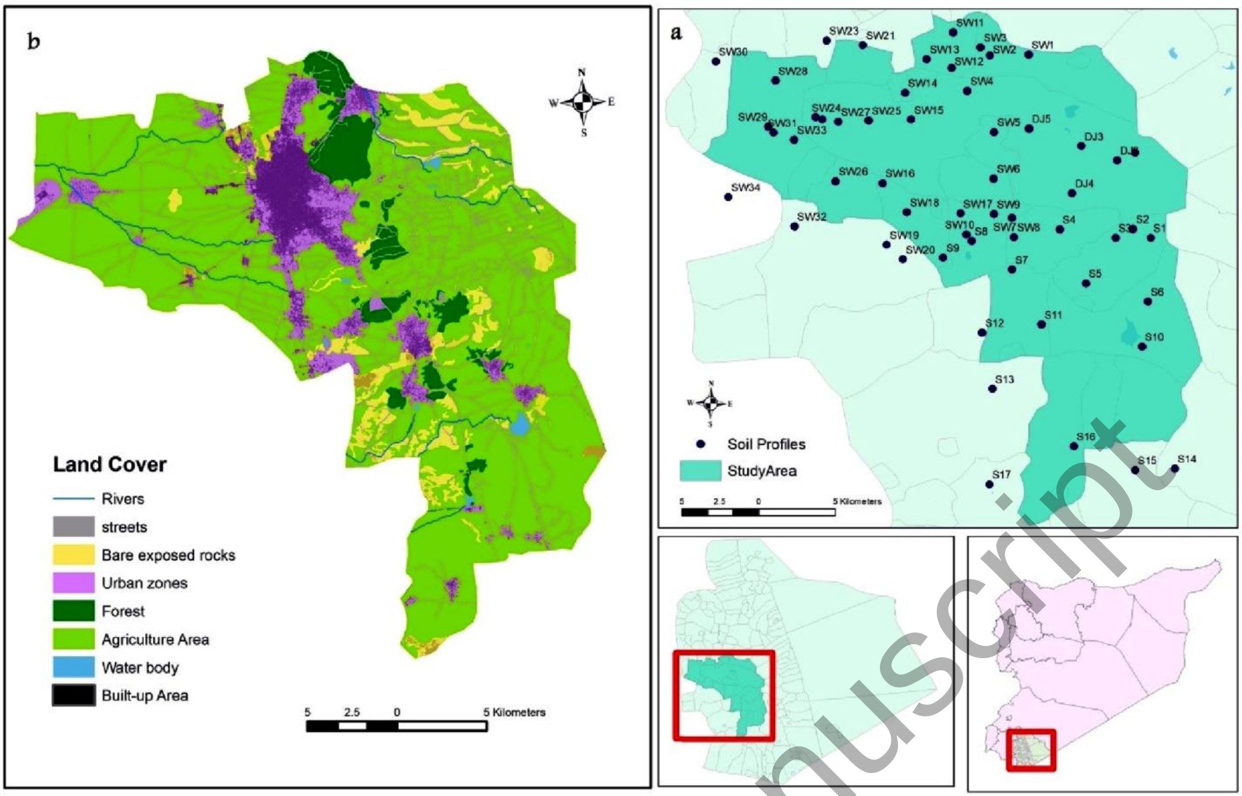


Fig. 1 (a) Location of the study area from the Al-Sweidaa governorate and sites of soil profiles, (b) Land cover map.

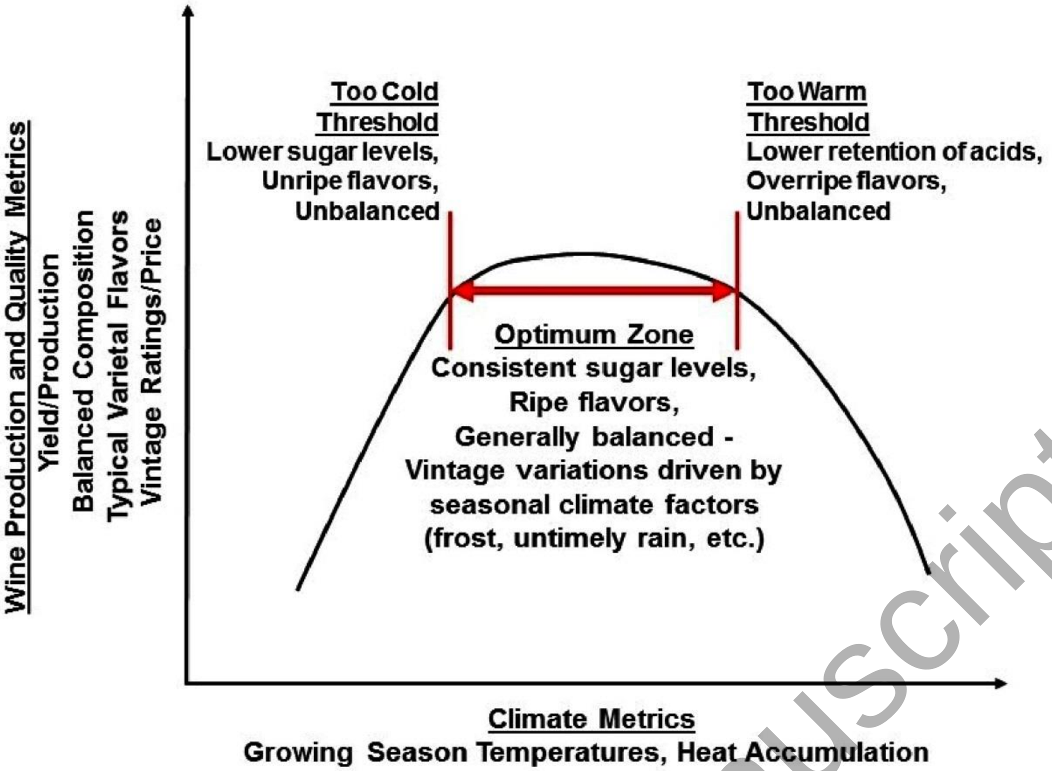


Fig. 2 Relationship and thresholds between climate and wine production and quality metrics (Jones 2015)**.**

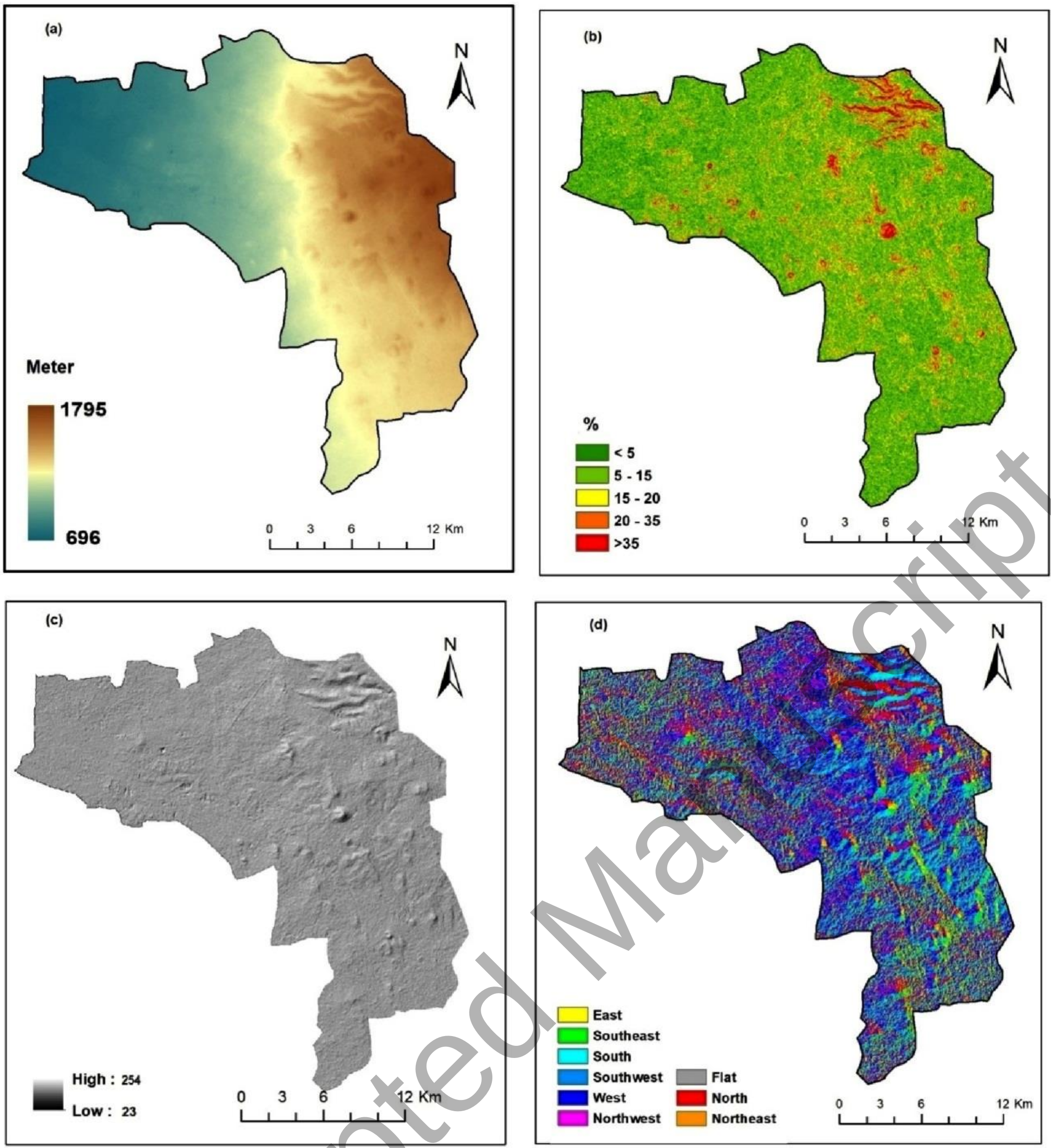


Fig. 3 Topographic characteristics (a) elevation (b) slope-percentage (C) hill-shade, (d) aspect**.**

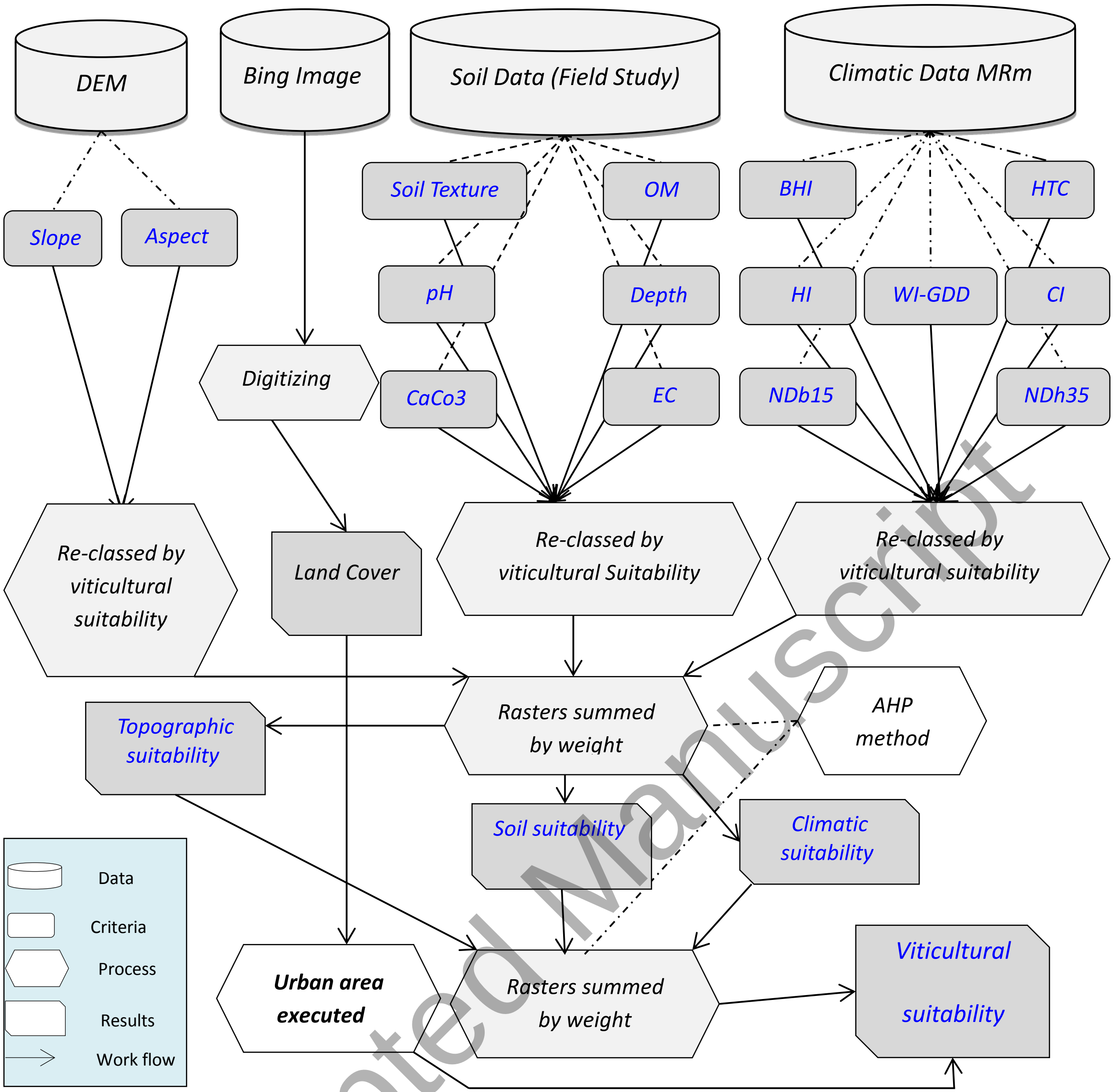
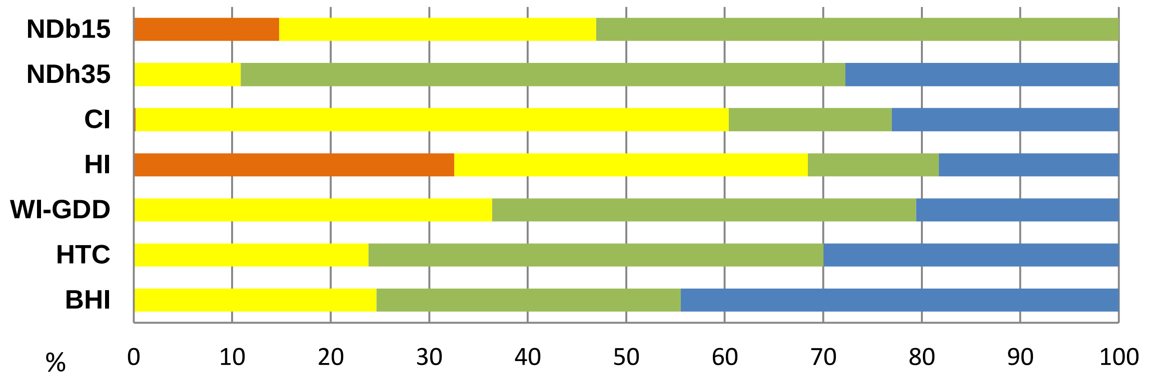


Fig 4. Methodological flowchart: assessing viticulture suitability.



	BHI	HTC	WI-GDD	HI	CI	NDh35	NDb15
N1		0.01		32.56	0.20		14.78
S3	24.65	23.82	36.39	35.89	60.22	10.88	32.19
S2	30.88	46.20	43.05	13.27	16.55	61.35	53.03
S1	44.47	29.96	20.56	18.28	23.04	27.78	

Fig. 5 Distribution of climate-viticulture indices and heat waves and cold waves for viticulture suitability.

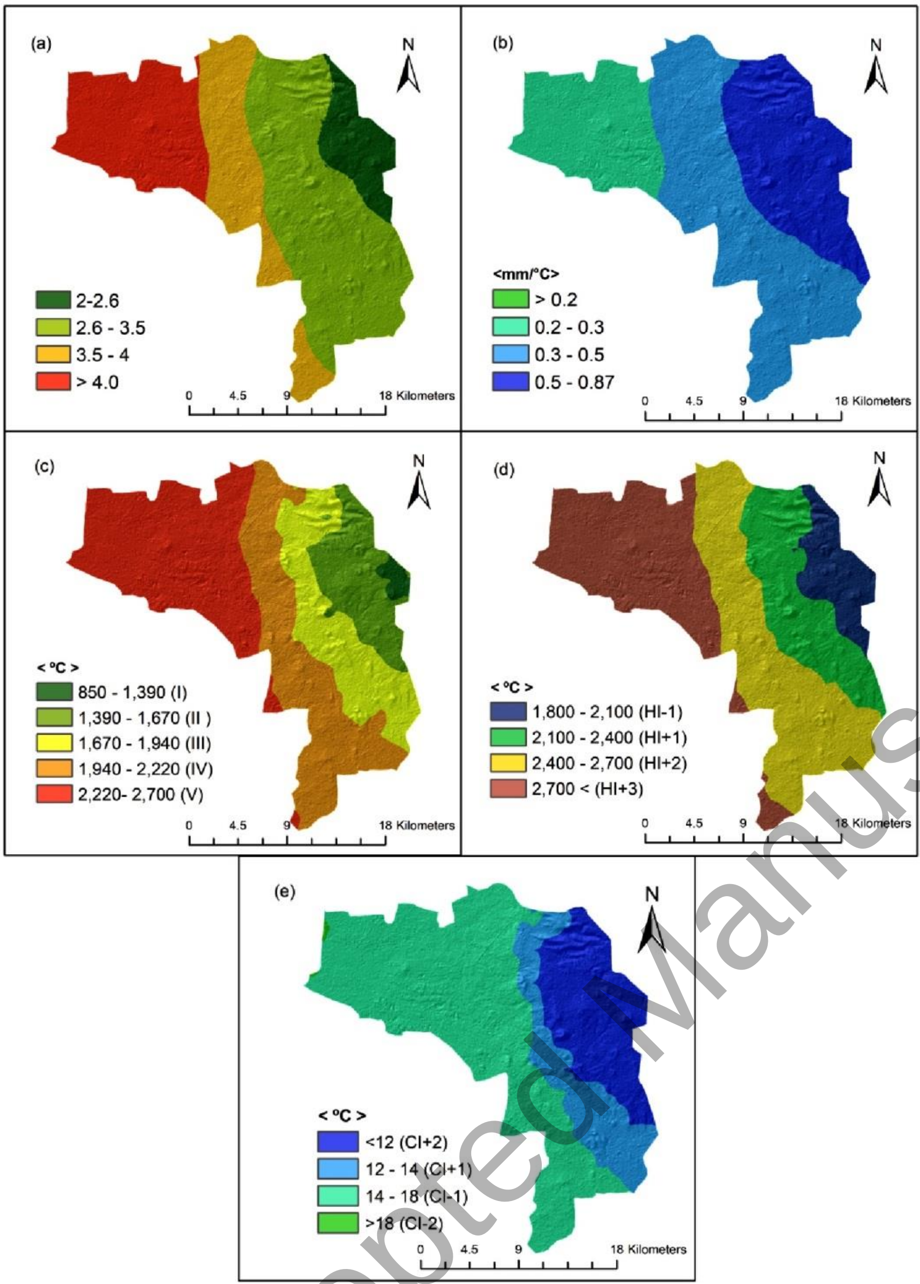


Fig. 6 Maps of Climate-Viticulture Indices: (a) Branas Heliothermic Index BHI; (b)Hydrothermal coefficient HTC; (c) Winkler Index WI-GDD; (d) Huglin Index HI; (e) Cool Night Index CI.

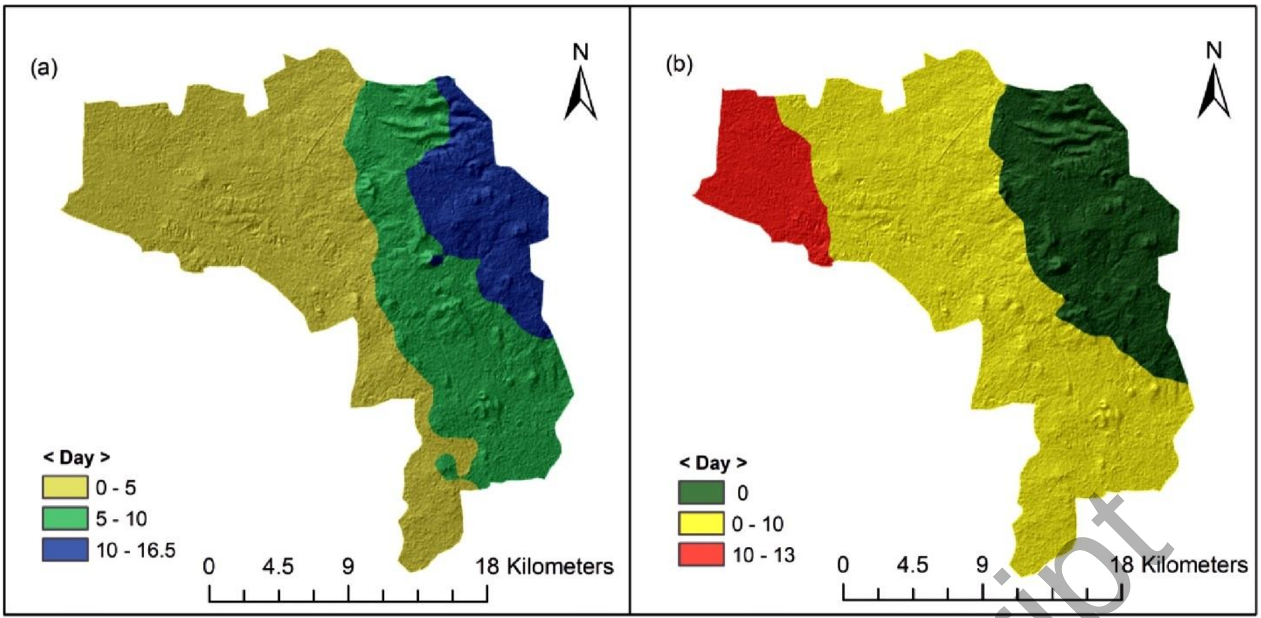
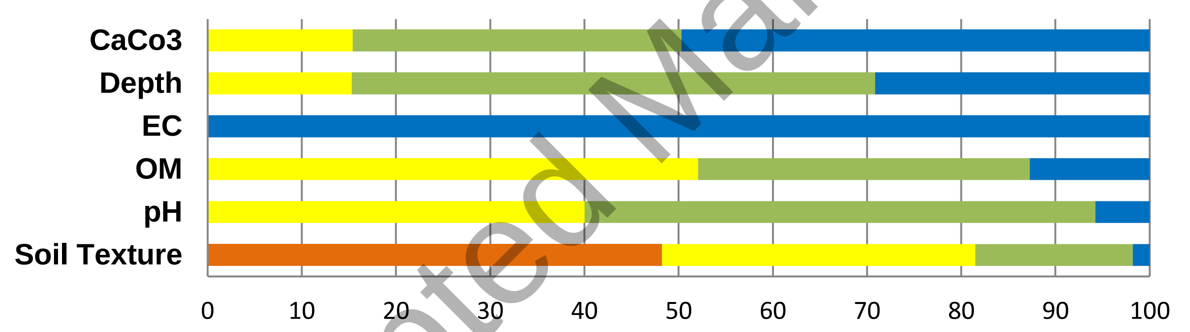


Fig. 7 Maps of heat wave and cold wave frequency during the vineyard growing season: (a) NDb15 number of days below 15°C during the flowering period; (b) NDh35 number of days high than 35°C during the ripening period.



%	Soil Texture	pH	OM	EC	Depth	CaCo3
N1	48.24					
S3	33.23	40.05	52.05		15.29	15.41
S2	16.72	54.18	35.22		55.55	34.87
S1	1.80	5.77	12.73	100.00	29.16	49.71

Fig. 8 Distribution of soil indicators for viticulture suitability.

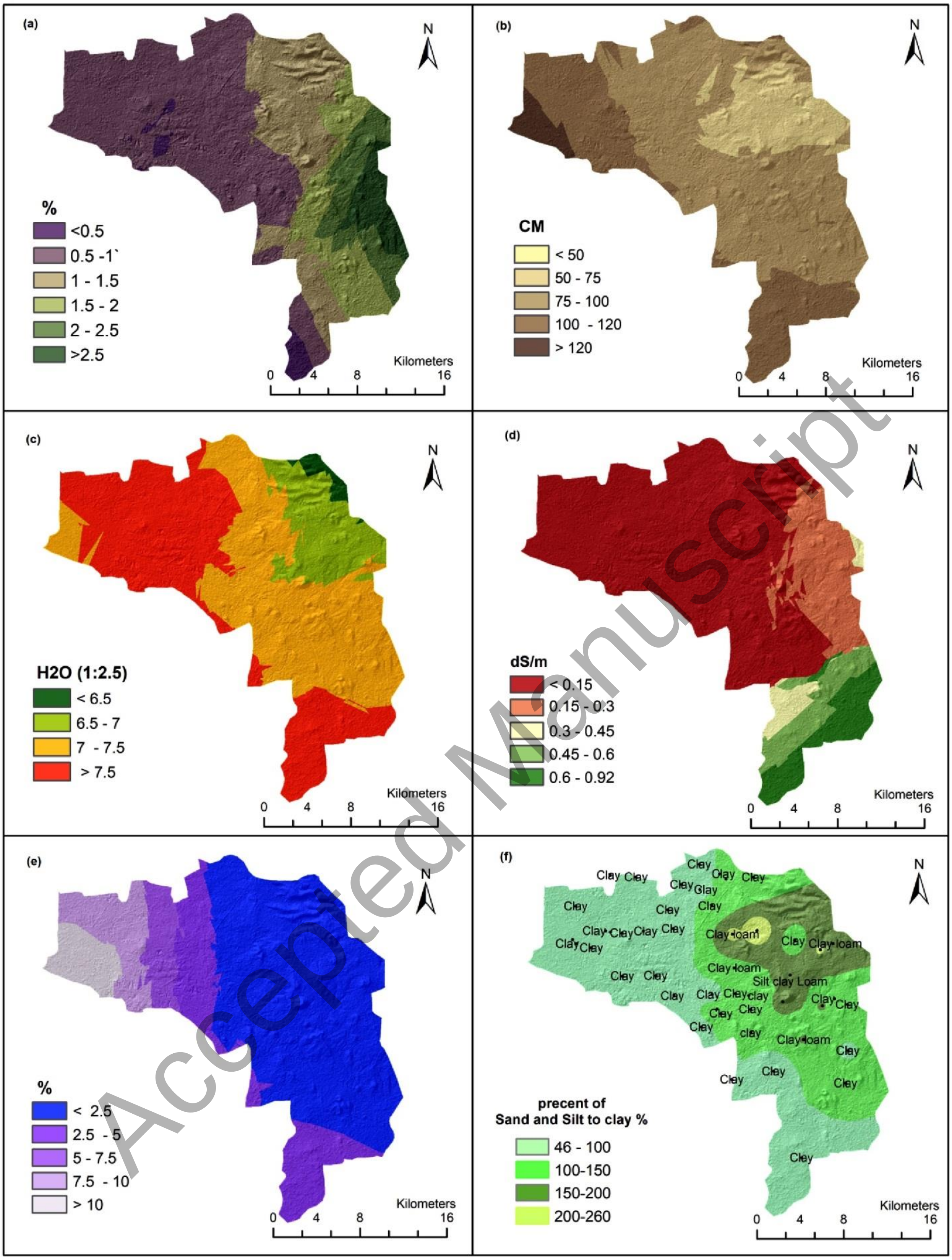
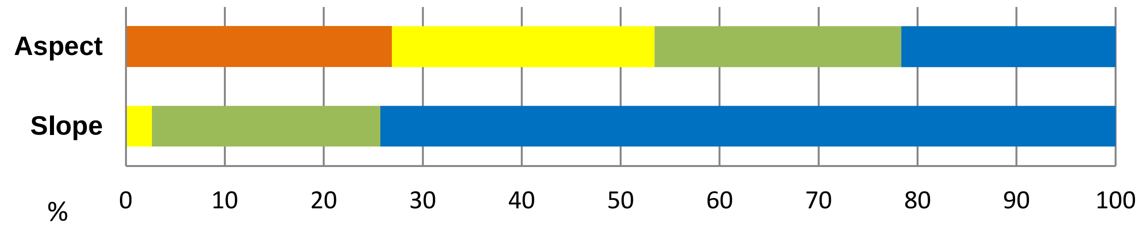


Fig. 9 Maps of soil indicators for viticulture suitability: (a) organic matter; (b) depth; (c) soil reactions (pH) of (1:2.5); (d) electrical conductivity; (e) soil's CaCO3; (f) soil texture.



	Slope	Aspect
N1		26.87
S3	2.64	26.56
S2	23.08	24.94
S1	74.28	21.64

Fig. 10 Topographic suitability for viticulture in the study area.

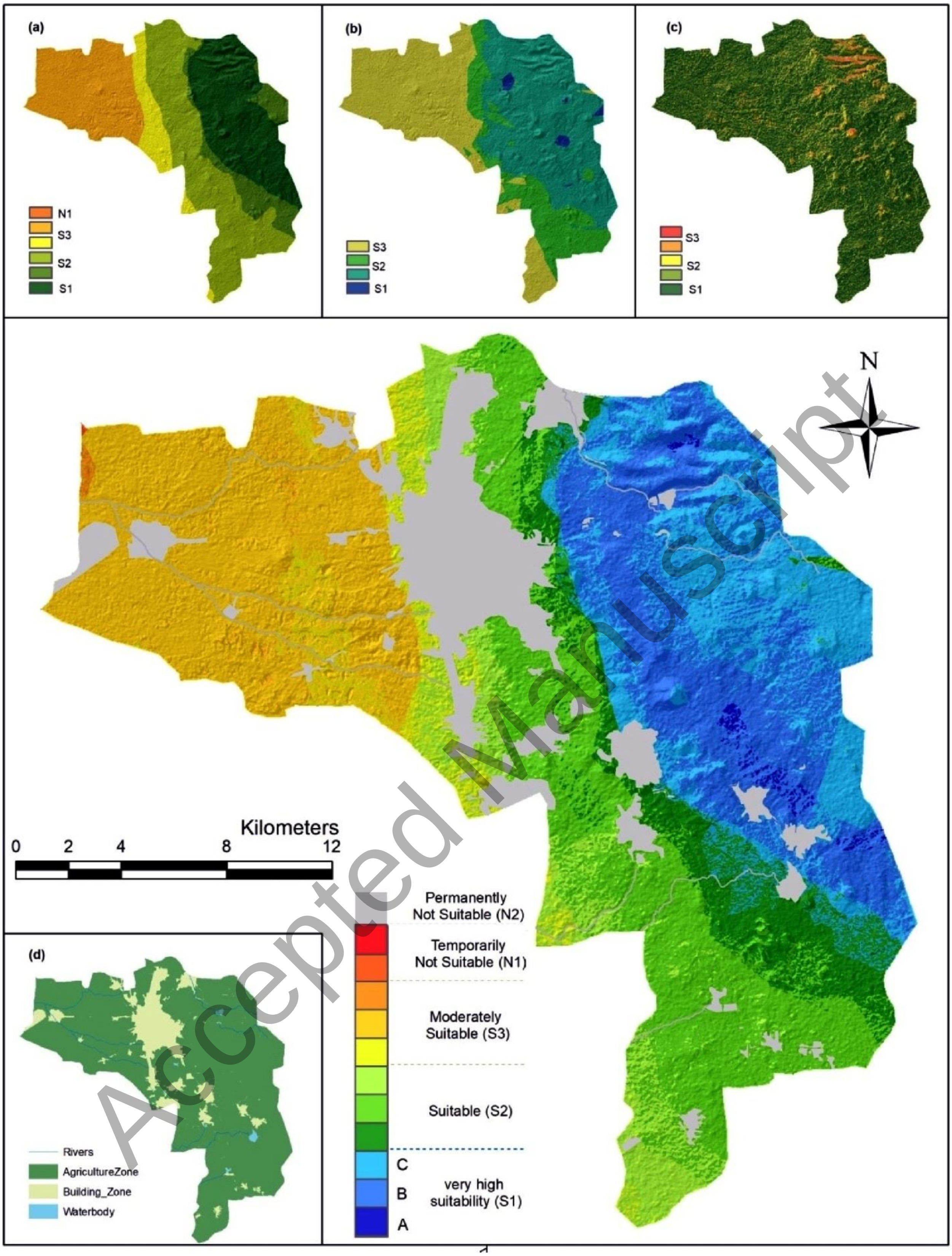


Fig. 11 Final maps of vineyards suitability: (a) map of climatic suitability, (b)map of soil suitability, (c) map of topographic suitability, (d) map of agriculture area and excluded urban area