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The application of advanced technologies in the research of *terroir* factors in viticulture and oenology

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Abstract

Faced with a very picky market and strong competition from high-qulity imported wines, it is necessary to shed light on the *terroir* characteristics of local wine-growing areas and the typicality of local wines, as this represents an opportunity to enhance the wine sector through geographical indications and the protection of small appellations. A necessary step in this complex process is the application of advanced technologies, i.e. new techniques and different modelling methods, accompanied by a spatial analysis of different parameters through the geographic information system (GIS).

This paper presents several examples of application of advanced technologies and development of innovative modelling methods in viticulture and winemaking in the Oplenac wine-growing district (Serbia), all of which have the potential for wider application and adaptation of developed methods to conditions in other wine-growing areas of the region. With the aim of studying the *terroir* factors, this paper presents modelling performed by applying the Analytical Hierarchy Process (AHP) method, which was used for modelling and classification of the studied abiotic *terroir* factors in hierarchical levels. The modelling and classification of the abiotic *terroir* factors in hierarchical levels was performed using the Geographical Detector Method (GDM). Modelling with TOPSIS method was used in this work to present an example of modelling and ranking of analysed anthropogenic *terroir* factors. The application of the GIS technology was used in this paper to present examples of mapping favorability classes of abiotic and anthropogenic *terroir* factors and small appellations in particular absolute, elite, historic and organic vineyards, i.e. viticultural parcels. The Random Forest Clustering (RFC) method was used to present examples of wine quality and typicality prediction. Through this modelling, a link is established between the *terroir* factors studied and wine quality and typicity, which forms the basis for the protection of geographical indications in the EU PDO/PGI system. Finally, a comprehensive classification of viticultural micro-areas was made based on all the viticultural-oenological models developed.

Key words: abiotic and anthropogenic *terroir* factors, modelling, multicriteria analysis, GIS

Introduction

Research on *terroir* factors occupies a central place in the European Union (EU) PDO/PGI system, as legislation requires evidence of a significant or decisive effect of specific natural and anthropogenic factors existing in the wine-growing area in question on the quality and characteristics of wine from that area (for PDOs). Determining causal relationships between the characteristics of a wine-growing area and the quality and characteristics of the wine, especially in the case of PDO designations, requires detailed research and extensive knowledge of the *terroir* of the area in question (Ninkov *et al*., 2019), which requires extensive scientific research and expert analysis. Exploring the multifactoriality of *terroir* requires significant effort, data, and scientific knowledge. However, certain advanced technologies are currently being used for these purposes, some of which have been identified in the OIV Zoning Resolution (Resolution OIV-VITI 423-2012) and the Precision Viticulture Resolution (Resolution OIV-VITI 593-2019).

Numerous *terroir* research activities in the Western Balkans region were carried out in Serbia, where, in addition to zoning of wine-growing areas, small appellations have been introduced, which are actually traditional terms for wines with geographical indications: absolute, elite and historic viticulture parcels, as well as organic viticulture parcels (organic wine-growing locations and micro-areas). For the use of the names of the small appellations on the labels, i.e. for the use of the corresponding traditional terms, it is necessary that the micro-area in question has extremely favourable or ideal soil, climatic, topographic and other necessary conditions for the successful cultivation of vines and the production of quality wines with the geographical indications, which is confirmed by the results obtained through the application of advanced technologies and corresponding innovative models.

For the research of *terroir* factors and their modelling, in addition to the application of the geographic information system (GIS), remote sensing, GPS devices and different software solutions, different models were used in this paper for the multicriteria analysis. One of the most important of the models used is the Analytical Hierarchy Process (AHP) method. This is a multi-attribute decision making (MADM) method that provides a powerful logical approach to solving complex multi-criteria decision types, breaking down the complex problem to obtain a hierarchical structure that shows the relationships among the objective, criteria, sub-criteria, and alternatives (Saaty, 1980; 2012). The Geographical Detector Method (MGD) applied in this paper relied on the use of the Geodetector programme, a software for measuring and assigning stratified (layered) heterogeneity. Stratified heterogeneity refers to phenomena that show more similarity within strata than between strata (http://www.geodetector.cn/). An important model for multicriteria analysis is the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. It is a ranking method proposed by Hwang and Yoon (1981) for solving multicriteria decision problems (Srđević, 2002). Random Forest Clustering (RFC) method is a machine learning method that uses a large number of nonlinear algorithms and a statistical learning method designed for classification, regression, and other tasks solved by constructing multiple decision trees and finding a class (classification) or a median/average prediction (regression) of the individual trees (Ho, 1995; 1998).

By applying these methods, i.e., machine learning with spatial analysis, many complex questions related to the study of *terroir* factors in viticulture and oenology can be answered.

Material and Methods

The realisation of the innovative modelling in this paper was carried out through research activities aimed at the multifactorial *terroir* potential, i.e. through: terrain research with application of the GIS technology and GPS devices; laboratory analysis of soil and wine; preparation and statistical and geostatistical data processing; modelling and mapping with application of appropriate methods, GIS, software and extensions; as well as through validation of the obtained results and the obtained innovative models. Examples of viticultural-oenological modelling are presented for the area of the Oplenac wine-growing district

(Sumadija wine-growing region).

Research of location, i.e. spatial data of 836 commercial vineyards in the area of Oplenac wine-growing district was carried out by two different applications of GIS technology: application of only geospatial technology and relevant spatial maps and application of GPS devices and geospatial technology. Spatial exploration of vineyards was carried out according to the instructions of the Joint Research Centre of the European Commission for surveying vineyard parcels in the system for their control (Kerdiles *et al.*, 2008).

For the spatial exploration of existing and former vineyards, as well as for the general exploration of the wine-growing area, the methods and procedures of GIS were used in accordance with the principles for the use of GIS established in the OIV Resolution OIV-VITI 423-2012. For determination of spatial data, that is, parcels on which vineyards used to be for the purpose of modelling of potential historic viticultural parcels, archival maps from the Product Specification for the Protection of the Geographical Indication of the wine "Venčački Rizling" (Product specification No. 320-202/82-04 from 8. June 1982), and the documentation on vineyards from the Foundation of King Peter I Karadjordjevic in Oplenac were used. Spatial analysis was carried out for 667 micro-areas in which vineyards used to be in the territory of the current Oplenac wine-growing district.

Research of climate factors was carried out for the period 1988-2017, and the data from synoptic and climatological stations were interpolated by applying the successive correlation method (Cressman, 1959) on a regular grid with a horizontal resolution of 1 km, with the aim of spatial representation of climate characteristics. The modelled and spatially represented climate data were researched in accordance with the principles of OIV zonal resolution: Resol. OIV-VITI 423-2012. For modelling soil *terroir* factors, we processed soil data from previous research conducted by the Institute of Soil Science in Belgrade (Mrvić *et al.*, 2013) and obtained an estimate of soil loss (t ha^{-1} god^{-1}) by applying the USLE model (Wischmeier and Smith, 1978). To verify and confirm the data on modelled basic soil *terroir* factors from previous studies, we conducted additional soil analyses at four representative localities.

Laboratory analysis of wine quality and typicity parameters from representative vintages was conducted for wine made from *Chardonnay* and *Cabernet Sauvignon* grapes. A total of 25 quality and typicity parameters were analyzed using the WineScanTM Flex interferometer (merging of multiple light sources), which is based on Fourier transform infrared spectroscopy/infrared spectroscopy with Fourier transform (FTIR) technology (OIV/OENO 390/2010).

The application of the AHP and MGD methods, as well as the GIS technology, were used for the research, modelling and classification of the abiotic *terroir* factors, which in turn were used for the determination and classification of locations and micro-areas in relation to the favorability of the abiotic *terroir* factors.

The TOPSIS method and GIS technology were used to research, modelling, and ranking of anthropogenic *terroir* factors, which were used to determine and classify the vineyards in terms of the favorability of the anthropogenic *terroir* factors.

Further use of the GIS technology was aimed at modelling and determining small appellations, in particular: potential absolute, elite, and historic vineyard parcels, as well as potential organic wine-growing locations and micro-areas in the I (first) and II (second, more rigorous) levels of modelling.

The predictions on the quality and typicality of the wine, i.e. confirmation of data on the most important selected *terroir* factors and their impact on the quality and typicality of the wine, especially the wine with geographical indications, were made by applying the RFC method.

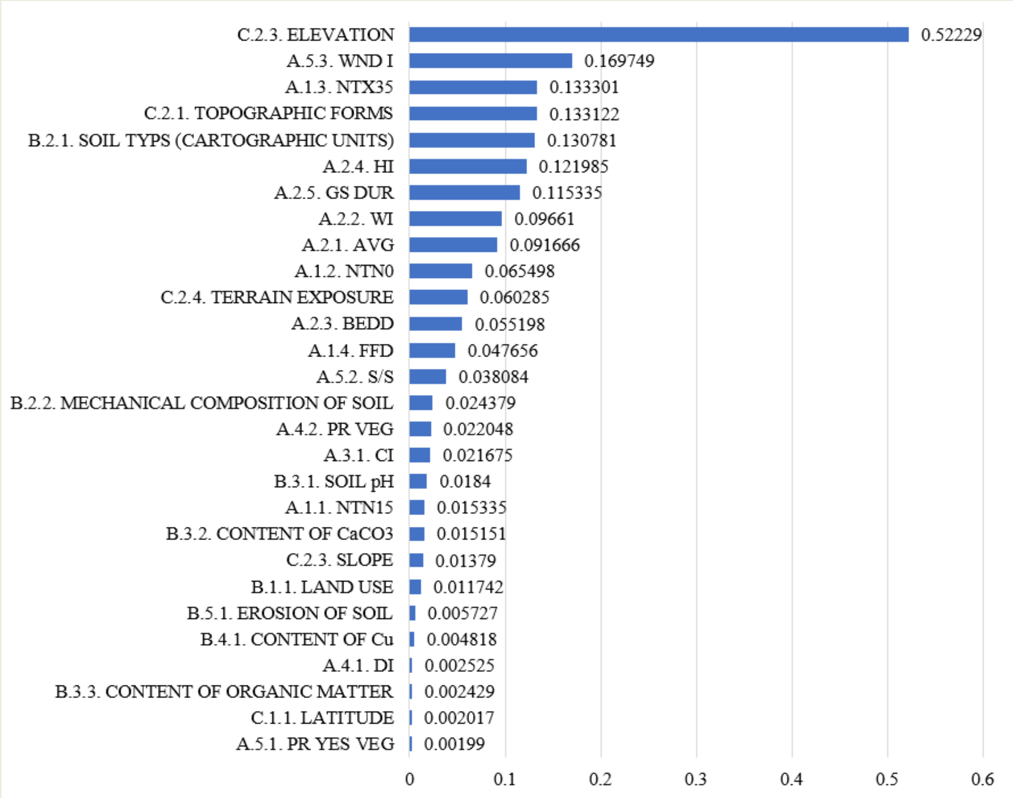
After the completion of the research and modelling results, and after the model validation, we developed an innovative scheme for a comprehensive characterization and classification of vineyards.

Results and Discussion

Modelling abiotic *terroir* factors

Modelling was performed by integrated application of the AHP method and GIS technology with three hierarchical criteria (general climate, soil and topographic *terroir* factors), 12 sub-criteria (*terroir* sub-factors) and 28 alternatives (basic *terroir* elements). At the first level of the hierarchy, the topographic *terroir* factor was selected as the most important criterion (general *terroir* factor). The next most important criteria, i.e., general *terroir* factors, were the soil and climate *terroir* factors. The consistency ratio determined in each case (CR) showed that there was a high consistency in the evaluation by the decision makers, and all importance ratings and rankings were confirmed as appropriate and valid.

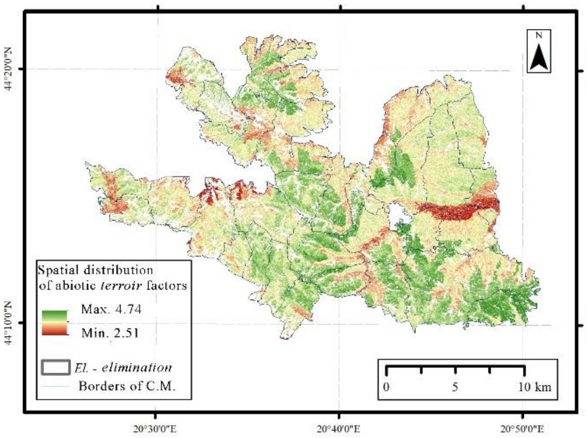
By applying the MGD method and determining the q value, the resulting factor detector showed that the highest q value is with the basic *terroir* element of altitude, and it can be concluded that this basic element has the highest importance among the studied abiotic *terroir* factors in terms of modelling the abiotic *terroir* factors (Graph 1).



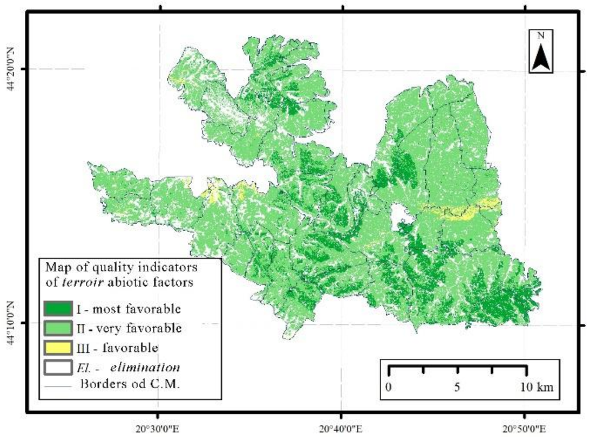
Graph 1 - Results of the factor detector for abiotic *terroir* basic elements

The risk detector of the MGD method was used to determine the average frequency of the basic *terroir* elements. The results of the risk detector show that in class I (most favourable), elevation as a basic *terroir* element has by far the highest frequency. On the positive side, of the 25 basic abiotic *terroir* elements, 15 elements in class V (least favourable) of the abiotic *terroir* factor quality indicators have no frequency at all (Table 1 in the Appendix).

By summing the reclassified favorability maps with the GIS technology, i.e. by summing the grid layers for all modelled basic *terroir* elements and for all modelled *terroir* subfactors and finally for the general *terroir* factors into a final sum map and by classifying them into equidistant classes of I (most favourable area), II, III, IV and V (unfavorable area) we obtained the final map of quality indicators for modelled abiotic *terroir* factors. The Oplenac wine-growing district has favourable abiotic *terroir* factors, and the obtained values of quality indicators for abiotic *terroir* factors ranged from minimum 2.51 (favourable class) to maximum 4.73 (most favourable class) (Map 1). The most favourable class (Class I) accounts for 14.16% of the area of the Oplenac wine-growing distict (Map 2).



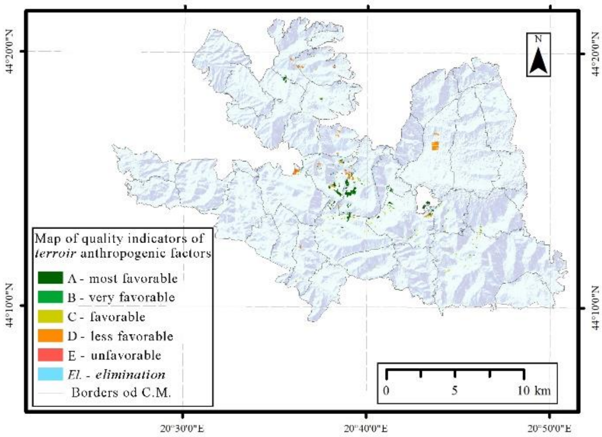
Map 1 - Spatial distribution of abiotic *terroir* factors



Map 2 - Map of quality indicators of abiotic *terroir* factors

Modelling of anthropogenic *terroir* factors

Based on research and modelling of anthropogenic *terroir* factors through application of the TOPSIS method, it was determined that the most significant anthropogenic factor is the alternative (anthropogenic *terroir* factor) vine variety. By connecting vectoral data from vineyards with class ranges of quality indicators of anthropogenic factors, we drafted the final map of anthropogenic *terroir* factors quality indicators, with favorability classes A (most favorable), B, C, D, and E (unfavorable). It was determined that, on the level of the entire wine-growing area, the share of the most favorable A class is 29.43% of the entire surface (111.20 ha) (Map 3).



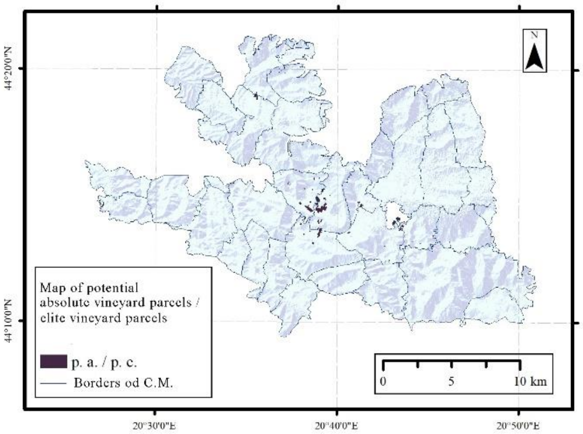
Map 3 – Map of anthropogenic *terroir* factors quality indicators

Modelling of small appellations

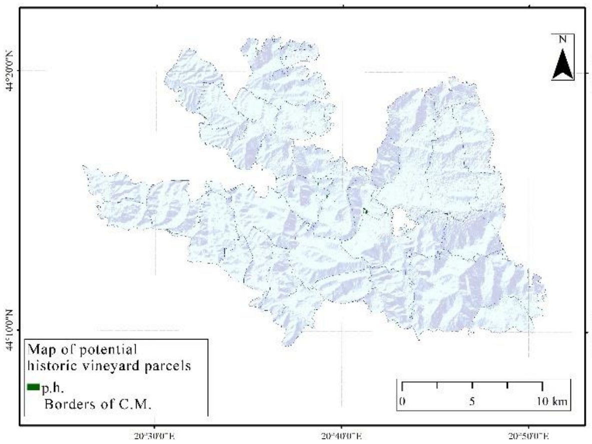
Modelling of absolute and elite vineyard parcels

By applying the GIS technology and selecting vineyards classified in class I (most favourable) of the modelled abiotic *terroir* factors and in class A (most favourable) of the modelled anthropogenic *terroir* factors, we created a map of potentially absolute vineyard parcels (p. a.), i.e., potentially elite vineyard parcels (p. e.). Of the total vineyards area of 282.03 ha, 91.18 ha are classified as potentially absolute (p. a.) and potentially elite (p. e.) vineyard parcels (Map 4).

By applying the GIS technology, i.e., by overlaying selected areas representing vineyards that meet the criteria for classification as p. a. or p. e., i.e., vineyards that meet the criteria for the traditional term for elite vineyard parcels and other legal conditions, and areas representing parcels that demonstrably had vineyards dedicated to the production of high quality grapes and wines, we created a map of potential historic vineyard parcels (p. i.). Of the total area of vineyards surveyed, 282.03 ha, 7.77 ha met the conditions for classification as p. i. (Map 5).



Map 4 - Map of potential absolute vineyard parcels / potential elite vineyard parcels



Map 5 - Map of potential historic vineyard parcels

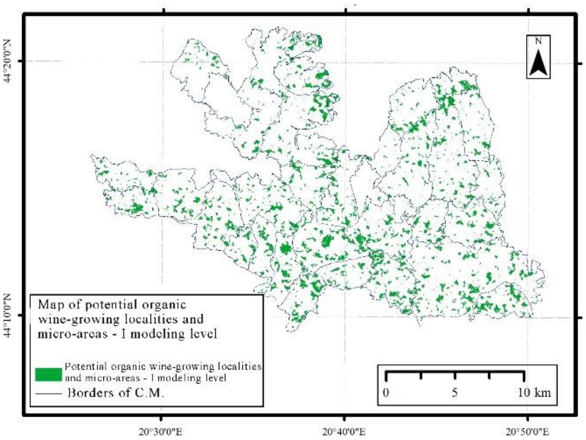
Modelling of potential organic wine-growing locations and micro-areas

I Modelling level

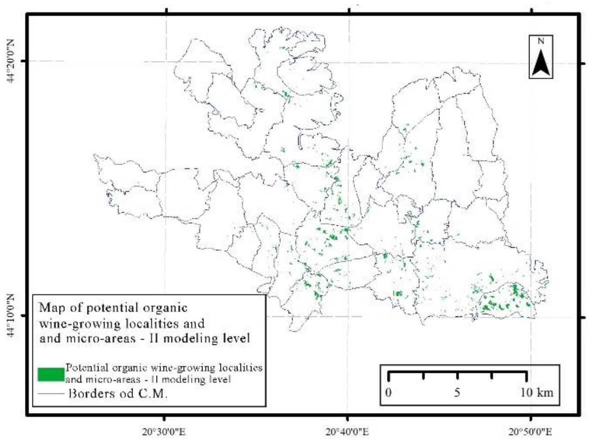
By creating buffer zones (using GIS technology) around the units at risk for organic cultivation, at a depth of 100 m around the potential pollutants, and by eliminating unfavourable soils that cannot be used for viticulture at the level of abiotic *terroir* factors, quality indicators I (most favourable) and II (very favourable), we selected potential organic wine-growing localities and micro-areas of the I modelling level (p. o. I) which totaled 3,658.16 ha (Map 6).

II Modelling level

At the II modelling level for determining the organic wine-growing locations and micro-areas, the same GIS operations were performed as at the previous modelling level, but in this case only operations in class I (most favourable) of the quality indicators for abiotic *terroir* factors were performed. From the total area of all vineyards, potential organic vineyard locations and micro-areas according to the II modelling level (p. o. II), 481.98 ha were selected (Map 7).



Map 6 - Map of potential organic wine-growing locations and micro-areas according to the I modelling level



Map 7 - Map of potential organic wine-growing locations and micro-areas according to the II modelling level

Model for prediction of quality and typicality of wine

By applying the RFC method, we selected two clusters representing common characteristics of the analysed quality and typicality parameters of wine of grapes of *Chardonnay* and *Cabernet Sauvignon* vine varieties. The obtained data, i.e. AIC, BIC and *silhouette* values, confirm the reliability of the model. The clustering of quality and typicity wine parameters confirmed the assumption that the studied quality and typicity wine parameters are grouped with respect to the predominant association of abiotic (cluster 1) versus anthropogenic *terroir* factors (cluster 2). In addition, application of the RFC method was used to determine the importance and ranking of examined quality and typicality wine parameters through use of the *Gini* index, wherein the dominant parameters that characterize the quality and typicality of wine were selected and correlated with the most important *terroir* factors determined through modelling of abiotic and anthropogenic *terroir* factors.

System (model) for comprehensive characterization and classification of vineyards

Based on the above modelling, a system (model) for comprehensive characterization and classification of vineyards was developed, in which vineyards are characterised based on two class groups for two basic models (modelling abiotic and anthropogenic *terroir* factors) and based on six class groups and marks within five thematic models (modelling small appellations and geographical indications for wine).

Conclusion

In order to evaluate the *terroir* factors with using the advanced technology, innovative multifactorial spatial models have been developed based on scientific expert research that allow to determine the contribution of the studied *terroir* factors to the successful cultivation of the vine and to the production of high quality wines typical of the studied wine-growing area, especially wines with geographical indications. Since the models developed are comprehensive and involve a multidisciplinary approach, we have developed two basic (for modelling and classifying abiotic and anthropogenic *terroir* factors) and three thematic models (for modelling small appellations), as well as a model for predicting the quality and typicality of wines that validates previous models and results obtained. The paper presents the spatial data of the final maps using the example of the Oplenac wine-growing district for the developed models supported by spatial research, where the localities, micro-areas and vineyards are presented in relevant favorability classes, i.e. in relation to relevant marks. Finally, we developed an innovative system for comprehensive characterization and classification of vineyards, based on classification of vineyards and their designation per eight different classifications for each of the developed viticultural-oenological models.

The obtained modelling data showed that there is high consistency with valuation by decision-makers, thus, all valuations of significance, i.e., rankings in models were confirmed as appropriate and valid. Therefore, the developed modelling ensures multifactorial and spatial procedures and methodologies for proving the connection between examined *terroir* factors and the quality and typicality of wines in accordance with the EU PDO/PGI system, and for potential protection of small appellations.

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Other sources

http://www.geodetector.cn/ - Geodetector

Appendix

Table 1 – Results of risk detector for abiotic basic *terroir* elements

Basic *terroir* elements	Favorability class				
	V	IV	III	II	I
A. 1. 1. NTN15			3.716552	3.65564	3.735621
A. 1. 2. NTN0	3.234000	3.652477	3.700285	3.793158	3.649085
A. 1. 3. NTX35	3.539651	3.766637	3.807786	3.607576	3.010778
A. 1. 4. FFD	3.483707	3.666108	3.697433	3.786948	3.717534
A. 2. 1. AVG		3.461709	3.750025	3.742464	3.47903
A. 2. 2. WI	3.051559	3.52062	3.770632	3.73291	3.484431
A. 2. 3. BEDD		3.454441	3.767311	3.687429	
A. 2. 4. HI	3.435747	3.652964	3.79528	3.759373	3.53842
A. 2. 5. GS DUR	3.459234	3.693722	3.773277	3.764157	3.483371
A. 3. 1. CI	3.225870	3.600385	3.731481	3.698123	3.69563
A. 4. 1. DI			3.719066	3.68573	
A. 4. 2. PR VEG		3.596517	3.590888	3.746721	3.719862
A. 5. 1. PR YES VEG			3.684472	3.715903	3.717127
A. 5. 2. O/Z		3.611316	3.577685	3.671491	3.78694
A. 5. 3. WND I	3.424475	3.633209	3.79132	3.833117	3.586522
B. 1. 1. Manner of soil use		3.685494	3.70121	3.790294	3.806086
B. 2. 1. Types of soil – cartographic units	3.489231	3.585675	3.737055	3.75909	3.810533
B. 2. 2. Mechanical soil composition		3.816748	3.709151	3.759384	3.626496
B. 3. 1. pH soil reaction			3.573458	3.677953	3.745755
B. 3. 2. $CaCO_3$ content		4.003857	3.700026	3.872904	3.778557
B. 3. 3. Organic matter content		3.70498	3.783877	3.689507	3.71927
B. 4. 1. Total copper content (Cu_T)			3.836583	3.741721	3.703161
B. 5. 1. Soil loss through water erosion		3.215821	3.480654	3.701701	3.712547
C. 1. 1. Geographic latitude				3.419524	3.709702
C. 2. 1. Topographic forms	3.585836	3.547378	3.679662	3.891818	3.807718
C. 2. 2. Elevation	3.056989	2.840018	3.554886	3.592399	3.936552
C. 2. 3. Terrain slope	3.700496	3.758795	3.719083	3.674789	3.639924
C. 2. 4. Terrain exposure	3.555627	3.668595	3.718752	3.751237	3.832794