INTRODUCING HETEROGENEITY MEASUREMENTS IN TERROIR STUDIES. APPLICATION IN THE REGIÃO DEMARCADA DO DOURO (N PORTUGAL)

Joaquín CÁMARA[1,*], Alberto LÁZARO[1], Vicente GÓMEZ-MIGUEL[1]

[1]*Departamento de Producción Agraria, Universidad Politécnica de Madrid, 28040 Madrid, Avda. Puerta de Hierro, 2, Spain*
**Corresponding author: Cámara. E-mail: joaquincamaragajate@yahoo.es*

Abstract
Terroir zoning studies have to manage the heterogeneity and complexity of the landscape properties and processes. The varying geology is one of the main landscape properties conditioning the spatial variability of terroirs. An entropy-based index used to characterize the heterogeneity of soil particle size distribution has been recently recognized to be controlled by the lithological properties at landscape scale. This index, known as the Balanced Entropy Index (BEI), which has been identified as a very good predictor of soil water content, is a promising tool in geosciences because it provides a continuous parameterization of soil texture that enables establishing quantitative relationships between soil texture and all the hydropedological attributes related to it. In this study, carried out in the Portuguese winegrowing region called Região Demarcada do Douro (RD Douro), we explored the BEI in the lithostratigraphic units, and its potential relationship with the vineyard distribution and characteristics at plot scale. The data set for this work was the soil map of RD Douro scale 1/25 000, the vineyard distribution, and the information of the soil map database, which includes analytical and morphological data of 1 217 soil profiles. Results evidenced that, in areas with similar lithological properties, vineyard plant density is linearly related with the soil texture heterogeneity, being this relationship stronger in metamorphic lithologies than in granitic lithologies. In light of this and other remarkable results we concluded that the BEI is a useful new tool that might have multiple applications in terroir studies.

Keywords: soil texture heterogeneity, Balanced Entropy Index, plant density, fractals, RD Douro

1 INTRODUCTION

Terroir concept refers to an area in which collective knowledge of the interaction between the identifiable physical and biological environment and applied vitivinicultural practices develops, providing distinctive characteristics for the products originating from this area. Terroir zoning studies try to define the landscape complexity and to delimitate those physical and biological features such as soil, topography, climate and geology. Besides their scale dependence, one of the main problems when studying these features is that all of them are interconnected, and in most of the cases these relationships remain unquantified. In this context the quantification of traditional qualitative features, as soil texture, can facilitate the establishment of functional relationships between physical and biological features at different scales.
Fractal parameters are useful descriptors of natural systems that consider the scaling behavior of the system, and they are capable of quantifying complex structures, which are hard to be measured with traditional geometry (Mandelbrot, 1983).
Natural systems are self-organized systems, and according to the Prigogine theory on dissipative structures the organization level of these systems, which is tied with the concept of heterogeneity or entropic level, should be measured using the Shannon's entropy (Nicolis and Prigogine, 1977), which is an information-theoretical parameter that may be interpreted as a measure of the complexity of a distribution (Shannon, 1948a,b).
In 2005, an index based on Shannon's entropy was proposed to measure the heterogeneity of the soil particle size distribution. This index, the Balanced Entropy Index (BEI), was introduced in Martín et al. (2005a) and it is given by the simple formula

$$BEI = \frac{\sum_i P_i \log P_i}{\sum_i P_i \log l_i},$$

where the numbers l_i are the scale lengths of the three basic size intervals (l_1 = 0.001, l_2 = 0.024 and l_3 = 0.975) and P_i's are the soil's clay-silt-sand fractions. The formula above provides a continuous parameterization of the soil texture, it can be easily computed from conventional textural data and represents an efficient and straightforward way of evaluating particle size distribution heterogeneity from textural data. In the last years, some works have investigated this index with promising results, concluding that BEI is an exceptional predictor of soil water content (Martín et al., 2005b), and remarking this measurement as a suitable tool to establish quantitative relationships between hydropedological attributes at different scales (Cámara et al., 2015).

However, additional analyses and studies are still to be performed to evaluate the BEI suitability in the estimation of variables related to soil texture.
The BEI calculated with the clay-silt-sand fraction takes values between 0 and 1 (Figure 1), but the BEI can also be estimated using more fractions of soil particle size distribution, and then, the range of the BEI values changes. It is important to take this into account in order to compare the BEI results.

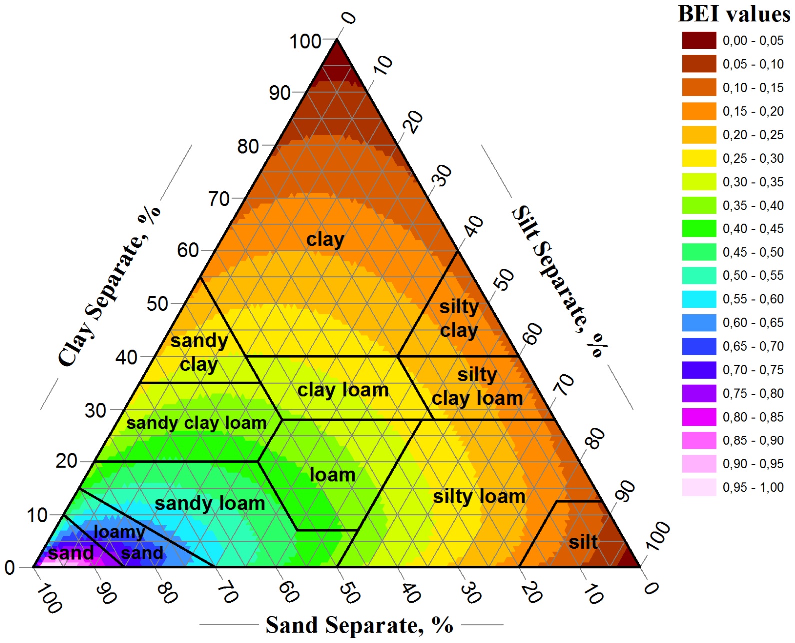

Figure 1: Soil texture triangle with BEI values obtained from the clay-silt-sand fractions

The BEI value may be interpreted as follows: the bigger the value of BEI the more heterogeneous the soil particle size distribution and in turn the richer the soil's texture. When BEI is maximum, the probability of extracting a mass unit of the soil with a determined particle size is equal for any size. On the other hand, BEI is minimum when all the soil particles are classified within the same particle size fraction, then the probability of one fraction is equal to 1, while the probability of the other fractions is 0. A thorough interpretation of the BEI formula and its theoretical properties in terms of texture analysis is given in Martín et al. (2005a).
Nowadays, the use of pedotransfer functions is generalized in the study of soil-water use by grapevine (Brillante et al., 2016), but as far as we know no authors have used the BEI in terroir studies.
The objective of this study was to investigate the relationships between the soil texture heterogeneity and the vineyard characteristics at plot scale. The work was carried out using data corresponding to the Portuguese wine growing region "Região Demarcada do Douro" (RD Douro), and it represents the introduction of soil texture heterogeneity measurements in terroir studies.

2 MATERIALS AND METHODS

2.1 Study area

The Portuguese wine growing region "Região Demarcada do Douro" (RD Douro) is located in the Northern part of Portugal (Figure 2), it covers 2 490 km^2, of which 371 km^2 are under vineyard. The geology of this region consists of metamorphic and igneous rocks formed by the main orogenies that have affected the Iberian Peninsula. Igneous rocks emerged during the late Paleozoic era by the Variscan orogeny, and the metamorphism caused by this event transformed the materials deposited during the Cambrian period. The subsequent Alpine orogeny balanced the Iberian Peninsula to the West, draining the inland sea that covered the Douro Basin to the Atlantic Ocean. This event eroded the secondary and tertiary deposits, and it brought to the surface the old materials that conform the current landscape.

2.2 Data set

The resources used to carry out this study were the soil map of RD Douro scale 1/25 000 (Figure 2), the analytical and morphological data of the 1 217 soil profiles used to elaborate the soil map, and the vineyard information of the RD Douro with individualized data of the vineyard plots (plant density, vine variety, altitude, exposition, etc.).

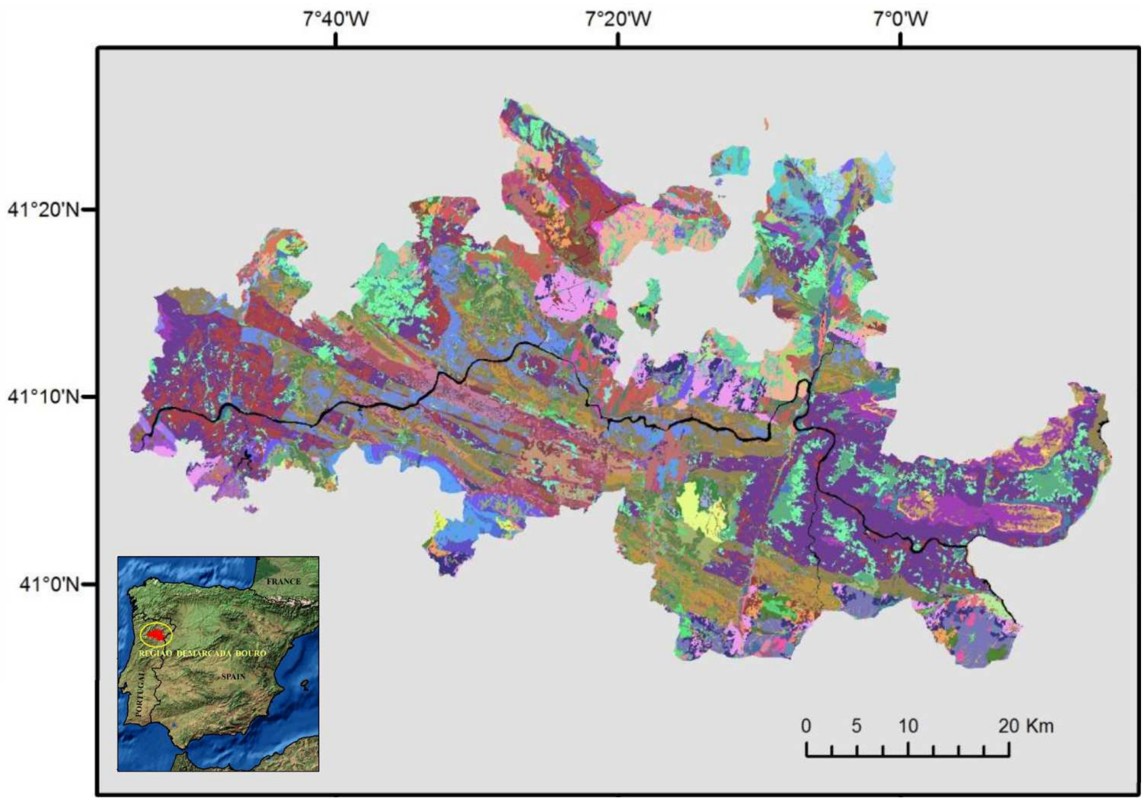

Figure 2: Location of the RD Douro, with a view of the soil map of the region, scale 1/25 000.

The soil map of the region, scale 1/25 000, includes 78 lithological groups, of which only the main 16 lithological groups have been selected for this study. These 16 groups cover the 90.7 % of the RD Douro, and they include the 91.1 % of the vineyard. A brief description of this 16 lithological groups is provided in Table 1.

Table 1: Lithological groups of the region included in this study

Code	Lithological group	
	Type of rock	Brief description
I1	Igneous	Granite: medium grained, two-mica
I2	Igneous	Granite: medium to coarse grained, two-mica, porphyritic
I3	Igneous	Granite: medium to coarse grained, megacrystic, two-mica
I4	Igneous	Granite: fine to medium grained, two-mica
I5	Igneous	Granite: medium grained, muscovite, porphyritic
I6	Igneous	Granite: medium to coarse grained, two-mica, porphyritic
I7	Igneous	Granite: medium to coarse grained, two-mica
M1	Metamorphic	F. Desejosa: chloritic phyllites, with intercalations of metasiltites and metagreywackes
M2	Metamorphic	F. Pinhão: phyllites, quartzophyllites and metagreywackes
M3	Metamorphic	F. Rio Pinhão: metagreywackes and chloritic phyllites
M4	Metamorphic	F. Quartzito Armoricano: quartzites and schists
M5	Metamorphic	F. Bateiras: chloritic phyllites, metagreywackes , and metaquartzogreywackes
M6	Metamorphic	F. Ervedosa do Douro: phyllites, chloritic quartzophyllites, and metagreywackes
M7	Metamorphic	F. Quinta da Ventosa: quartzophyllites with intercalations of metasandstone
M8	Metamorphic	F. Desejosa: carbonaceous metagreywackes
M9	Metamorphic	F. Pardelhas: schists with intercalations of metasiltites

2.3 Methods

In order to analyze the potential influence of soil texture heterogeneity in viticultural properties at plot scale, the BEI has been related to one viticultural property of vineyards that is associated with the soil water availability, the plant density. In this work, the BEI was obtained from the clay-silt-sand fractions of the soil samples, and thus, the BEI values ranges from 0 to 1.

First, data was grouped by lithological groups, obtaining two values for each lithological group; the average BEI of all the surficial soil samples collected in the encompassed area by the lithological group, and the average plant density of the vineyards located in the same area. Textural data from 1056 soil samples were used in this step. An ANOVA test was performed to statistically analyze the variability of BEI values in the lithological groups.

Once this was done, the next step was to relate, plot by plot, the BEI of the surficial soil sample collected in the plot with the plant density of the vineyard. Only the vineyard plots where a soil profile was described for the elaboration of the soil map was taken into account. The number of plots considered in this point was 164.

Cartographic operations were carried out using the software ArcGIS 10.3, and the statistical analysis was performed using the software Statgraphics centurion XVII.

3 RESULTS AND DISCUSSION

3.1 Quantitative approach to the lithological groups and the vineyard of the RD Douro

Table 2 provides a quantitative characterization of the role played by each lithological group in the region and in the vineyard distribution.

Table 2: Quantitative approach to the studied lithological groups

Code	Study area		Vineyard			Soil profiles	
	km^2	%	km^2	%	OI (%)	All	In vineyards
I1	167.86	6.74	11.27	3.03	6.72	54	2
I2	130.68	5.23	10.00	2.69	7.68	61	3
I3	94.94	3.81	7.11	1.92	7.50	52	4
I4	65.46	2.63	7.83	2.11	11.96	43	4
I5	61.24	2.46	4.34	1.17	7.09	36	2
I6	32.80	1.32	2.78	0.75	8.48	14	5
I7	30.93	1.24	1.91	0.52	6.19	11	2
M1	734.79	29.50	138.62	37.32	18.87	295	56
M2	421.83	16.93	78.46	21.12	18.61	199	42
M3	194.31	7.80	42.34	11.40	21.80	124	22
M4	91.31	3.67	1.42	0.38	1.56	23	1
M5	89.64	3.60	18.84	5.07	21.02	46	12
M6	65.70	2.64	8.95	2.41	13.62	41	5
M7	33.96	1.36	2.31	0.62	6.81	31	2
M8	25.05	1.01	1.24	0.33	4.94	11	1
M9	18.61	0.75	0.80	0.22	4.31	15	1

Metamorphic lithologies comprise most of the RD Douro, and also involve most of the current vineyard. The Occupation Index (OI), that represents the percentage of the lithological groups which is covered by vineyard, shows that vineyards are mostly placed on metamorphic lithologies.

3.2 Results grouped by lithological groups

The results of the ANOVA test found significant differences for the variable 'BEI' between the two studied types of rock, granitic rocks and metamorphic rocks. The mean value of BEI for the soil samples collected from soils developed on granitic rock was 0.562±0.005, while the mean value of BEI for the soil samples collected from soils developed on metamorphic rock was 0.424±0.003. This result suggests that BEI, and thus, the soil texture heterogeneity is controlled by the type of rock on which the soils have developed.

The main result of this study is showed in Figure 3, where negative linear relationships can be appreciate between the average plant density of the vineyards located in a lithological group and the average BEI of all the surficial soil samples collected in the same area, when lithological groups are grouped by type of rock. This negative relationship is stronger for the metamorphic lithologies ($R^2 = 0.865$) than for the granitic lithologies ($R^2 = 0.484$). These trends evidence that, within comparable types of rocks, lower values of surficial BEI are related to bigger plant densities, which is linked to the availability of soil water by plants. Thus, lower values seem to be related to higher availability of soil water for vines, and then higher densities of plants can be established.

This result is consistent with the reported capability of BEI as predictor of the soil water content under different pressures (Martin et al., 2005b), with the novelty that the effects of this capability can be detected at plot scale.

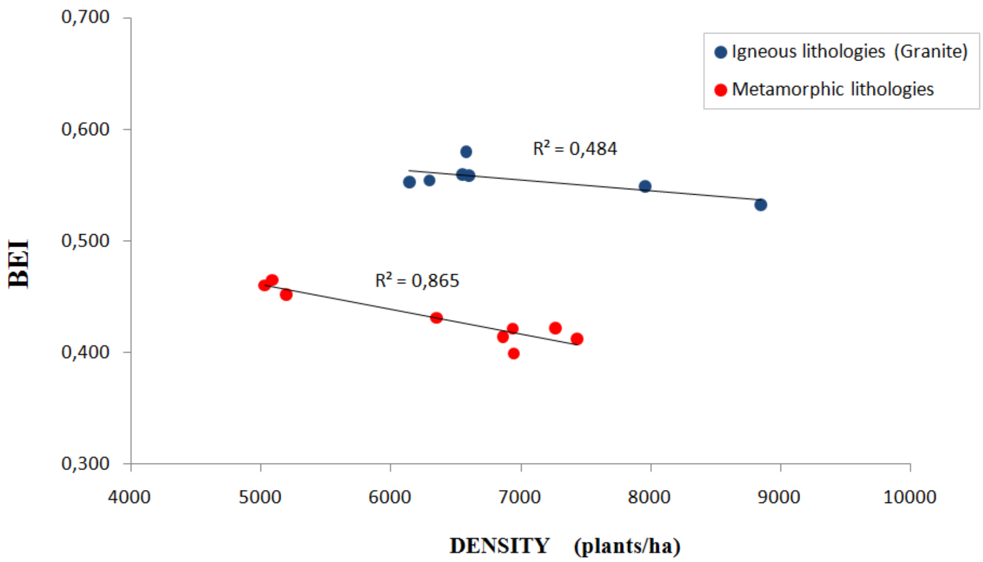

Figure 3: Average plant density of the vineyards vs. average BEI of the surficial soil samples collected within each lithological group.

3.3 Results obtained for individual plots

The results described in the previous point 3.2 are also detectable in Figure 4, where the plant density of individual plots was related to the soil texture heterogeneity of the surficial soil sample collected in the same plot.

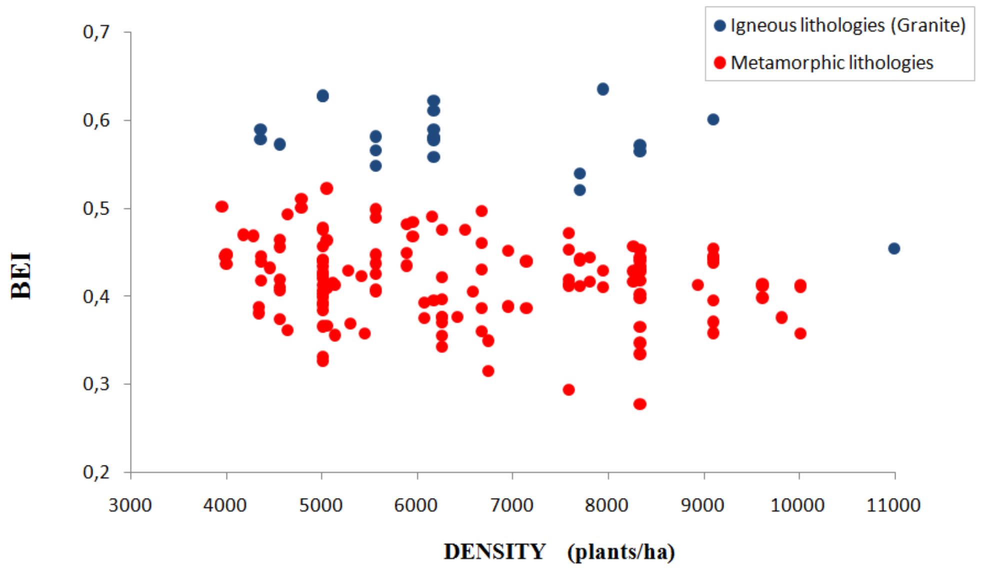

Figure 4: Plant density of the vineyard plots vs. the BEI of the surficial soil sample collected in the plot

It is noteworthy that the plant density is a decision of the plot owner, that usually was taken many years ago based on expertise and without quantitative physical criteria. Even so, the results show the same trends that those observed for the average values of the lithological groups, and also evidence that BEI values of surficial soil samples are controlled by the type of rock that underlies the vineyard.

4 CONCLUSION

The relationship between the soil texture heterogeneity and some vineyard characteristics at plot scale, such as plant density, was investigated in the Portuguese wine growing region "Região Demarcada do Douro" (RD Douro).

Soil texture heterogeneity was characterized using the Balanced Entropy Index, an entropy-based parameter of soil particle-size distributions.

This work evidences that the BEI of surficial soil samples, and therefore the soil texture heterogeneity of those samples, is controlled by the bedrock lithology that underlie the surface.
Significant statistical differences were found between the mean value of BEI for the soil samples collected from soils developed on the two different types of rock studied, granitic rocks and metamorphic rocks.
Results show that, in vineyards within comparable lithologies, plant density decreases with coarser textures. This relationship follows a linear trend with the average values of BEI and plant density obtained for the lithological groups, but it is also visually detectable representing plot by plot the plant density against the BEI value of a surficial soil sample.
As the plant density is traditionally related to the availability of soil water for the vines, results suggest that lower values of BEI are related to major availability of water at plot scale, at least for the range of BEI values obtained in this work.

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