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Article

DETERMINANTS FOR THE VITICULTURAL SYSTEMS SUSTAINABILITY

DETERMINANTES PARA A SUSTENTABILIDADE DOS SISTEMAS VITIVINÍCOLAS

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SUMMARY

The adoption of a sustainable approach has been recognized as a competitive and resilience factor for the vine and wine sector. This research aimed to address the variables that explain the sustainability of the viticultural systems practiced in the Douro Demarcated Region, in a dimensional and global perspective of sustainability. In total 110 vineyard farms were randomly selected and a matrix of sustainability indicators grouped by economic, environmental and social dimension was used. In order to analyse the main determinants of the different dimensions of sustainability, an econometric analysis was carried out considering different typologies or groups of determinants: efficiency; training system; vineyard landscaping; geographical determinants; destination of the grapes; type of work used; other determinants. Based on the estimations of eight models, an important divergence in the results was found, especially between the estimates of the models developed through the global sustainability index than the estimates of the indices disaggregated by dimension. This disparity in results indicates that the analysis of the determinants of sustainability should be carried out in a disaggregated manner (at the level of sustainability dimensions). Divergent results were also deduced depending on the dimension of sustainability. For instance, the model with the highest explanatory power concerned the economic dimension, while the efficiency determinant was not significant in the social and environmental dimensions. In light of these findings, policy measures are proposed.

RESUMO

A adoção de uma abordagem sustentável tem sido reconhecida como um fator de competitividade e resiliência para o sector vitivinícola. Esta investigação teve como objetivo abordar as variáveis que explicam a sustentabilidade dos sistemas vitivinícolas praticados na Região Demarcada do Douro, numa perspetiva dimensional e global da sustentabilidade. No total foram selecionadas aleatoriamente 110 explorações vitícolas e utilizada uma matriz de indicadores de sustentabilidade agrupados por dimensão económica, ambiental e social. Para analisar os principais determinantes das diferentes dimensões da sustentabilidade, foi efetuada uma análise econométrica considerando diferentes tipologias ou grupos de determinantes: eficiência; sistema de condução da vinha; orientação do terreno; determinantes geográficos; destino das uvas; tipo de trabalho utilizado; outros determinantes. Com base nas estimativas de oito modelos, verificou-se uma divergência importante nos resultados, especialmente entre as estimativas dos modelos desenvolvidos através do índice global de sustentabilidade e as estimativas dos índices desagregados por dimensão. Esta disparidade de resultados indica que a análise dos determinantes da sustentabilidade deve ser efetuada de forma desagregada (ao nível das dimensões da sustentabilidade). Foram observados resultados divergentes consoante a dimensão da sustentabilidade. Por exemplo, o modelo com maior poder explicativo foi o respeitante à dimensão económica, enquanto a eficiência não foi um determinante significativo nas dimensões social e ambiental. Tendo em conta estas conclusões, são propostas medidas políticas.

Keywords: Indicators, sustainable dimensions, sustainability index.
Palavras-chave: Indicadores, dimensões de sustentabilidade, índice de sustentabilidade.

INTRODUCTION

Viticulture significantly influences several aspects of European and global life. Portugal ranks as the 10th largest wine producer and the 8th largest exporter by value and volume worldwide (OIV, 2024). Within Portugal's Demarcated Douro Region, the viticultural systems exhibit high heterogeneity, facing diverse

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challenges that impact their sustainability and that of the surrounding environments, including all stakeholders in the wine production chain (Santos *et al*., 2020).

The adoption of a sustainable approach has been recognized as a competitive and resilience factor for the sector (Keichinger and Thiollet-Scholtus, 2017; Flores, 2018). The Triple Bottom Line (TBL) theory, developed by Elkington (1994), is widely regarded as the most comprehensive theoretical model for addressing sustainable development or agricultural sustainability (Hayati, 2017). This theory posits that People, Planet, and Profit are essential principles of sustainability, and advocates that sustainable development occurs when organizations take responsibility for environmental health, social equity, and economic viability (Santiago-Brown *et al*., 2015; Graça *et al*., 2017; Hayati, 2017; Marta-Costa *et al*., 2022).

The application of appropriate sustainability assessment methodologies is crucial not only for implementing measures that facilitate a transition towards sustainability (Ramos, 2019; Trigo *et al*., 2021, 2022), but also for enhancing organizational commitment to sustainability values (García-Cortijo *et al*., 2023).In more recent research, sustainability has been associated with economic efficiency, focusing on identifying the relationship between the two variables and measuring the trade-offs between efficiency and each dimension of sustainability. In this context, the concept of eco-efficiency, which establishes the relationship between economy and ecology, is particularly relevant (Pang *et al*., 2016; Czyżewski *et al*., 2018, 2019; Vásquez *et al*., 2019; Silva *et al*., 2022). Silva *et al*. (2022) described eco-efficiency as a microeconomic incorporation of the theoretical formulation of sustainability. This concept emphasizes minimizing the environmental impacts of economic activity to prevent the depletion of the ecological foundations of ecosystems.

The majority of research on eco-efficiency in agriculture has focused on estimating the determinants of the economic-ecological performance of agriculture in specific regions. This research often employs methods such as simple Data Envelopment Analysis (DEA) (Gomes, 2008; Grzelak *et al*., 2019), two-stage double bootstrap and truncated regression (Bonfiglio *et al*., 2017), and Stochastic Frontier Analysis (Berre *et al*., 2015; Rosano Peña *et al*., 2018). These techniques are frequently complemented by sustainability indicators to measure the economic, environmental, and social dimensions involved in the process (Gerdesen and Pascucci, 2013; Rosano Peña *et al*., 2018; Belém *et al*., 2021). When supplemented with optimization methodologies, these approaches can serve as decision-making tools, offering optimal choices between transformation processes by combining scientific, technical, and economic considerations (Belém *et al*., 2021).

Additionally, authors like Silva *et al*. (2022) have incorporated the Moran Spatial Index to analyse the spatial distribution of eco-efficiency in agricultural production, interpreting it as a sustainability indicator. Consequently, Koskela and Vehmas (2012) argue that eco-efficiency can be regarded both as an environmental performance indicator and as a business strategy for sustainable development.

The concept of eco-efficiency and its methodologies are extensively explored in the work of Belém *et al*. (2021). Building on the findings of Koskela and Vehmas (2012), the authors highlight that the definitions and applications of eco-efficiency are linked to achieving high production levels with reduced use of natural resources, thereby generating more added value with lower environmental impact; that is, the ratio between economic value and environmental influence (e.g., Berre *et al*., 2015; Rosano Peña *et al*., 2018). Eco-efficiency is also used as a management strategy to enhance an organization's eco-efficiency (e.g., Silva *et al*., 2022).

Eco-efficiency enables the measurement of sustainability in a relative dimension, quantifying the potential for reducing environmental impacts while increasing production through innovation and the dissemination of best practices identified in analyses (Silva *et al*., 2022). More recent studies, such as those by Czyżewski *et al.* (2018) and Grzelak *et al*. (2019), have pursued the estimation of Environmental Sustainable Value using the eco-efficiency concept.

Many works dedicated to eco-efficiency (e.g., Pang *et al*., 2016; Czyżewski *et al*., 2018, 2019; Vásquez *et al*., 2019) focus on identifying indicators that link economic efficiency to environmental sustainability, often neglecting the social component. Therefore, a change in eco-efficiency does not necessarily correspond to a change in overall sustainability. This is because the eco-efficiency ratio measures only the relative level of environmental pressure in relation to the volume of economic activity, rather than addressing the absolute levels of environmental pressure (Bonfiglio *et al.*, 2017).

In the agricultural sector, numerous studies have attempted to link sustainability and efficiency, considering either an eco-efficiency or eco-effectiveness approach (Berre *et al*., 2015; Bonfiglio *et al*., 2017; Czyżewski *et al*., 2018, 2019; Grzelak *et al*., 2019; Vásquez *et al*., 2019). However, when considering the eco-effectiveness criterion, Czyżewski *et al*. (2018) demonstrated that the priority shifts from maximizing production to minimizing the strain on the natural environment, often through environmental subsidies.

Studies such as that of Rosano-Peña *et al*. (2014) have applied the method of directional distance functions and DEA, using sustainability indicators from economic, environmental, and social dimensions in the Brazilian context. Similarly, Gerdessen and Pascucci (2013) combined a multidimensional perspective by using two economic, two social, and four environmental indicators along with DEA to operationalize the complex and sophisticated concept of sustainability.

However, studies relating sustainability and efficiency in viticulture are scarce, with the work of Jradi *et al.* (2018) on this topic standing out. This study developed an efficiency estimation using the DEA method on 38 wine producers in the Bordeaux area. The findings can provide valuable guidance to farmers in selecting vineyard practices that enhance the performance and sustainability of their viticultural systems.

In this regard, it becomes imperative to scientifically substantiate the determinants of sustainability, aiming for more rigorous and replicable procedures. The prospective study conducted by Ayele and Derseh (2021) is an example of such efforts, seeking to identify the survival factors of small and medium companies in the Eastern Gojjam Zone (Ethiopia). However, there are numerous antecedents to sustainability that can motivate or influence farmers to adopt actions in favour of more sustainable agriculture (Laurett *et al*., 2021). These factors may evolve over time and shape the concept, perception, and assessment of sustainability.

This work aimed to assess the variables explaining the sustainability of the viticultural systems practiced in the Portuguese Douro Demarcated Region, from both a dimensional and global perspective. The goal is for the findings of this research to contribute to the development of more appropriated methodologies to explain sustainability factors. Ultimately, these methodologies should assist stakeholders in the sector in enhancing the sustainability performance of their production systems and in proactively addressing contemporary constraints related to environmental, social, and economic issues in viticulture (Costa *et al*., 2016; Keichinger and Thiollet-Scholtus, 2017; Flores, 2018; Matias *et al*., 2021).

MATERIALS AND METHODS

Research design

This work arose from the identification of sustainability indicators for winegrowing systems within the Triple Bottom Line framework, which integrates the economic, environmental, and social dimensions of sustainability. For this purpose, the matrix of 27 sustainability indicators identified for Douro winegrowing systems by Marta-Costa *et al.* (2022), ensuring a balanced representation across these three dimensions, was applied.

To determine the variables that explain the sustainability of these systems, several determinants were included, such as efficiency, vineyard training systems, landscaping practices, geographic factors, grape destination, and labour types, as drawn from the literature (Santos *et al.*, 2020, 2021; Marta-Costa *et al.*, 2022). Since some initial indicators overlapped with the technical efficiency estimates for farms calculated by Santos *et al.* (2020) using the DEA method, it was necessary to adjust the sustainability indicator matrix.

Subsequently, the econometric regression model was constructed to estimate the influence of key variables on the performance of the global sustainability indices, using the Ordinary Least Squares (OLS) method. To address heteroscedasticity, the Huber-White correction was applied to obtain robust estimators for the coefficient covariance.

Data

The data used in this study was collected through a structured face-to-face survey conducted of a sample of 154 vineyard farms, 110 of which were located in the Douro region (northeast Portugal), with the remaining located in the northwest of the country. Specifically, the data analysed in this paper pertains to the 110 Douro grape producers, representing approximately 2% of the vineyard farms within the respondent universe. The larger sample was used for the normalization of the indicators. The Douro producers were distributed across several classes of area, including one to five hectares (31), five to ten hectares (32), ten to twenty hectares (30), and vineyards with over 20 hectares (17). Additionally, they were proportionally distributed among the three sub-regions of the Douro region, as indicated in Table I.

The selection of vineyard farms based on wide geographical distribution and varying sizes of vineyard land aimed to ensure representation of the diverse characteristics of viticultural systems in the region. The geographical distribution criterion considers the specific orographic and edaphoclimatic conditions that influence cultivation alternatives, while the variation in vineyard land sizes reflects different property management options and associated interests.

The survey data included six main sections of information covering different aspects about the respondent, the entrepreneur, the farm, the vineyard, its inputs and outputs, and further information more related to environmental and social issues. The agricultural season of inquiry was 2017 (cross-sectional data).

Sustainability indicators

To identify sustainability indicators for winegrowing systems, the Triple Bottom Line framework outlined by Elkington (1994) was used, along with the concept proposed by Masera *et al*. (2000), which asserts that sustainability cannot be evaluated in isolation but only in comparative or relative terms.

Based on these principles, the matrix of 27 sustainability indicators, as defined by Marta-Costa *et al*. (2022) for the Douro viticultural systems, was used (Table II). These indicators are evenly distributed across the three dimensions of sustainability, with nine indicators assigned to each of the environmental, economic, and social dimensions.

Table I

Area and number of vineyard farms of the survey

Variable		Subregion		
		Baixo Corgo	Cima Corgo	Douro Superior
Area of vineyard farms (ha)	1 ≤ area < 5	33.33	35.70	22.85
	5 ≤ area < 10	83.63	97.92	53.31
	10 ≤ area < 20	145.72	231.95	59.73
	area ≥ 20	182.34	816.60	105.33
Number of vineyard farms (%)		39 (35%)	49 (45%)	22 (20%)
Sampling rate (%)[(1)]		3.0	1.8	1.4

[(1)] Respondent population calculated according to the criteria defined above and the data made available and not published by the IVV, by municipality in the winegrowing regions of northern Portugal.

Table II

Descriptive statistics of the Sustainability Indicators defined for the study

Sustainability Indicators	Mean	Std. Dev.	Minimum	Maximum
Environmental area				
1. Grape yield (kg/ha)	5783.76	2649.00	1800.34	16531.01
2. Use of fertilisers and phytopharmaceuticals (€/ha)	503.75	400.05	9.39	3141.80
3. Contribution to physical soil degradation (traction) (H/ha)	31.47	14.54	0	74.48
4. Landscape Physiographic Quality Index	3.07	1.12	0.85	5.00
5. Adoption of the organic farming method (%)	0.03	0.16	0	1.00
6. Agri-environmental aid received (€/ha)	439.91	294.94	58.53	1684.26
7. Waste destination (%)	0.98	0.13	0	1.00
8. Soil analysis (%)	0.96	0.19	0	1.00
9. Good agricultural practices (%)	0.93	0.26	0	1.00
Economic area				
10. Benefits/costs ratio	1.03	0.45	0.26	3.06
11. Labour productivity (Eur/annual work unit)	11547.85	10954.37	-47386.87	44778.56
12. Entrepreneur and Family Income (REF) (€/ha)	1269.17	2049.27	-6873.29	9297.80
13. Business or investment capacity (€/ha)	641.54	531.12	8.70	4216.57
14. Sales price grape (€/kg)	0.785	0.211	0.399	1.56
15. Degree of dependence on external production factors (€/ha)	1867.24	1344.50	467.17	9717.01
16. Degree of indebtedness (%)	0.08	0.27	0	1.00
17. Grape destination (own processing) (%)	20.47	35.04	0	100
18. Organization of information (%)	0.45	0.50	0	1.00
Social area				
19. Farm labour force (days/ha)	52.87	20.12	21.12	128.75
20. Evolution of activity in the last 10 years (%)	48.64	38.41	0	100.00
21. Sustainability of the activity (%)	78.18	28.23	0	100.00
22. Land structure (ha)	20.18	12.17	4.60	61.50
23. Adoption of new production techniques/systems (%)	0.67	0.47	0	1.00
24. Qualification (%)	0.67	0.47	0	1.00
25. Labour remuneration (€/day)	36.75	8.49	0	56.45
26. Participation and intervention in organizations in the sector (%)	78.18	18.57	0	100.00
27. Other sources of income (%)	0.61	0.49	0	1.00

Source: Own data adapted to the matrix of Marta-Costa *et al*. (2022).

Each indicator was individually calculated for each farm and subsequently normalized into a nondimensional value ranging from 0 (worst value) to 100 (best value). This normalization was achieved by comparing each farm's performance with the best values obtained, following the methodology developed by González-Esquivel *et al*. (2020) and Marta-Costa *et al*. (2022). This procedure is analogous to economic efficiency measurements used in performance assessment contexts (Santos *et al*., 2020, 2021).

The integration of these new values was carried out per assessment area and then into a global sustainability index, which coincides with the equitable average of the three dimensions, following the Triple Bottom Line approach.

At this stage, the matrix of 27 sustainability indicators for the Douro viticultural systems, as presented by Marta-Costa *et al*. (2022), was revised by removing economic, environmental, and social indicators that overlapped with the efficiency estimations from in Santos *et al*. (2020) (described in detail in the subsection on sustainability determinants). Specifically, indicators (1) grape yield, (11) labour productivity, and (19) farm labour force were removed. The adjustment led to a refined matrix of 24 indicators, evenly distributed across the three sustainability dimensions (8 indicators per dimension). This revision ensured that the indicators used were distinct and did not duplicate information already captured in the efficiency estimations.

Sustainability determinants

As a determinant of sustainability, the technical efficiency of farms was included, based on the results obtained by Santos *et al*. (2020). In their research, the DEA method was employed for estimations because it does not impose a parametric structure on the data. Efficiency levels were calculated using input and output variables through an input-based approach with a Debreu-Farell radial distance function. Specifically, the volume of grape production (kg) was used as the output variable, while land (ha), labour (days), capital (euros), and intermediate consumption (euros) were considered as input variables.

Finally, an analysis of the three dimensions of sustainability, based on a model of nine and eight indicators per dimension, and the global sustainability index, based on 27 and 24 indicators, was conducted, considering different typologies or groups of determinants. These determinants include efficiency, training system, vineyard landscaping, geographic factors, destination of the grape, type of labour used, and other relevant determinants (as outlined in Table III).

In addition to technical efficiency, which allows for assessing the extent to which production systems optimise the use of their resources and is therefore considered a crucial factor of sustainability (as reported by Santos *et al*., 2021), the remaining selected variables corresponded to the main differentiating characteristics of the different systems practiced in the Douro region, as identified by Marta-Costa *et al*. (2022) and Santos *et al*. (2020).

Table III

Determinants for sustainability of farms in the sample

Variables	Unit	Partition	Value
Efficiency[(1)]	%	-	48.75
Training systems	% farms	Cordon	59.09
		Guyot	14.55
		Traditional	4.55
		Mix of systems	21.82
Landscaping systems	% farms	Terraces	35.45
		Walled terraces (WTERRACES)	8.18
		Plan	12.73
		Vertical planting	6.36
		Mix of systems	37.27
Geographical localisation	% farms	Baixo Corgo (CCORGO)	35.45
		Cima Corgo (CCORGO)	44.55
		Douro Superior	20.00
Grape destination - wine	% kg	Port	42.82
		Muscat	9.35
		Other wines	47.83
Grape destination - production chain	% kg	Wine in-house transformation (TRANFORMATION)	20.47
		Grapes sales	79.53
Type of workforce – gender	% days	Men	55.82
		Women	44.18
Type of workforce – origin	% days	Familiar	7.56
		Hired labour	92.44
Type of workforce – time of permanence	% days	Permanent	58.69
		Temporary	41.31
Area	Ha	Total	1868.41
		Port wine (AREA)	1668.31
Company type	% of farms	Sole proprietorship (SOLE)	68.18
		General partnership	31.82
Accounting type	% of farms	Simplified	54.55
		Organized	44.55
Farmer or manager age	Years	Age	51.54

[(1)] According Santos *et al*. (2020). Note: In brackets are the names of the variables used in the modelling.

Econometric modelling

The econometric regression model specified by Equation 1 was used to estimate the influence of the main variables on the performance of the global sustainability indices (GLOBAL27 and GLOBAL24), considering their disaggregated forms across the three dimensions.

$$SI_i = \alpha + X_i'\beta + \varepsilon_i \qquad \textbf{Eq. 1}$$

Where, *SI* represents the sustainability index, corresponding to either the 27 and 24 indicators or 9 and 8 indicators used, for the farm *i*; α is the constant term; X_i' represents the vector of determinants considered in previous section; β is the vector of coefficients to estimate; and ε_i is the disturbance term.

RESULTS AND DISCUSSION

Eight models corresponding to the eight sustainability indexes were estimated, and the results are presented in Table IV. These models were estimated using the Ordinary Least Squares (OLS) method, with the Huber-White option applied to obtain coefficient covariance estimators that are robust to the presence of heteroscedasticity.

Considering the Wald F-statistic values, all models converged to indicate that the joint effect of the 20 explanatory variables was statistically significant in explaining the behaviour of the corresponding sustainability index. This outcome suggests that the set of explanatory variables collectively contributed to explaining variations in the sustainability index across the observed vineyard farms.

Table IV

Results of the models to explain the determinants of sustainability

Explanatory Variables	Dependent Variables							
	GLOBAL 27	**GLOBAL 24**	**ECONOMIC 9**	**ECONOMIC 8**	**ENVIRONMENTAL 9**	**ENVIRONMENTAL 8**	**SOCIAL 9**	**SOCIAL 8**
Constant	45.146***	50.352***	22.496***	31.377***	40.962***	45.070***	71.982***	74.607***
Efficiency	4.484	-0.884	15.613***	8.104**	7.486*	3.456	-9.645	-14.212
Training system								
Cordon	0.808	0.592	-0.434	-1.025	1.068	1.193	1.792	1.608
Guyot	-1.633	-1.949	-1.531	-1.895	-0.181	0.155	-3.188	-4.109
Traditional	-3.288	-4.147	2.269	1.179	-1.002	-0.452	-11.133*	-13.169*
Vineyard landscaping								
Plan	2.705	3.560*	-1.694	-0.583	2.579	2.167	7.231*	9.096*
Terraces	1.997	2.419*	0.233	-0.045	-0.174	-0.726	5.933*	8.028**
Wterraces	2.469	3.220	-3.443	-3.512	2.487	2.224	8.363*	10.948*
Subregion								
Bcorgo	-3.829**	-4.184	-0.260	-0.597	-4.706**	-5.382**	-6.521*	-6.572
Ccorgo	-1.403	-1.574	-0.292	-0.941	-4.669**	-5.045**	0.751	1.263
Grape destination								
Port	-2.159	-3.434	12.241***	11.297***	-0.327	1.417	-18.392**	-23.014**
Muscat	1.181	0.626**	7.933**	6.508**	1.806	0.743	-6.198	-5.373
Transformation	0.052***	0.060***	0.112***	0.121***	0.013	0.010	0.031	0.049
Kind of labour								
Men	-0.001	-0.001	0.001	0.001*	-0.001	-0.001	-0.002	-0.002
Women	-0.002	-0.001	-0.007***	-0.006	0.001	0.001	0.001	0.003
Familiar	-0.006	-0.005	-0.001	0.001	0.004	0.006	-0.021	-0.020
Permanent	0.001	0.001	0.003***	0.003***	-0.001	-0.001	-0.001	-0.001
Other determinants								
Area	0.127**	0.089	0.106*	0.036	0.060	0.077	0.214	0.156
Sole	1.115	0.586	3.484***	2.958***	-1.583	-2.149	1.443	0.949
Simplified	-4.783***	-5.157***	-13.156***	-14.521***	1.751	2.106	-2.943	-3.056
Age	0.015	0.021	0.045	0.026	0.038	0.034	-0.039	0.002
Wald F-statistic	15.123***	16.055***	71.643***	84.416***	1.872**	2.220***	4.380***	4.776***
R^2	0.427	0.414	0.794	0.818	0.136	0.122	0.260	0.278

Level of significance: *10%; **5%; ***1%.

Considering the R^2 values, a significant divergence in the models' fit became apparent. The models exhibiting the highest fit, with values around 80%, were the two models explaining the economic dimension of sustainability. Conversely, the two models that elucidate the environmental dimension of sustainability presented the lowest fit, with values around 13%.

There were no significant differences in the results between the models in which the indices were adjusted and those in which they are not, when compared pairwise within their respective categories. For example, there were no distinctions between the GLOBAL27 and GLOBAL24 models, nor between the ECONOMIC27 and ECONOMIC24 models. This lack of differentiation arose from a very high correlation (above 97% in all cases) between the indices in their corresponding categories.

The findings demonstrate that the prior adjustment of the three sustainability indices presented in the work of Marta-Costa *et al*. (2022), aimed at removing indicators also present in the efficiency estimates, enables efficiency to be considered as a potential determinant of the various dimensions of sustainability. Therefore, this association between efficiency and sustainability finds support in other studies, such as that of Santos *et al*. (2019), which regarded the inverse of technical inefficiency as a sustainability indicator of economic scope.

The disparities become even more pronounced when contrasting the outcomes of the models elucidating the determinants of the aggregate sustainability indices (GLOBAL27 and GLOBAL24 models) with those of the models exposing the three dimensions of global sustainability in a disaggregated manner. The results of the models delineating the determinants of the aggregate indices tend to encapsulate intermediate values compared to their corresponding models explaining the three disaggregated dimensions.

If there is a notable variance in results between analysing aggregated and disaggregated indexes, conclusions drawn from estimates using aggregated sustainability indexes could be flawed. For instance, when evaluating the outcomes of the GLOBAL27 and GLOBAL24 models, one could wrongly conclude that the explanatory variable "efficiency" was not significant in explaining sustainability behaviour. However, disaggregated analysis may reveal that this variable is significant in determining the behaviour of the economic dimension of sustainability.

When conducting a disaggregated analysis of sustainability, the behaviour of the economic dimension tended to be more thoroughly elucidated by the explanatory variables under consideration in the analysis.

- Efficiency emerged as a significant variable for the economic dimension of sustainability. As farm efficiency improved, this type of sustainability also improved.
- The variables related to the "Destination of the grape" also proved to be significant in explaining the behaviour of economic sustainability. Specifically, directing more grapes to Port or Muscat wines and increasing on-site grape transformation by the producer were associated with improvements in this dimension of sustainability.
- The type of work performed in vineyard farms may have played a crucial role in explaining the behaviour of economic sustainability. Permanent labour, including both family and hired labour, emerged as a significant factor in both models estimating this dimension. This suggests that farms with a more professional workforce tend to exhibit higher levels of economic sustainability. However, the other variables in this group did not demonstrate a clear relationship.
- Other determinants that were significant for this dimension in both models include "sole" and "simplified". "Sole" indicates that the vineyard is the sole economic activity of the farm owner, suggesting that more professional farms tend to exhibit higher levels of economic sustainability. Conversely, the use of a "simplified" accounting system by smaller farms suggests that smaller farms tend to exhibit lower levels of economic sustainability in this dimension.

The efficient utilization of production factors helps to minimise the waste of resources, leading to more profitable systems with a reduced environmental impact. In this regard, Rosano-Peña *et al*. (2014) concluded that achieving a balance across the three dimensions of sustainability is feasible. The relationship between efficiency and the environment has been articulated through the concept of eco-efficiency, which entails higher production levels coupled with lower environmental costs (Berre *et al*., 2015; Rosano Peña *et al*., 2018; Belém *et al*., 2021).

However, concerning the environmental dimension of sustainability, only geographical factors or determinants were found to be significant. Farms situated in the Baixo Corgo and Cima Corgo sub-regions exhibit lower levels of environmental sustainability compared to those in the Douro Superior sub-region. Additionally, this study found no relationship between efficiency and the environmental dimension in the adjusted model comprising 24 indicators.

In the social dimension of sustainability, three groups of factors have been identified as significant. Firstly, farms with a "traditional" training system exhibit lower levels of sustainability compared to those with a "mixed" system. This discrepancy can be ascribed, among other factors, to the more negative evolution of the activity over the last decade, including reductions in area, use of machinery, and limited adoption of innovative practices. Additionally, the lack of enthusiasm shown by producers in continuing with traditional systems, coupled with the absence of a successor for the activity, contributes to this situation. The weaker land structure of vineyard farms in this group, lower qualifications of viticulturists, and a smaller number of farms integrated into organizational structures are also noteworthy factors influencing sustainability levels.

The type of farm design has also emerged as significant for this dimension of social sustainability. Additionally, there was evidence of lower remuneration for the labour force associated with this system compared to others.

The relationship between labour and sustainability has been a subject of study, particularly within the framework of eco-efficiency. In this context, Silva *et al*. (2022) gathered estimated coefficients for family labour, land ownership, and the gender of the producer, which were statistically equal to zero, indicating no discernible causal relationship between these factors and the level of agricultural eco-efficiency. However, in the case of Douro viticulture, an inverse negative and significant relationship was observed in the model not adjusted with 27 indicators, specifically for the variable related to female gender. Although not statistically significant, there was a perceived negative relationship between male labour and permanent labour, particularly within the environmental dimension. This observation was supported by Grzelak *et al.* (2019), whose main finding indicated that higher capital endowment and lower labour intensity are beneficial for environmentally sustainable practices. However, the result suggests that farming with a higher labour endowment may be less eco-efficient, which contradicts the commonly known perception of this issue (Grzelak *et al*., 2019).

Finally, directing a larger portion of grapes towards "Port" wine production has demonstrated a significant and negative impact on social sustainability.

The absence of a relationship between "efficiency" and the social aspect was also noted, supported by observations from Santos *et al*. (2021, 2022), who emphasized the lack of social determinants of efficiency. These remarks contrast with the expected interactions between the sustainability pillars defined by Elkington (1994), which should naturally emerge over the medium to long term. Additionally, the findings of Rosano-Peña *et al*. (2014) demonstrated that efficiency tends to integrate the three dimensions in various ways. Furthermore, the analysis of the global sustainability index in this study mitigates some of the observations made for each of its dimensions. This suggests that analysing sustainability from a global perspective may be less effective than analysing each dimension individually, particularly when the former results from a mere accounting calculation, as argued in Elkington's latest exposition (2018).

In terms of methodology, eco-efficiency traditionally measures technical efficiency by focusing on environmental variables, primarily assessing the relationship between economic output and environmental impact. However, this study introduces a novel approach that not only estimates the technical efficiency of Douro wine farms but also incorporates a range of farm characteristics to analyse how both technical efficiency and these factors influence overall sustainability. This includes a thorough analysis of the economic, social, and environmental dimensions. By moving beyond the conventional focus on economic and productive efficiency within environmental contexts, this approach integrates the often-overlooked social dimension of sustainability, as highlighted by Massuça *et al.* (2023). As a result, it provides a more holistic and comprehensive understanding of sustainability in viticulture.

CONCLUSIONS

There were still slight differences in results when adopting the global index approach versus disaggregated sustainability indexes, underscoring the advantages of disaggregated analysis of sustainability. This finding aligns with Elkington's (2018) assertion that sustainability cannot be adequately analysed from an accounting perspective alone. While the three dimensions emphasized in Elkington's earlier study (1994) remain crucial for sustainability, aggregating them into a global index may obscure the nuances of each dimension. Instead, sustainability factors should complement each other through their interaction across dimensions. However, the outcomes indicate that improvements in production efficiency were not translating into enhancements in the environmental and social dimensions of the Douro region's production systems.

Based on the previous results, several policy recommendations can be proposed. The findings from the general characterisation of the production system, as reflected in the regression analysis, indicate a specific approach to agricultural practices that is notably conservative and emotionally tied to the producers' roots, rather than being driven primarily by professional or commercial objectives.

Therefore, fostering the professionalization of farms could lead to enhancements in their economic efficiency. This could involve implementing formal accounting systems, dedicating fulltime efforts to viticultural activities, and increasing on-site grape transformation into wine.

Improving efficiency levels beyond their current status is crucial, as it could also positively impact the social and environmental dimensions of sustainability; that is, a more efficient use of resources may have spillover effects on social and environmental sustainability aspects.

In terms of structural determinants, it was found that they cannot be changed in the short term. However, modifications to training and landscaping systems over the medium to long term can facilitate more sustainable viticultural practices from a holistic perspective.

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