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Clustering olive oil mills through a spatial and economic GIS-based approach

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ABSTRACT

Sicily ranks as the third-largest region in Italy for olive growing and olive oil production, holding the second position nationally regarding the number of active olive oil mills. This pioneering study integrates spatial and economic analyses to examine the geographical distribution of olive oil mills in Sicily and their relationship with the localization of olive groves. Using Local Indicators of Spatial Association (LISA), we conducted an advanced analysis of spatial patterns of olive oil mills, considering travel time on the road network. The adopted methodology addresses issues related to overestimation based on straight-line assumptions and the neglect of travel speed. Unlike traditional Euclidean distance approaches, our methodology provides a detailed understanding of the spatial relationships between olive oil mills and olive groves, revealing distinct patterns linked to elevation and proximity to olive groves. By linking profitability indicators with spatial clusters, we identify different thresholds of economic sustainability. Consequently, these findings contribute to a more comprehensive understanding of the olive oil industry, suggesting more environmentally sustainable practices. Policymakers, researchers, and industry stakeholders can leverage this knowledge to make informed decisions that foster the long-term sustainability of the olive oil sector.

1. Introduction

Olive (*Olea europaea* L.) is an iconic tree domesticated since the early bronze age (Kaniewski et al., 2012), with a multifunctional trait of its production and olive groves characterize the Mediterranean landscape (Chiappini et al., 2024; Messina and Modica, 2022). Olive tree cultivation plays a significant economic role in the Mediterranean food sector, contributing to the region's agricultural vitality since it encompasses trade and environmental sustainability by providing employment opportunities in rural areas and playing a role in environmental conservation by preventing soil erosion and promoting biodiversity (Di Vita et al., 2015; Donner and Radić, 2021). Additionally, olive tree production attracts tourists interested in experiencing the cultural and culinary heritage of olive oil consumption and provides diversification in the agricultural sector and landscape (Uylaşer and Yildiz, 2014; Dancausa Millán et al., 2023; Zanchini et al., 2022).

The European Union provides approximately two-thirds of the world's olive oil production, and together with three other Mediterranean countries, it accounts for a production share of just under 97% compared to the global total (IOC) (Table 1). The EU uses just under half of the olive oil produced in terms of consumption. At the same time, there is a progressive increase in consumption in non-Mediterranean countries (31.6%), led by the United States, where olive oil has been growing (12% of consumption compared to the global total) at the expense of traditional seed oils (IOC). Spain has the highest share of olive oil production within the EU, contributing to just under 44% of the world's production, with nearly 1.5 million tons in 2022. Italy follows with 329,000 tons, equivalent to 9.68%, and Greece with 232,000 tons, accounting for just under 7% of the worldwide production (IOC) (Table 1).

Differences in economic and social structure, plant characteristics, and cultivation methods across the North to the South of the peninsula concur to characterize different olive-growing models (Stillitano et al., 2017). Italy's olive production predominantly comprises small

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Table 1
The table shows the worldwide olive oil production and consumption in 2022 (source: our calculations based on International Olive Council data, IOC, www.internationaloliveoil.org, last accessed 26 November 2023).

Country/Region	Olive oil production		Olive oil consumption	
	[Gg]	%	[Gg]	%
Greece	232.0	6.83	106.3	3.28
Italy	329.0	9.68	481.7	14.87
Portugal	206.0	6.06	63.0	1.94
Spain	1491.5	43.89	587.3	18.13
European Union (UE)	*2271.0*	*66.83*	*1550.5*	*47.86*
Algeria	91.0	2.68	92.0	2.84
Morocco	200.0	5.89	150.0	4.63
Syria	105.5	3.10	90.5	2.79
Tunisia	240.0	7.06	30.0	0.93
Turchia	235.0	6.92	170.0	5.25
Mediterranean Third Countries	*996.5*	*29.33*	*664.0*	*20.50*
United States of America (USA)	15.5	0.46	395.0	12.19
Brazil	0.0	0.00	100.5	3.10
Extramediterranean Countries	*130.5*	*3.84*	*1025.0*	*31.64*
Worldwide total	***3398.0***	***100.00***	***3239.5***	***100.00***

family-owned micro-businesses with high production costs and low profitability (Di Vita et al., 2015; Coppola et al., 2018) The challenges in covering production costs (and thus making a profit) have led many olive growers to invest minimally in modernizing their olive groves (Stillitano et al., 2017; Spada et al., 2022). Consequently, numerous businesses manage centuries-old, difficult-to-mechanize olive groves subject to alternating productivity. On the commercial front, many producers, unable to rely on economically viable business sizes, struggle to implement effective marketing strategies.

The Italian regions with the largest olive grove areas are Apulia (~345,000 ha), Calabria (just under 180,000 ha), and Sicily (~145,500 ha) (ISTAT, 2012).

The values for olive grove areas recorded by ISTAT during the census differ significantly from the remote sensing data used in the GIS-based analyses described in the following paragraphs. These discrepancies can be attributed to the differing data acquisition methodologies.

Olive oil mills have been investigated mainly regarding the environmental impact of olive oil production and waste management (Akar et al., 2023; Elkadri et al., 2023; Salomone and Ioppolo, 2012; Saouini et al., 2023). The study by Valenti et al. (2017) assessed the availability of olive pomace for biogas production in the province of Catania (Sicily), while the recent research by Vicario-Modroño et al. (2023) evaluated the sustainability of olive oil mills in Andalusia based on composed indicators and proposed a global sustainability index.

The last half-century has witnessed a rapid technological modernization of the sector, which has led to the near disappearance of the old discontinuous cycle mills by 'pressing' in favor of new mills equipped with modern continuous cycle machinery, in which metal crushers have replaced the old tools of stone mills. The most commonly used extraction system is two-, three-phase, or two-and-a-half-phase centrifugation.

A survey carried out by ISMEA (2015) on the reality of Italian olive mills shows that in Sicily, the productive size of oil milling facilities is made up of medium-small plants that, in 85% of cases, are at most 500 tonnes of olives milled per year.

Regarding the number of active mills in Sicily, it was decided to census the active mills distributed within the Sicilian territory by integrating the web databases with those provided by the Sicilian region and other public and private research structures.

In the proposed research, we analyzed the geographical distribution of olive oil mills in Sicily and their spatial patterns using the local indicators of spatial association (LISA). As variables linked to their actual localization, we considered their elevation and spatial relation with the olive grove distribution. In particular, following the service area and travel time concepts, we analyzed the spatial relationships between olive oil mills and olive grove localizations.

This research used the travel time calculated on the road network and associated road speeds to generate service areas. Each olive oil mill represents the position of an object (i.e., the facility) from which the algorithm calculates the maximum traveled distance for a given vehicle in the allotted maximum time and also considers the speed limits for that vehicle type. Moreover, although based on measuring travel time on a road network, few previous studies used travel time as easily updateable basic information. Until a few years ago, most of them were based on analyzing a static (i.e., physically downloaded) road network (e.g., Adewopo and Locher, 2011; Bilaşco et al., 2018; Gu et al., 2017; Senes et al., 2016).

As for the economic aspects, contributions in this field are pretty limited. Previous literature on the economic analysis of olive oil mills mainly focused on conducting cost analyses from a profitability perspective (Günlük, 2014; Bertolotti, 2014) while another strand of research explored the economic aspects, costs, and potentialities related to waste disposal costs within olive oil production, including the disposal of biomass and Olive Mill Wastewaters resulting from olive oil processing (Lanfranchi et al., 2016; Strano et al., 2014).

In terms of cost analysis, one study evaluated the costs of milling for small-to-medium-sized olive companies, focusing on the final cost of the packaged unit (Bertolotti, 2014), while other studies examined the Life Cycle Costing (LCC) for three-phased olive mills in the Milas region, analyzing each typology of costs in all life cycle stages of a product.

Additional research has investigated the biomass produced through olive oil processing, evaluating its economic viability and exploring alternative applications beyond traditional disposal methods (Lanfranchi et al., 2016). The economic dimensions of prevailing disposal systems employed by olive oil mills were analyzed to guide the selection of alternatives aimed at minimizing costs associated with Olive Mill Wastewater management (Strano et al., 2014).

To our best knowledge, this research is the first in the literature to propose a spatial and economic analysis of olive oil mills' geographical localization coupled with studying the location and distribution of olive groves.

The main objective of this paper is twofold and refers to the following points:

a) An advanced spatial pattern analysis of olive oil mills localization.
b) Measurement of the profitability of olive oil mills by comparing the economic results held in areas with low- and high-density olive growing and assessing the potentialities linked to the different spatial distribution of olive oil mills.

The remainder of the paper is organized as follows: In the second section, we delve into the methodological aspects of our survey. This includes an introduction to the study area and our data collection methods. We explore the spatial analyses of the localization of olive oil mills, defining their service areas and conducting spatial pattern analysis. Additionally, we assess the potential impact of olive oil mill wastewater in these service areas and outline the research design for our economic analysis. Moving on to the results, we present an analysis of olive oil production in Sicily, shedding light on the spatial patterns of olive oil mills and groves. We then explore the economic aspect, analyzing the profitability of olive oil mills. The subsequent discussion section explores the limitations of traditional costing methodology, emphasizing the oversight of after-sales costs that are often excluded when costs are traced only in the manufacturing stages. Finally, we conclude our paper by summarizing key findings and implications of our research.

The proposed analysis of the geographical distribution and economic characteristics of olive oil mills in this study could potentially offer insights for identifying and exploring possible circular business models in the olive oil industry.

2. Material and methods

2.1. Study area and data collection

The study area is the territory of the Sicilia region (southern Italy), the largest island of the Mediterranean basin, accounting for a surface of 25,420 km^2 (Fig. 1).

Sicily is the third largest olive-growing region in Italy in terms of olive-growing area (145,595 ha), olive production (352,388.60 tons), and olive oil production (56,393.90 tons), equal to, respectively, 13.4%,14.32%, and 15.2% of the national total (ISTAT, www.censimenti.it).

The database on olive oil mills implemented with the following research utilized several official sources (public and private) supplemented with direct field surveys. All the used official sources are provided in Table S1 of supplemental materials. In consideration of possible overlaps, the data in each of the databases acquired and analyzed were compared with each other to eliminate potential duplications and repetitions of the same processing plant. In addition, given the nature of the analyzed mills, with location and additional information freely accessible on the internet, it was possible to retrieve further information on the individual mills through a specific internet search, such as company name, plant location address, plant activity status, phone or mobile numbers of the owners, e-mail and links to any company websites. Additionally, direct phone calls and in situ visits for those cases with doubts about the consistency and completeness of the obtained information allowed us to refine our database on the Sicilian olive oil mills.

Fig. 1. Geolocalization of the study area, the Sicilia region. In light grey are the boundaries of the nine Sicilian provinces, labeled in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Once the final list of mills operating in the territory was drawn up, they were located using their geographical coordinates (i.e., longitude and latitude) obtained from Google Maps and transformed as a points vector layer.

As reference data concerning olive groves, we used the official land use land cover (LULC) map released in 2008 by the Sicilian Click or tap here to enter text.region (Regione, 2008), implemented at a nominal spatial scale of 1:10,000 and following the Corine Land cover legend (https://land.copernicus.eu/en/products/corine-land-cover, last access 15 November 2023).

2.2. Spatial analyses of olive oil mills localization

For each olive oil mill surveyed, we derived its elevation using as a reference the digital elevation model (DEM) with a ground sample distance of 10 m, provided by the National Institute of Geophysics and Volcanology (INGV) (Tarquini et al., 2012, 2023).

To estimate the density of olive oil mills over the study area, i.e., to visually assess their spatial variation, a kernel density estimation (KDE) was implemented. KDE is based on a moving window superimposed over the study area and estimates the density surface of the analyzed variables at each location according to a distance-weighted kernel function, producing smoothed surfaces (Gatrell et al., 1996; Modica et al., 2012; Vizzari, 2011; Vizzari and Sigura, 2015). KDE is a non-parametric interpolation technique that assesses the influence of each event of the analyzed variable (i.e., the olive oil mills distribution) on its neighborhood. The surface estimation occurs around each event according to a specified radius (i.e., the bandwidth h) and the function (i.e., the kernel) (Gatrell et al., 1996; Gatrell and Bailey, 1995; Oyana, 2021). In this research, KDE was implemented, imposing a search radius of 15 km within the boundary mainland of Sicily and expressing the results as olive oil mills per square kilometer.

To assess the spatial dependence, i.e., autocorrelation, of the olive oil mills allocation, we applied the global Moran's I index (Moran, 1950), which measures the covariation of a variable measured at multiple locations (Burrough et al., 2015) and allowed to detect if their actual distribution is random, scattered or clustered (Molaei Qelichi et al., 2017). In this case, we considered, as a variable y, the elevation of each census olive oil mill, and the I coefficient formula can be written as follows (equation (1)):

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(y_i - \bar{y})\left(y_j - \bar{y}\right)}{\left(\sum_{i=1}^{n}(y_i - \bar{y})^2\right)\left(\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\right)} \quad (1)$$

where n is the number of point locations (i.e., the surveyed olive oil mills); w_{ij} is an element of the spatial proximity matrix (Lloyd, 2011), i.e., the spatial weight, assuming values of 1 or 0, whether two points are contiguous or not, and calculated in this case as a function of the inverse squared distance between the paired i and j data locations (a threshold band of 15 km was applied as Euclidean distance); y_i is the attribute value (i.e., the elevation of the site location of the investigated olive oil mills, in this case) and $\bar{y}$ its mean value (equation (2)).

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \quad (2)$$

Moran's I index values can range from −1 to +1. A positive value of I indicates that the analyzed data have a clustering of similar values, while, if negative, the clustering occurs among dissimilar values (scattering) (Lloyd, 2011). A value of 0 indicates a spatial pattern that is not different from a random phenomenon, i.e., there is no spatial autocorrelation (Lloyd, 2011). The $z_{I-\mathrm{score}}$ (measuring the standard deviation) was also provided and calculated as follows:

$$z_{I-\mathrm{score}} = \frac{I - E[I]}{\sqrt{V[I]}} \quad (3)$$

where,

$$E[I] = -\frac{1}{n-1} \quad (4)$$

And

$$V[I] = E\left[I^2\right] - E[I]^2 \quad (5)$$

The p-value associated with the $z_{I-\mathrm{score}}$ is a measure of statistical significance (i.e., probabilities) and indicates if rejecting the null hypothesis is possible, i.e., a complete spatial random distribution of the values associated with the analyzed features. Higher $z_{I-\mathrm{score}}$ values reflect a more intense clustering.

To better select the appropriate distance of the threshold band to be used in calculating LISA indicators, the proper scale of the analysis must be defined. In this research, to determine the threshold band of Moran's I index, we implemented a method known as incremental spatial autocorrelation (ISA) that allows for avoiding the choice of arbitral values. In turn, choosing an appropriate distance threshold will lead to a more accurate calculation of the other spatial statistics (Grekousis, 2020). The ISA approach is based on the calculation of the global Moran's $z_{I-\mathrm{score}}$ at different band thresholds for a series of incremental distances. The highest values of the $z_{I-\mathrm{score}}$ (i.e., peaks) reflect the distances at which spatial clustering is more robust.

2.3. Definition of olive oil mills service areas

For each of the surveyed olive oil mills, we used a location intelligence analysis to identify its service area, i.e., that polygon underlying a given road network reachable by a specific vehicle within a maximum distance or travel time. This analysis has been performed using the Location Lab plugin (support.com/location-lab-qgis-plugin" title="https://gis-support.com/location-lab-qgis-plugin">https://gis-support.com/location-lab-qgis-plugin, last access 15 November 2023) for QGIS (https://qgis.org/en, last access 15 November 2023), which allows location intelligence analyses based on third-party APIs of road network providers such as OpenRouteService (ORS, https://openrouteservice.org, last access 15 November 2023). ORS is based on the free collaborative project Open Street Map (OSM, www.openstreetmap.org, last access 15 November 2023), which means performing analyses using free quota plans is also possible. In this study, we calculated the service areas in terms of the maximum distance to each oil mill, imposing a maximum distance limit of 15 km on the road route. This value was undertaken considering that a medium-sized truck could reach the nearest oil mill in a maximum acceptable time of 45 min, thus assuming an average speed of 20 km h^{-1}. Once we obtained the service areas, we superimposed the LULC map, extracted the olive groves falling in each of them, and calculated their relative surface.

2.4. Spatial pattern analysis

As suggested in the literature (Getis and Ord, 1992), to have a deeper understanding of spatial patterns in olive oil mills distribution, we coupled Moran's I with the Getis-Ord G_i^* local statistics (Getis and Ord, 1992; Lloyd, 2011; Ord and Getis, 1995), which provides a measure of spatial association of a specific attribute's values and allows the assessment of spatial clustering. Moreover, unlike other spatial indices, it enables the discrimination between hot spots (i.e., high values) and cold spots (i.e., low values) over the analyzed study region, giving a spatial picture of clusters formed by the analyzed variable. This is the reason why this analysis is also denoted as hot spot analysis.

As spatial units, we considered the obtained service areas, and we calculated the G_i^* index using the olive grove surface (in hectares) falling in each of them as the attribute value.

The G_i^* was calculated as follows (Equation (6)):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{ij} y_j - \bar{y} \sum_{j=1}^{n} w_{ij}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij} \right)^2 \right]}{n-1}}} \tag{6}$$

The symbology is the same as previous formulae, while S is the standard deviation (Equation (7)), calculated as follows:

$$S = \sqrt{\frac{\sum_{j=1}^{n} y_j^2}{n} - \left(\frac{\sum_{j=1}^{n} y_i}{n} \right)^2} \tag{7}$$

Since we analyzed polygon features, their geometrical centroids have been used in distance calculations. As suggested in the literature, we used a fixed distance and calculated it following the ISA approach (Grekousis, 2020). As in the case of Moran's *I* index, the statistical consistency of the obtained results is assessed through a z_{score} along with an associated p-value, and also for this index, higher values of the z_{score} reflecting a more intense clustering, while values near 0 are typical of the absence of spatial clustering. A high positive z_{score} associated with a small p-value indicates spatial clustering of high values (i.e., hot spot). In contrast, a low negative z_{score} with a small p-value is typical of spatial clustering of low values (i.e., cold spot).

For each service area, we calculated the average yearly olive production and the amount of crushed olives [t ha^{-1}], multiplying the olive groves' surface falling in each for a coefficient of 1.25, which was last obtained by analyzing the official data at the regional level. The potential yearly production of olive oil mill wastewater (OOMW) was finally obtained by multiplying the amount of crushed olives for a coefficient of 0.8, which represents the estimated coefficient of vegetation water per unit of crushed olives, produced using the different extraction technologies (Hassen et al., 2023; IOOC, 2004).

2.5. *The economic analysis*

2.5.1. *Data collection*

The average costs and revenues of olive oil milling operations in various homogeneous areas of the island were determined through specific on-site surveys at mill factories with the support of the local associations of mill operators, Assolio.

The average data on revenues and costs were provided by the provincial producers' associations, Assolio, who gathered information through a survey referencing a representative sample of mills (categorized by plant size and olive oil extraction system). This facilitated the collection of average data on productions and prices for each territorial area, representing the entire regional sector.

Once the location and density of olive groves and mills at the regional level and for each of the nine provinces were identified, the revenues at the provincial level were estimated. These revenues, derived from the milling service provided to olive growers, were calculated multiplying the quantities of average productions realized in the last three olive-growing seasons (2020/21; 2021/2022; 2022/2023) by the average price recorded for each province in the last agricultural year.

It was necessary to calculate an average revenue by province since the value of olive processing varies within the same province in terms of the quantity of olives milled by each producer. Subsequently, using the spatial analysis results, economic indicators were associated with each of the previously identified clusters. Specifically, by applying the Getis-Ord G_i^* Index to the Service Areas, we meticulously analyzed the distinct territorial hot and cold spots to estimate the average profit of each olive mill, establishing a correlation between the total costs incurred by the mill operator and the subsequent revenues derived from the price applied for the olive milling service.

2.5.2. *Determination of economic indicators*

In line with previous literature (Pappalardo et al., 2013), the economic indicators utilized to assess the profitability of Olive oil milling operations, specifically it was calculated as follows:

Profit = Total Revenues - Total costs

Total revenues (TR): The provision of olive processing services (milling) for olives was calculated as the quantity of olives pressed (three-year average 2020–2022) multiplied by the price (referenced to the last available year, 2023).

Total Costs (TC): TC encompasses fixed and variable costs of plant overheads associated with production during the accounting year. *Variable costs* are expenses that fluctuate depending on the company's production and sales volume. *Fixed costs* include plant overheads related to olive processing activity but are not tied to specific production lines. These costs are generally independent of the olive mill's specific business activities.

More in detail, according to previous literature, average total costs were calculated in three different classes; materials, labour and services. *Materials* include all non capital inputs, such as water, electricity input and other specifics; *labour and services* inclued the costs of labour (including family labour and non farming services carried out by external companies (renting machineries, waste removal, renting and transport, commission) *quotas and other duties* that include machinery and building depreciation, fixed equipment, circulating and current capital, taxes and fees (Di Vita et al., 2013). All values were referenced to the year 2023.

3. Results and discussions

3.1. *Analysis of the olive oil production in Sicily*

The province that recorded the highest average values of crushed olives (65,614 t), of oil produced (10,336 t), and, therefore, of yield percentage (15.75%) was Agrigento even though it is the province of Palermo (39,428.41 ha) that has the largest olive grove area in Sicily. The best ratio between crushed olives and olive-grove surface area is in the province of Trapani (1.95 t ha^{-1}). At the same time, Agrigento still holds the regional record for the amount of oil produced per hectare of olive grove.

Based on our surveys, the number of olive oil mills surveyed in Sicily and currently active amounted to 603 units (Fig. 2).

The provinces with the highest number of active olive mills surveyed are those of Agrigento and Palermo, followed a short distance away by Trapani. At the same time, only 35 olive mills are located in the province of Enna, which has the lowest number of mills on the island (Table 2) (see Table 3 and 4).

The spatial localization was defined for each olive mill surveyed as georeferenced vector data (Fig. 3).

3.2. *Service area analysis*

This research used the travel time calculated on the road network and associated road speeds to generate service areas. Usually, an algorithm for determining service areas is based on a road network graph and a set of base points. Each base point, in our case, each olive oil mill, represents the position of an object (i.e., the facility) from which the algorithm calculates the maximum traveled distance for a given vehicle in the allotted maximum time and also taking into account the speed limits for that vehicle type. Using a location intelligence analysis, we identified the service area of each olive oil mill by imposing a maximum distance of 15 km from it and a travel time of 45 min calculated on the

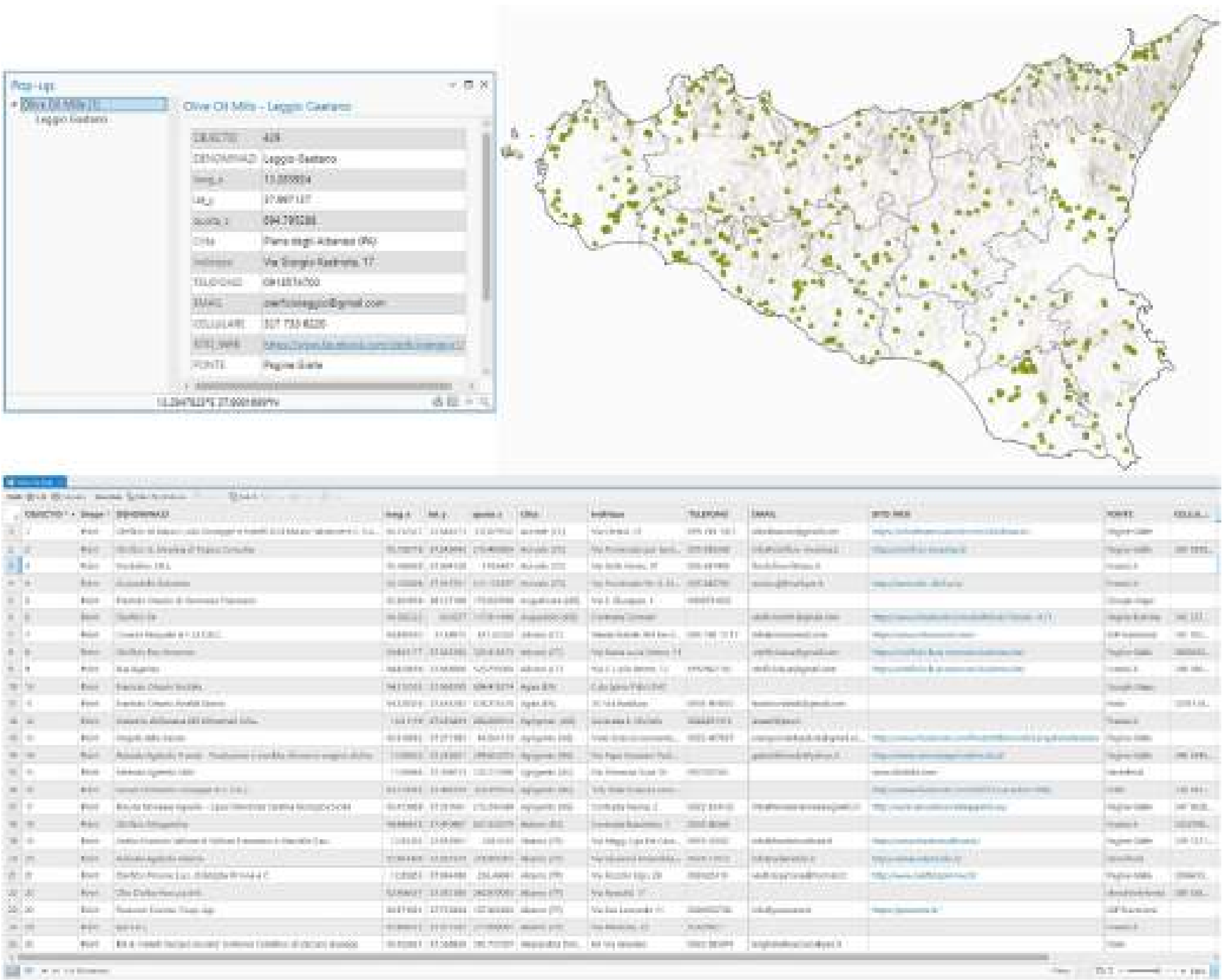

Fig. 2. Graphical excerpt of database implemented in this research concerning the 603 surveyed Sicilian olive oil mills active in 2023. For each of them, we collected and organized the following information: name of the olive oil mill (i.e., company name), geographical coordinates, elevation, city, province, address, website, email address, telephone number, source of the provided information.

Table 2
Distribution of the 603 surveyed olive oil mills and olive groves surface in the study area according to the territory of the nine Sicilian provinces, and details about the crushed olives and the olive oil production.

Province	Olive Oil Mills		Olive groves surface		Total crushed olives	Olive oil production	Oil yield	Average crushed olives	Average olive oil production
	[N]	[%]	[ha]	[%]	[t]	[t]	[%]	[t ha $^{-1}$]	[t ha $^{-1}$]
Agrigento	111	18.41	32,295.67	16.61	65,614	10,336	15.75	2.03	3.20
Caltanissetta	42	6.97	11,406.35	5.87	9440	1402	14.85	0.83	1.23
Catania	61	10.12	12,389.50	6.37	15,970	2093	13.10	1.29	1.69
Enna	35	5.8	13,995.81	7.20	7456	1042	13.98	0.53	0.74
Messina	73	12.11	39,428.41	20.28	9218	1397	15.16	0.23	0.35
Palermo	100	16.58	37,366.89	19.22	30,804	4724	15.33	0.82	1.26
Ragusa	47	7.79	10,333.46	5.32	14,111	1778	12.60	1.37	1.72
Siracusa	41	6.8	11,702.83	6.02	8899	1109	12.46	0.76	0.95
Trapani	93	15.42	25,485.12	13.11	49,620	7463	15.04	1.95	2.93

actual road network. In other words, we considered the area a truck can reach in 45 min (i.e., the travel time) starting from a given olive oil mill, assuming an average speed of 20 km h^{-1}. The service area approach demonstrated its reliability in different research fields and across different spatial scales, from regional, as in the proposed study, to national-wide, as in the case of Pokharel and Latta (2020), that proposed service area identification in the forest sector based on the road network analysis across the United States.

Fig. 4 shows the service areas obtained for the 603 surveyed olive oil mills, classified according to the olive groves' surface area in each.

This approach allowed us to overcome the difficulties in using Euclidean distance approaches, which tend to overestimate the service

Table 3
Distribution of olive oil mills and groves in the study area according to elevation ranges with a bandwidth of 100 m.

Elevation ranges	Olive oil mills		Olive groves	
[m a.s.l.]	[n]	[%]	[ha]	[%]
0–100	131	21.72	29,884.90	15.37
100–200	109	18.08	37,946.93	19.52
200–300	75	12.44	34,161.92	17.57
300–400	71	11.77	30,865.54	15.88
400–500	81	13.43	25,776.30	13.26
500–600	57	9.45	19,040.97	9.79
600–700	45	7.46	10,186.42	5.24
700–800	21	3.48	4527.99	2.33
800–900	4	0.66	1516.47	0.78
900–1000	8	1.33	408,507	0.21
1000–1100	1	0.17	67.61	0.03
1100–1200	0	0.00	18.52	0.01
1200–1300	0	0.00	2345	0.00
Totale	**603**	**100**	**194,404.42**	**100**

area of a given facility since it assumes that trucks can travel in a straight line and at a constant speed. Moreover, using only the road distance, without any information on the average travel speed for a given vehicle, also leads to overestimating the calculated service area, as it only considers the length and not the travel time. In turn, travel time is a suitable proxy in these types of analyses, representing a synthetic indicator of the cost of transport since the cost of trucks is estimated based on working hours.

Moreover, although based on measuring travel time on a road network, few previous studies used travel time as easily updateable basic information. Until a few years ago, most of them were based on analyzing a static (i.e., physically downloaded) road network (e.g., Adewopo and Locher, 2011; Bilaşco et al., 2018; Gu et al., 2017; Senes et al., 2016).

As highlighted, our approach used the actual road network based on open-source web applications, which could be easily updated and shared for future or different applications. The use of an open-source QGIS plugin working on APIs of road network providers such as OpenRouteService (ORS), based on the free collaborative project Open Street Map (OSM), allowed the implementation of a flexible and easily updatable tool for decision-makers and stakeholders.

Service area analysis can help determine the geographical area that an olive oil mill serves, which is crucial for planning and decision-making. For instance, most olive oil mills in the Mediterranean region are small domestic enterprises scattered around the country. Applying service area analysis can help understand these mills' accessibility and effectively plan their operations. Moreover, the proposed method could be integrated with advanced surveys regarding olive oil mills with recognized historical importance to understand better these important agri-food buildings characterizing several Mediterranean rural landscapes (Praticò et al., 2023).

3.3. Spatial patterns of olive oil mills and olive groves

The KDE analysis shows that the major density of olive oil mills is in Trapani, Agrigento, and Ragusa provinces, where the maximum value of 0.1 plants per square kilometer was registered (Fig. 5).

Following the ISA approach, as a distance threshold for Moran's *I* and G_i^* indices, we choose the first peak of the $z_{I-\text{score}}$ graph, representing the appropriate scale for further analyses (Grekousis, 2020). In the case of Moran's *I*, we applied 30 incremental distance bands with an Euclidean bandwidth of 2000 m from a beginning distance of 10,000 m up to 68,000 m (Fig. 6). The first peak corresponded to the maximum peak and was obtained at 36,000 m. Therefore, we calculated Moran's *I*,

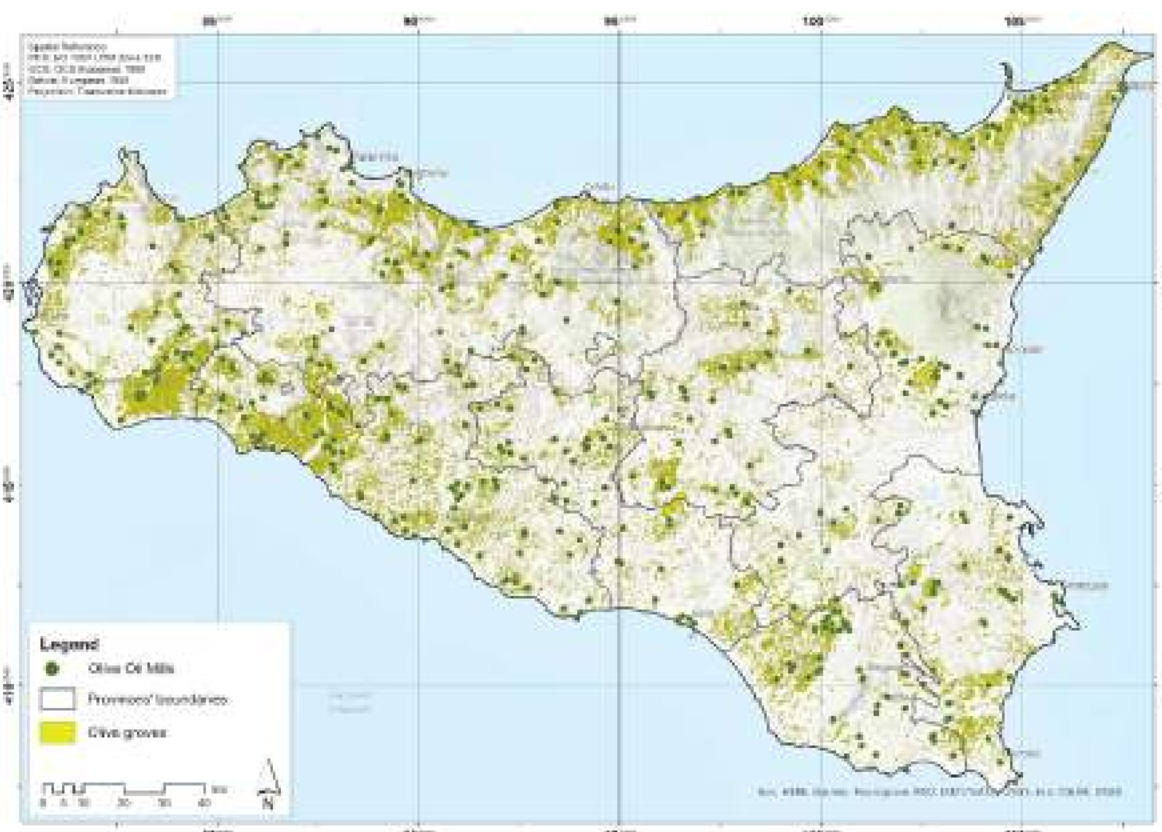

Fig. 3. Map of the 603 surveyed olive oil mills (OOM) and geographical distribution of olive groves in Sicily. In light grey are the boundaries of the nine Sicilian provinces.

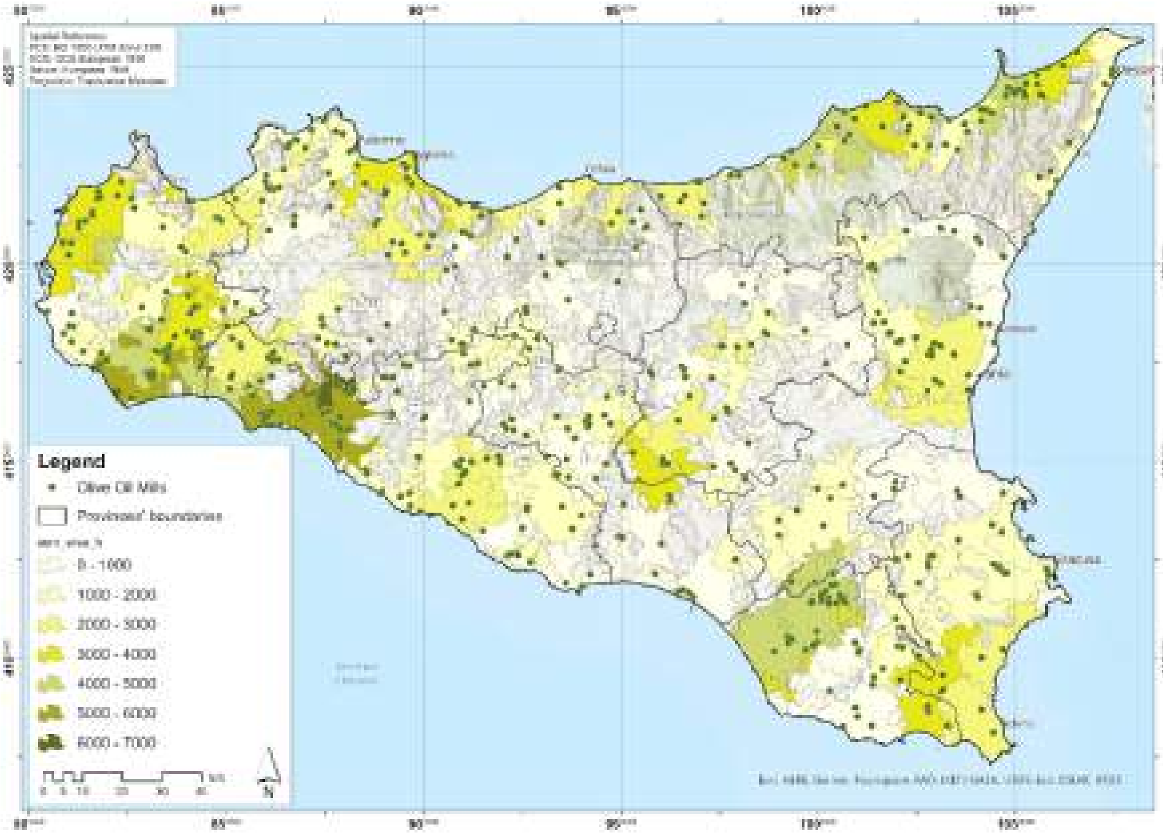

Fig. 4. Map of the service areas obtained for the 603 surveyed olive oil mills and classified according to the surface of olive groves falling in each of them. In light grey are the boundaries of the nine Sicilian provinces.

index applying a fixed band of 36,000 m, obtaining an I value 0.322 ($z_{I-\text{score}} = 47.306$ and p-value <0.01). These results confirm that the distribution of Sicilian olive oil mills, analyzed according to their elevation, has a significant spatial clustering.

Similarly, also in the case of the in the case of G_i^* index, we applied 30 incremental distance bands with a Euclidean bandwidth of 2000 m from a beginning distance of 10,000 m up to 68,000 m (Fig. 7). As in the previous case, the first peak corresponded to the maximum peak and was obtained at 18,000 m ($z_{I-\text{score}} = 45.992$ and p-value <0.01).

Therefore, we calculated G_i^* index, applying a fixed band of 18,000 m. We rendered the G_i^* index results in the classic map organized with the three confidence level classes (99%, 95%, and 90%) for hot-spot (in red) and cold-spot (in blue) polygons and another class (in light grey) for the rest of polygons showing non-significant results (Fig. 8).

The LISA approach has proven to be very interesting because it focuses on the spatial relationships between each observation and its surroundings rather than providing a single summary of these relationships on the map (Rey et al., 2023), allowing for a more detailed understanding of the spatial data structure of the analyzed olive oil mills. As also demonstrated by other scholars, these indicators are reliable in analyzing the spatial patterns of activities or phenomena at different spatial scales (Lanorte et al., 2013).

In combination, service area identification and LISA can provide valuable insights into a given dataset's spatial distribution and relationships. For instance, they can help identify areas of high demand within a service area or detect patterns in the distribution of service facilities.

Our research demonstrated the reliability of the LISA indicators (in this study, Moran's I and Getis-Ord G_i^* indices) in analyzing and detecting spatial patterns of critical agroforestry facilities (i.e., clusterization phenomena), and as in the case of the biomass/bioenergy sector (Van Holsbeeck and Srivastava, 2020). Moran's I was 0.32 with a z-score of 47.31 (p-value <0.01) applied to the olive oil mills using their elevation as the attribute value, clearly detecting a strong clusterization. Similarly, the map of the Getis-Ord G_i^* index clearly shows three hot-spot areas (Fig. 8) of the obtained service areas, the most important one located between the provinces of Trapani and Agrigento, the second falling in the Messina province, and the third in Ragusa and partially in the Catania province. This analysis confirms what emerged with the KDE, also, in this case, as for Moran's I, with a high value of z-score (i.e., 45.99) with a very small p-value (<0.01).

3.4. Economic analysis of olive oil mills' profitability

The outcomes of spatial analysis show that most Sicilian olive groves fall within the service areas (85.81%). Only in two provinces, Caltanissetta and Palermo, this percentage is lower than 80% (Table S3 Supplemental material). These same data highlight a significant difference in the average amount of olives processed per mill among the various provinces. Also, in this case, the highest values are found in the western part of Sicily, while the lowest values concern the province of Messina and the central area of the island.

Table S2 in the supplementary material provides specific information on the service areas, which are preliminary for the economic analysis of the two extreme and opposite clusters (blue and red), aligned with a confidence level greater than 99%, particularly the cold-spot and hot-spot areas. The intermediate clusters, those with lower confidence levels (95%, 90%), were omitted from the economic analysis as they were considered to have an insignificant impact.

As regards the economic analysis at the regional level, the results report that the average revenue for a single milling operation in Sicily stands at just above 55,000 euros per registered mill. Analyzing the data at the provincial level reveals (Table S3 supplemental material) a significant difference in average values per mill, both in terms of revenue

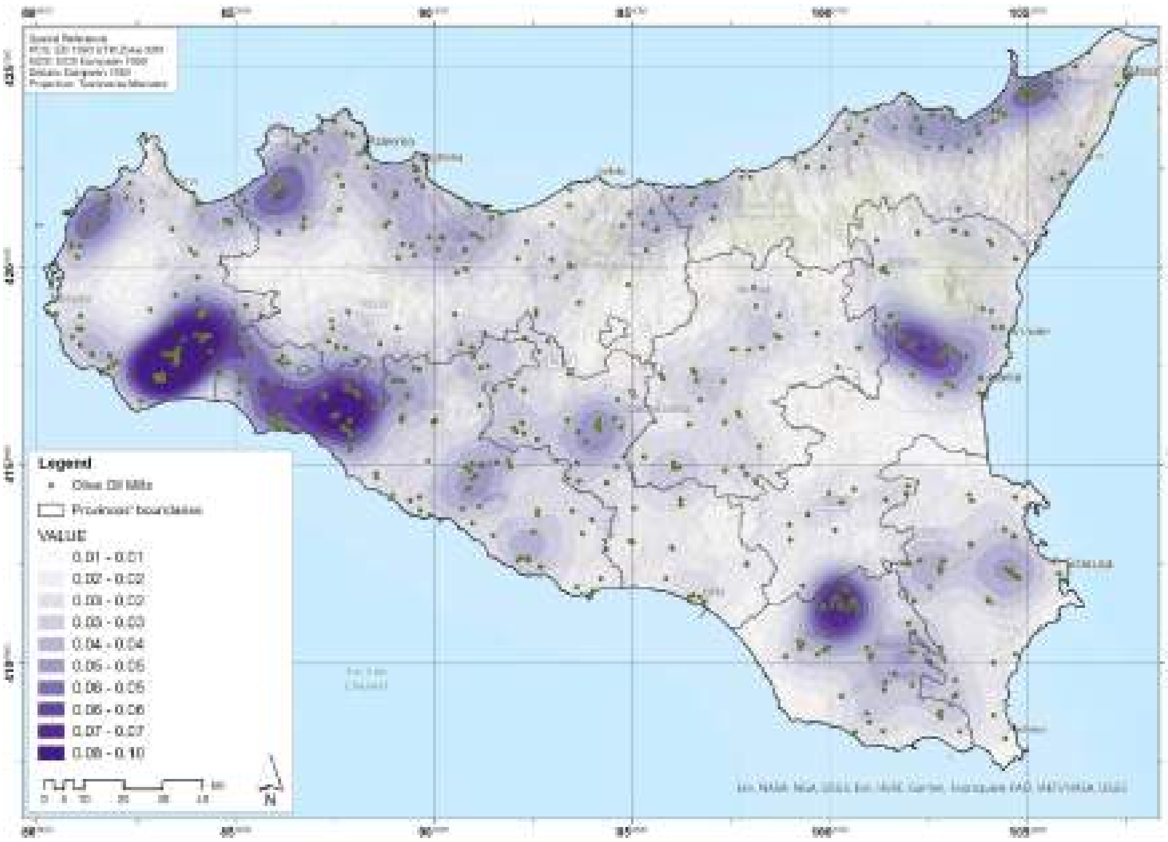

Fig. 5. Kernel Density Estimation (KDE) of the surveyed olive oil mills expressed as number per square kilometer. In light grey are the boundaries of the nine Sicilian provinces.

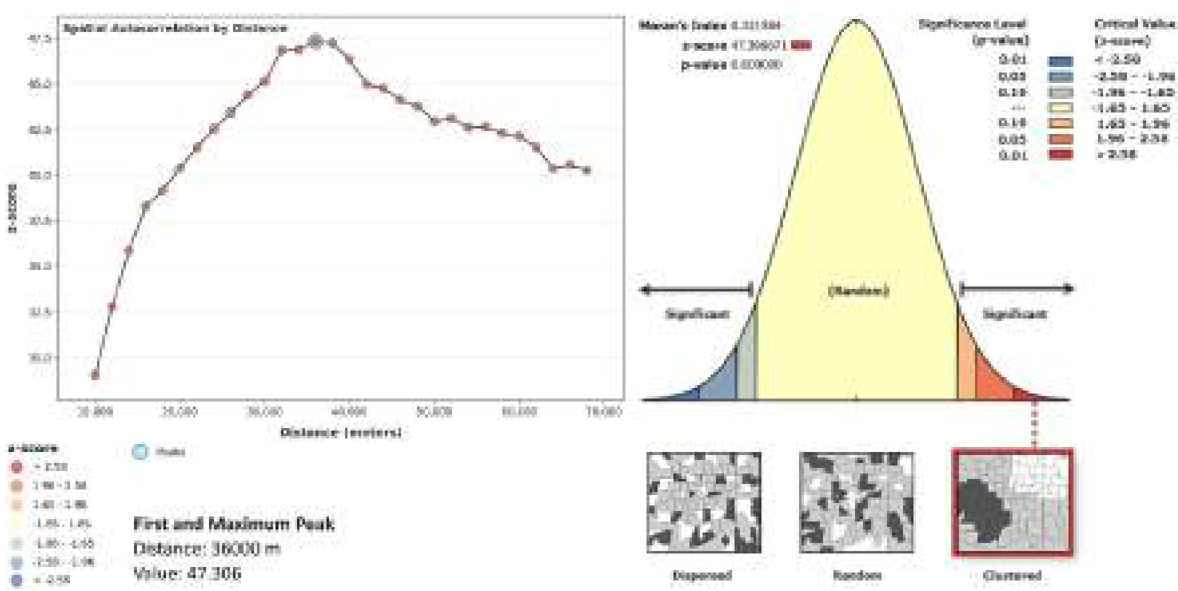

Fig. 6. On the left, the graph representing the incremental spatial autocorrelation (ISA) based on Moran's *I* index applied to the olive oil mills using their elevation as attribute value, applying 30 incremental distance bands with a Euclidean bandwidth of 2000 m from a beginning distance of 10,000 m. Values are represented as z_{score}. On the right, a graph depicting the normal distribution highlighting the significant statistical intervals of p-values and z-scores (corresponding to the three confidence level classes of 99%, 95%, and 90%) and reporting the obtained global Moran's I index and z-score (with a p-value <0.01).

and profit, between the western provinces (especially Trapani and Agrigento) and the central-eastern ones.

Suppose we consider the average profit margin per mill. In that case, the gap is extremely wide when considering the value slightly lower 41,000 euros calculated in Agrigento compared to the approximately 7700 euros in Messina, despite having a nearly identical price for the milling operation (165.00 euros/ton) and average milling cost per ton only slightly lower. This significant difference is attributed almost exclusively to the olive grove area available to the mills located in the Trapani and Agrigento areas, given that the milling price in western

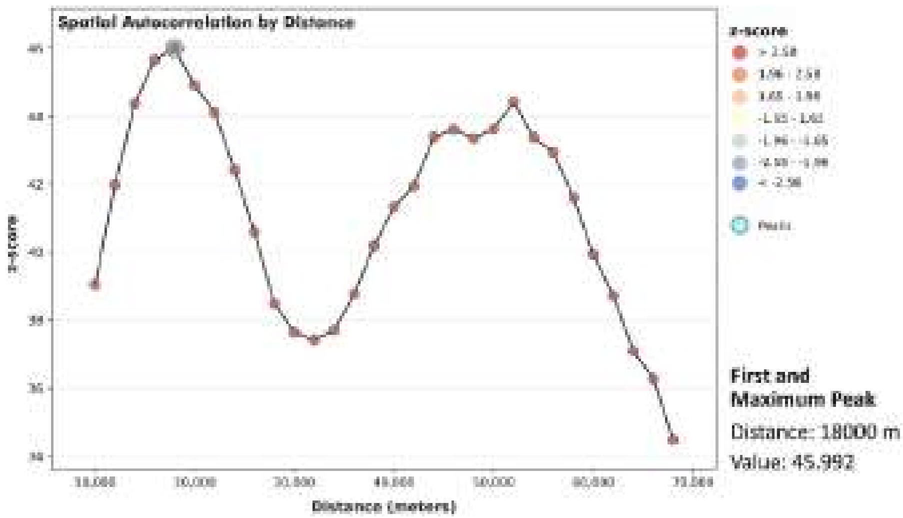

Fig. 7. Incremental spatial autocorrelation (ISA) based on Moran's I index applied to the service areas of olive oil mills using the surface of olive grove falling in each of them as attribute value, applying 30 incremental distance bands with an Euclidean bandwidth of 2000 m from a beginning distance of 10,000 m. Values are represented as z_{score}.

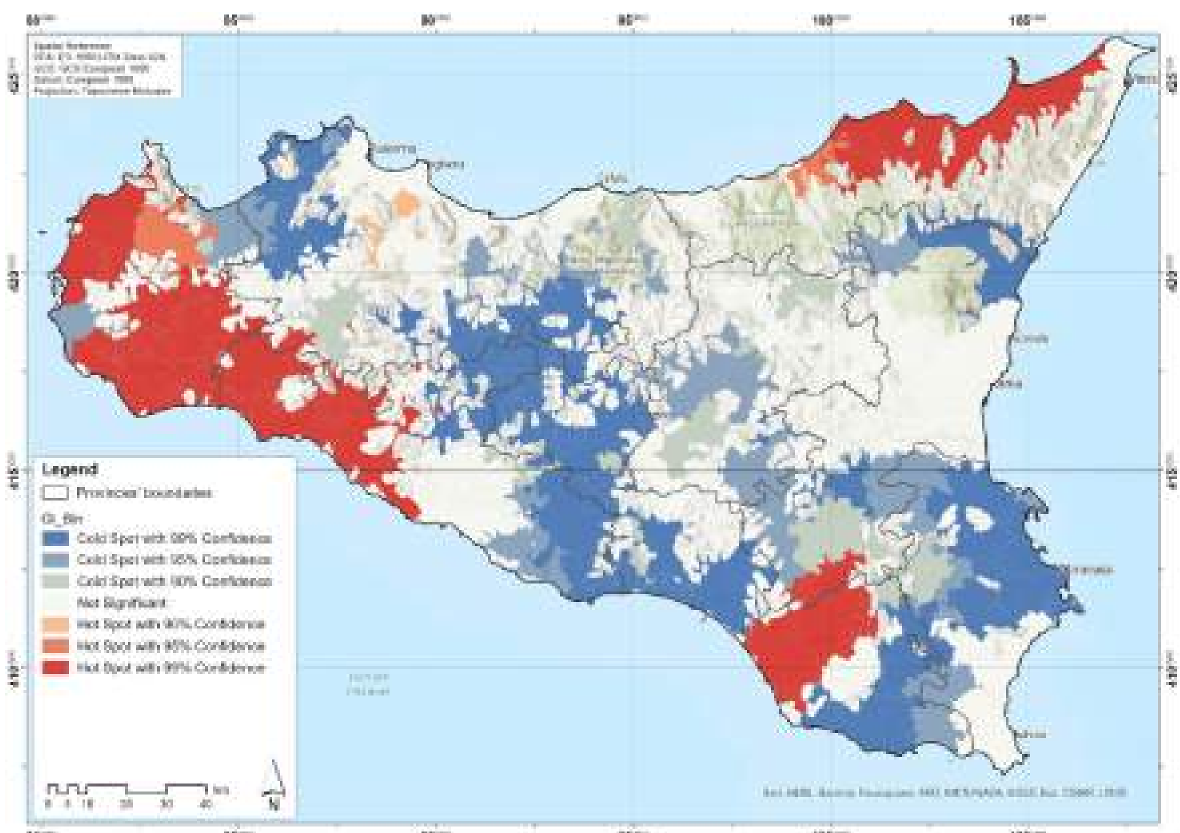

Fig. 8. Getis-Ord G_i^* index of the obtained service areas and mapped according to cold-spot and hot-spot areas and the three confidence level classes (99%, 95%, and 90%). The light grey class indicates service areas that showed no significant results. In light grey are the boundaries of the nine Sicilian provinces.

Sicily is generally lower than in the eastern part of the island.

Refocusing the analysis on the two reference clusters (hot spot and cold spot), as anticipated, the overall production data tends to favor the hot spot areas in terms of the quantities of olives processed. However, the milling service prices appear to be higher in areas with fewer mills or olive cultivation areas, namely the cold spot cluster areas. Nevertheless, the total outputs are higher for mills in hot spot areas, with an average revenue value of just above 68 thousand euros. The minimum values for both clusters were identified in the eastern areas of the island. In contrast, the maximum values were concentrated between the Trapani and Agrigento areas in the western part of Sicily. Furthermore, as indicated in Table 5, a significant disparity arises in the estimated average profits per mill. Specifically, the average earnings in hot spot areas, totaling around 29,300 euros, are nearly double those in cold spot areas (17,700 euros). Ultimately, the average margin identified in both the hot spot and cold spot clusters is only marginally higher than the

Table 4
Olive oil production and average net farm value in Hot e Cold Spot cluster.

		Olive Oil Mills	Olive surface within Serviced Areas	Average Olive surface per Mill
		n.	ha	ha
Minimum Values	Hot Spot Olive oil mills	43	21,934.49	510.10
	Cold Spot Olive oil mills	17	738.79	43.46
Average Values	Hot Spot Olive oil mills	49.75	17,433.10	350.41
	Cold Spot Olive oil mills	21.29	3991.06	187.50
Maximum Values	Hot Spot Olive oil mills	61	18,689.92	306.39
	Cold Spot Olive oil mills	22	5514.25	250.65
Sicily	**Hot Spot Olive oil mills**	***204***	***71,619.13***	***351.07***
	Cold Spot Olive oil mills	***151***	***28,114.89***	***186.19***

regional average values, standing at approximately 33,000 euros of profit in the hot spot areas compared to just under 20,000 euros in the cold spot areas.

Relevant outcomes emerge from the economic analysis applied to the two analyzed clusters (hot and cold spots). The analyses have shown that as the concentration of olive groves and mills increases, a growing profit delta (δ) is realized. This delta represents the difference between revenues and total costs incurred by the mill owner. Therefore, it can be asserted that the profit of individual mills increases with the growing confidence level of their respective service areas, calculated using the Getis-Ord G_i^* index.

Within the Italian olive oil production chain, among the revenue streams that contribute to defining the overall income of olive mills, the one derived from olive milling is seldom the primary source (Stillitano et al., 2017). The revenues that significantly impact the formation of total income are, understandably, those resulting from the sale of bulk oil and packaged oil. In fact, according to investigations conducted by ISMEA (2015), revenues from the olive milling service account for approximately 15% of the total income.

Furthermore, there is a progressive decrease in the percentage share of income obtained through olive milling as the size of the business increases. It has been reported to be approximately 33% of the total in mills processing less than 500 tons of olives per year, gradually decreasing to values below 10% in larger-scale production entities (ISMEA, 2015).

Therefore, in Sicily, considering that primary olive processing facilities are generally of medium or small size (Valenti et al., 2017), the revenues derived from milling assume a considerable significance. However, this study represents the first attempt to evaluate the partial profitability of olive mills, providing some economic assessments on milling operations in relation to the density of plantations located in areas close to the mills.

The novelty of this study lies in its ability to establish a connection between the olive mill and the territory encompassed by olive-growing areas served by the mill. Consequently, it facilitates establishing a relationship between potentially suitable olives for milling and the mills themselves. This approach allows for determining the potential profit margin for mill operators through a spatial analysis that considers the actual density of cultivated surfaces and primary processing centers. This distinguishes it from conventional economic analyses, which typically focus on politically homogeneous areas like regions, provinces, municipalities, or PDO/PGI-designated areas (Di Vita et al., 2015; Lanfranchi et al., 2016).

4. Conclusions and implications

Integrating LISA indicators alongside service area analysis has proven instrumental in gaining valuable insights into the dynamics of olive oil mills and the distribution of olive groves. LISA has demonstrated its efficacy in pinpointing the localization of facilities, aiding in identifying areas with concentrated or sparse facilities. For example, it has provided a nuanced understanding of the spatial arrangement of olive oil mills concerning factors such as proximity to olive groves, transportation networks, and, consequently, market demand.

Using spatial analyses through GIS software functionalities enhances the precision of technical and economic outcomes in agricultural sectors. Specifically, analyzing olive cultivation areas in Sicily within designated catchments enables a deeper comprehension of the potential growth possibilities in the primary olive processing sector. This extends to the potential increase in the number of facilities and the achievable turnover. Applying service area analysis can help determine the geographical area that an olive oil mill serves, i.e., their accessibility, and this is crucial for planning and decision-making. The GIS methodology employed allowed the analysis to be refined to focus on homogeneous clusters, ensuring that the economic assessment targeted realities with a confidence level above 99%. This innovative approach created a direct connection between the olive mills and the surrounding territory, defined by the olive-growing areas they serve.

Through detailed spatial analysis, which takes into account the actual density of cultivated surfaces and the strategic placement of primary processing centers, this method enabled the determination of potential profit margins for mill operators.

It also distinguishes itself from conventional economic analyses focusing primarily on politically homogeneous regions. Companies have to face numerous challenges in pursuing increased profitability and competitive advantages. The analysis of costs associated with Olive Mill Wastewater management is pivotal for operators who must contend with disposal expenses.

Table 5
Average Net profit margin of milling service in hot spot and cold spot cluster.

		Olives Pressed per Mill	Average Cost	Total Costs	Milling Service Price	Total Revenues	Profit Margin per Mill
		t	Euro/t	Euro	Euro/t	Euro	Euro
Minimum Values	Hot Spot Olive oil mills	119.26	91.82	10,950.91	165.00	19,678.23	8727.32
	Cold Spot Olive oil mills	59.35	106.95	6346.90	200.00	11,869.30	5522.40
Average Values	Hot Spot Olive oil mills	390.19	98.69	38,509.20	173.75	67,794.83	29,285.63
	Cold Spot Olive oil mills	208.78	98.69	20,605.49	183.57	38,326.17	17,720.68
Maximum Values	Hot Spot Olive oil mills	622.49	86.58	53,893.13	165.00	102,710.24	48,817.11
	Cold Spot Olive oil mills	509.23	86.58	44,087.91	165.00	84,023.34	39,935.42
Sicily	**Hot Spot Olive oil mills**	***438.84***	***98.66***	**43,296.98**	***173.75***	**76,248.92**	**32,951.94**
	Cold Spot Olive oil mills	***232.74***	***98.66***	**22,962.45**	***183.57***	**42,724.26**	**19,761.81**

In essence, the multifaceted application of spatial tools enriches our understanding of the olive oil industry's dynamics. It empowers stakeholders with a more strategic and nuanced approach toward planning, expansion, and decision-making within this sector.

From such insights, public policymakers and businesses engaged in this private production domain can glean valuable indications concerning the number of potentially sustainable olive oil mills within a given territory. The outcomes of this study could inevitably shape decisions regarding industry policies, carrying significant implications for the affected regions, both in terms of economic and environmental sustainability and employment. In other words, our proposed methodology could represent an effective tool in planning the olive sector at regional and national levels. Furthermore, the evidence emerging from our study opens up interesting perspectives for innovation in olive oil mill business models. The in-depth understanding of spatial, economic, and environmental dynamics paves the way for exploring more sustainable and circular practices within the olive oil sector. Thoughtful resource management, including the proper disposal of by-products such as olive mill wastewater, could play a pivotal role in shaping resilient and sustainability-oriented business strategies.

Finally, the results we obtained can be further analyzed through additional studies and empirical evidence to verify the reproducibility of the model in other Mediterranean areas, establishing within which range the results align with those obtained by us. Nevertheless, the GIS-based approach has proven reliable for broad-area analysis as it employs a territorial approach for homogeneous production areas.

CRediT authorship contribution statement

Giuseppe Modica: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Conceptualization. **Angelo Pulvirenti:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation. **Daniela Spina:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Salvatore Bracco:** Validation, Supervision. **Mario D'Amico:** Supervision, Project administration, Funding acquisition, Conceptualization. **Giuseppe Di Vita:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2024.100207.

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