Journal of Infrastructure, Policy and Development 2025, 9(2), 10185.
https://doi.org/10.24294/jipd10185

Article

Land-use evolution in an island urban setting: A three-decade analysis of Machico, Madeira (1990–2018)

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CITATION

Lousada S, Gómez JMN, Fernandes M, et al. (2025). Land-use evolution in an island urban setting: A three-decade analysis of Machico, Madeira (1990–2018). Journal of Infrastructure, Policy and Development. 9(2): 10185. https://doi.org/10.24294/jipd10185

ARTICLE INFO

Received: 8 November 2024
Accepted: 9 December 2024
Available online: 18 February 2025

Abstract: The sustainable development of Madeira Island necessitates the implementation of more precise and targeted planning strategies to address its regional challenges. Given the urgency of this issue within the context of sustainability, planning approaches must be grounded in and reinforced by a comprehensive array of thematic studies to fully grasp the complexities involved. This research leverages Geographic Information Systems (GIS) to analyze land use and occupancy patterns and their evolution within the municipality of Machico on Madeira Island. The study provides a nuanced perspective on the urban structure's stagnation in the region, while concurrently highlighting the dynamic shifts in agricultural practices. Furthermore, it elucidates the transformation of predominant native vegetation within the municipality from 1990 to 2018. Notably, the research underscores the alarming decline in native vegetation due to anthropogenic activities, emphasizing the need for more rigorous monitoring by regional authorities to safeguard and preserve these valuable landscapes, habitats, and ecosystems.

Keywords: CORINE land cover (CLC); geographic information systems (GIS); land use and occupancy; territorial management; urban planning

1. Introduction

The growing demand for detailed information on land cover, its uses and dynamic trends has driven the creation of numerous global soil datasets. These datasets facilitate the acquisition of land-cover data gathered through Earth observation via satellites (Lousada et al., 2022; Neumann et al., 2007). Several initiatives and programs, both at national and international levels, played a pivotal role in propelling this advancement. It's worth noting that various global and continental scale data sets on land-cover data derived from satellite Earth observation have stimulated and generated diverse mapping patterns (Baig et al., 2022; Bildirici et al., 2022; Boston et al., 2023; Fagua et al., 2023; Loures et al., 2019; Lousada et al., 2021; Lousada et al., 2022; Naranjo et al., 2020; Vulevic et al., 2021; Zhang et al., 2023).

In brief, land use cover maps are immensely valuable data owing to their widespread applicability and interdisciplinary nature. These maps provide essential information on the biophysics cover of the Earth's surface, playing a crucial role in researching and modeling territorial dynamics (Chen et al., 2023; Jiang et al., 2023).

Additionally, maps depicting land use and land cover play a vital role in maintaining equilibrium among economic, social and environmental considerations within a specific region (Hasan et al., 2023; Shimizu et al., 2023). Facilitating the examination of notable alterations in landscapes, investigating cycles, and discerning trends is made possible. In this framework, the Land Monitoring Service's Initial Operations (GIO-Land), a component of the European Copernicus Program, is an operational project with the objective of furnishing diverse compilations of land-cover information. This encompasses the utilization of regularly refreshed satellite imagery at a six-year cadence, spanning almost every European nation, as emphasized by several authors (Hao et al., 2023; Wang et al., 2023). Moreover, users can access various data sources through geographic information systems (GIS), enabling the monitoring of alterations in terms of land. These systems facilitate detailed analyses of land cover and identify changes over time (Melchiorri et al., 2018; Orusa et al., 2023b; Puniach et al., 2018). Urbanization, a transformative process profoundly influencing the economic and social advancement of developing nations (Yaakub et al., 2022), highlights the worldwide challenge stemming from the unresolved clash between human-made systems and environmental elements (Chang et al., 2023). The necessity for instruments supporting policymaking focused on sustainable planning arises across different levels of governance. In this scenario, the swift progress of GIS in recent decades has provided researchers with powerful resources for spatial analyses and modeling (Orusa et al., 2023b, 2023a). Furthermore, the system proficiently tracks variations in human activity as well as the urban ecological state (Geng et al., 2023; Ma et al., 2023).

Continuing from the preceding section, the Urban Atlas (UA) encompasses more intricate data, specifically classifying high-resolution satellite images (SPOT 2.5 m, ALOS 2.5 m; RapidEye 5 m). This categorization enables the differentiation of major coverage categories, with the smallest mapping unit established at 0.25 hectares and an estimated precision of 5 m. The UA aids in creating land-cover maps for 305 major European cities with populations surpassing 100,000 residents. Nonetheless, it is important to highlight that the UA includes merely 20 land-cover classifications, a significantly reduced quantity when compared to CORINE Land Cover (CLC or 'Corine') (Lousada et al., 2022; Naranjo et al., 2020). Collectively, terrestrial systems involve every procedure and undertaking linked to human land utilization, integrating technological and organizational progress, categorizations, land gains, and unintended cultural and environmental elements arising from social activities (Geng et al., 2023; Li and Yang, 2023; Xing et al., 2023).

Consequently, a concerted effort was undertaken across Europe to systematically monitor changes in land cover. This endeavor culminated in the establishment of the CLC inventory, executed through the utilization of satellite imagery. The European Environment Agency (EEA) has overseen the compilation of this collaborative database, which finds application in numerous organizations across Europe. The initiative is co-financed by both the European Commission and member states (Lousada et al., 2022; Naranjo et al., 2020). In terms of map attributes, the heterogeneity of land cover arises from the implementation of diverse techniques and underlying patterns. This encompasses varied layouts, syntactic considerations, schematic heterogeneity, and semantic factors (Rukhovich et al., 2023; Zhao et al., 2023). Hence, as these alterations stem from a unique strategy employed in the map development process, distinguishing land use becomes challenging when utilizing alternative mapping methodologies (Meier and Mauser, 2023; Orusa et al., 2023a). Established in 1985, the Environment Coordination CLC is the collaborative outcome of efforts from member nations of the European Community (EC). Its primary objective is to systematically gather and interpret geospatial data in a more precise and coordinated manner, driven by the following goals: (a) collecting and coordinating interdisciplinary data concerning the environmental state; (b) placing a primary focus on areas deemed as priorities within each EU state; (c) managing and organizing this data on both international and local scales; and (d) ensuring compatibility of all collected data (Janczewska et al., 2023; Lousada et al., 2022; Naranjo Gómez et al., 2020). As such, this database is a key resource for carrying out more intricate geographical analyses, especially when conducting studies that involve multiple categories of land use. There are three levels in the hierarchical structure of CLC. The first one includes five main categories, namely artificial areas, agricultural areas, forest and semi-natural areas, wetlands, and water bodies. What is more, there are fifteen components in the second level and forty-four elements in the following level. Nevertheless, it’s important to add that the main goal of the third-level components is to define the methodological scope for the aforementioned three classes (Gentilucci et al., 2023; Lousada et al., 2022; Naranjo et al., 2020; Siewert and Kroszczynski, 2023). A cooperative project across Europe has established a suitable set of standardized baselines for monitoring changes in terms of land cover. As a result, this information plays a key role in the integration process of the EEA’s information system, which contributes to a significant increase regarding the availability of information related with large land-cover variations (Bakkestuen et al., 2023; Tang et al., 2023). Notwithstanding the fact that CLC typically relies on satellite images to collect data, several countries such Germany, Austria, Finland, Ireland, Iceland, Norway, the United Kingdom, Sweden and Switzerland have been resorting to a different methodology, mainly from 2006 onwards. In fact, these nations have been gathering data mostly through the application of generalization techniques on national maps with high levels of detail (Parente et al., 2023; Văculișteanu et al., 2023; Wang et al., 2023). On the contrary, other European countries, such as Slovakia, Hungary, and Poland, rely on the CLC in order to obtain highly-detailed data, utilizing scale 1:50,000 maps. These maps have a minimum map unit (MMU) of 4 and a caption that considers the geographical specificities of the territory being analyzed (García-Ayllón and Martínez, 2023; Janczewska et al., 2023). Additionally, similar methodologies were used to estimate information predating the 1990 CLC data (Siewert and Kroszczynski, 2023). Yet, it is important to remember that countries like Germany and Ireland have modified their approaches when it comes to obtaining CORINE land-use maps, therefore finding alternatives to the photo interpretation methodology. On the other hand, the government of the Netherlands demanded the independent generation of CLC data (Faria de Deus et al., 2023; Papadopoulou et al., 2023; Siewert and Kroszczynski, 2023). Nevertheless, the maps of land-use obtained from CORINE are still perceived as an important tool when analyzing soil applications. The INSPIRE Directive 2007-2-EC (EUR-Lex—32007L0002—EN—EUR-Lex, sem data) acknowledges that CLC provides a higher level of standardization, in comparison to other European datasets. Since CLC is based on a general land-cover classification—a classification that is widely used throughout Europe – these advantages in terms of standardization encompasses both aspects from the semantic and technical domains (Tefera et al., 2023). As a matter of fact, alternative information sources might end up being beneficial in terms of compatibility and comparability. It’s however critical to understand that these sources are separate datasets (Lousada et al., 2022). Indeed, different methodologies can sometimes lead to a significantly high level of heterogeneity. This mainly occurs due to discrepancies in layouts, syntactic errors, schematic differences, and semantic considerations (Cao et al., 2023). Thus, it might become challenging to properly analyze alterations in land use given that some of these alterations may derive from the aforementioned discrepancies (Lousada et al., 2022). Even though land-use changes are dynamic across Europe, there isn’t a vast range of literature focusing on the temporal patterns of these phenomenon. In this regard, multiple studies have recently studied this topic. Their results have highlighted notable modifications in the continent’s land use (Chen et al., 2023; Faria de Deus et al., 2023; Parente et al., 2023; Rai et al., 2023). Among the most prominent land uses in European nations, agriculture stands out due to its wide range of regional specificities and well-defined dynamics (Liu et al., 2023). More than 35% of the land area in Europe is used for agricultural purposes, which is around ten times more than the area occupied by metropolitan areas (Statistics| FAO | Food and Agriculture Organization of the United Nations, sem data; Synthesis—European Environment Agency, sem data).

This type of challenges tend to be particularly problematic to islands since these coastal territories are usually more susceptible to change due to their isolation from mainland and their limitations in terms of area (Riera-Spiegelhalder et al., 2023), in addition to being highly affected by the presence of water (Commey et al., 2023; Faria de Deus et al., 2023). In this scenario, territorial planning emerges as an important instrument for safeguarding prosperity in these territories, as it directly addresses problems such as social inequalities and geographical imbalances, while boosting economic growth (Lousada et al., 2022).

In modern society, regional planning must inherently consider the future and be systematically developed to address public needs, avoiding arbitrary and uncontrolled progressions driven solely by political or individual perspectives on investments. Consequently, sustainable development and growth unquestionably stand out as the primary concerns and objectives for territories (Chen et al., 2023; Hu et al., 2023; Lukas et al., 2023).

This study, whose focus is the Machico municipality on Madeira Island, Portugal, has as its goal to analyze changes in land use within the peripheral or "ultraperipheral" and insular areas, namely islands. By investigating obstacles and opportunities for sustainable progress, this research aims to comprehend the main territorial dynamics and trends in these areas and what kind of consequences these might ultimately bring. The main aim is to identify the alterations in the use of land that occurred in the Machico municipality, from 1990 to 2018. This study holds significance in contributing to science by facilitating the collection of substantial data linked to land-use changes and offering an overview of their evolution in the Machico municipality over the past three decades. The gathered data is crucial for minimizing the increasingly intolerable flood events that pose serious risks of human loss and economic damage, as previously witnessed in the municipality along its primary watercourse.

During the initial decades of the 21st century, the Machico municipality witnessed significant territorial growth, particularly along its primary watercourse. This development resulted in evident land-use changes, notably impacting hydrological management, especially during episodes of extreme rainfall. The alterations over the years have led to a notable increase in impermeable surfaces, consequently elevating surface runoff and contributing to flooding. The water level is influenced not only by the water source, but also by the shape and types of existing vegetation. Factors such as underground infiltration and water leakage, influenced by soil characteristics, are associated with flood occurrences. Flawed urban planning exacerbates floods, with inappropriate land uses and infrastructure in stream beds, like levees, embankments, or dams.

The study of land-use changes in Machico municipality presents a particular character, marked by unique characteristics such as its location in a deep valley with steep slopes, limited warning time during flood disasters, and a shift in vegetation contributing to increased surface runoff. Proper land-use management, however, can alleviate geomorphological and hydrological challenges exacerbated by anthropic pressure. To mitigate flood impacts, impactful measures are needed to address the issue comprehensively rather than merely redirecting it from land management to hydraulic management.

In conclusion, the spatial patterns observed in the study prompt discussions and the ideological bases for future regional planning and management strategies and policies throughout the Machico municipality.

2. Methodology

2.1. Study area

Positioned in the North Atlantic within the Macaronesia region, the Madeira Archipelago is located between the latitudes 30°01′ and 33°08′ N and the longitudes 15°51′ W and 17°30′ W of Greenwich (Silva et al., 2021). Covering a total area of 796.77 km^2, the archipelago comprises Madeira Island—736.75 km^2; Porto Santo—2.17 km^2; the Desertas Islands—14.23 km^2 and the Selvagens—3.62 km^2 (Lousada et al., 2019; Lousada et al., 2022; Lousada and Castanho, 2022; Lousada and Loures, 2020; Silva et al., 2021).

The municipality of Machico occupies the easternmost extremity of the island, extending from the shores to the northern mountains and concluding at Ponta de São Lourenço. Covering a total expanse of 68.31 km^2, Machico's latitude and longitude coordinates are: 32°42′0″ N, 16°46′0.01″ W. It shares boundaries with the municipality of Santa Cruz to the southwest, the municipality of Funchal to the west, contiguous to a narrow strip north of the municipality of Santa Cruz, and the municipality of Santana to the northwest. Machico comprises five parishes: Santo António da Serra, Porto da Cruz, Caniçal, Machico, and Água de Pena (Alves et al., 2022; Lousada, 2023; Silva et al., 2021), as shown in **Figure 1**.

Figure 1. Municipality of Machico (source: (Alves et al., 2022)).

The municipality of Machico has a highly heterogeneous relief, attributed to the presence of weathering-resistant flows that give rise to some high-altitude peaks. These contrast with deep and narrow valleys with a V-shaped cross-sectional profile, along which various-sized rolled blocks can be observed, attesting to their high carrying capacity during torrential regimes. In the Machico Valley, highly weathered flows predominate, interspersed with layers of pyroclastic material that have shaped it into a U-shape. Due to their permeability, they facilitate the underground water capture in the municipality, where the aquifer has good productivity but in localized areas. With a coastal area bathed by the Atlantic Ocean to the north, east, and south, its morphology is characterized by several hills and mountain ranges, including Castanho (589 m), Pedreiro (792 m), Pico da Coroa (738 m), and Penha de Águia (590 m). The coastal slopes are steep, but erosion effects have resulted in black sand beaches. In Caniçal and Porto da Cruz, there are beaches with natural volcanic sand (Geologia, 2024; Machico, 2023). Below are some images of the municipality of Machico and its five parishes, Santo António da Serra, Porto da Cruz, Caniçal, Machico, and Água de Pena, as shown in **Figure 2**.

Figure 2. Views of the parishes that form the municipality of Machico.

Regarding the climate, the municipality of Machico experiences a short, warm, arid summer with almost cloudless skies, and a long, mild, dry winter with partially overcast skies. Throughout the year, strong winds are common. Generally, the temperature varies from 15 °C to 26 °C, rarely dropping below 12 °C or exceeding 28 °C (*Clima, condições meteorológicas e temperatura média por mês de Machico (Portugal) - Weather Spark*, sem data).

Regarding the population, in 2021, according to the 2021 Census data, the resident population in the Autonomous Region of Madeira was 250,744 inhabitants. The municipality of Machico accounts for approximately 8.2% of the population of Madeira Island, with 19,593 inhabitants, and the parish of Machico is the most populous with 9,828 inhabitants. So, the municipality of Machico shows a trend of population reduction, from 22,126 inhabitants in 1981 to 21,747 in 2001, and to 19,593 in 2021 (*Portal do INE*, sem data). Machico ranks fourth among Madeira's municipalities both in terms of population and population density, standing at 320.1 inhabitants per square kilometer (Pereira, 2023).

2.2. Applied methodology

The data employed contained two information layers, both of which are public and open, making it feasible to replicate this study in a different workspace. The focus of the analysis is the municipality of Machico on Madeira Island.

Initially, information on land use was collected. The EEA offers a geodatabase utilizing polygonal graphical features, illustrating land use across the European Union for the years 1990, 2000, 2006, 2012, and 2018 through the CLC project (*CORINE Land Cover — European Environment Agency*, sem data). Concerning the utilization of remote sensing data, information was provided through shapefiles. These files were administered using ArcGIS 10.5, where a project was created, and subsequently, the shapefiles were incorporated as layers, representing vectorial information.

The mapping system employed was the Universal Transverse Mercator (UTM), with a scale of 1:100,000 in the Geodesic Reference System, corresponding to the Madeira 1936 / UTM zone 28N (EPSG:2191) (GmbH (https://www.klokantech.com/), sem data). The Minimal Cartographic Unit (MCU) was set at 25 hectares. The precision achieved has advanced over time, decreasing from over 50 m in 1990 to under 25 m in 2000, 2006, and 2012, and ultimately reaching less than 10 m in 2018. Furthermore, the information of the polygons was hierarchically organized into three layers (**Table 1**).

Table 1. Layers of the CORINE land cover (source: (*CORINE Land Cover — European Environment Agency*, sem data) *).

Level 1	Level 2	Level 3
1. Artificial surfaces	1.1. Urban fabric	1.1.1. Continuous urban fabric
		1.1.2. Discontinuous urban fabric
	1.2. Industrial, commercial and transport	1.2.1. Industrial or commercial units
		1.2.2. Road and rail networks and associated land
		1.2.3. Port areas
		1.2.4. Airports
	1.3. Mine, dump and construction sites	1.3.1. Mineral extraction sites
		1.3.2. Dump sites
		1.3.3. Construction sites
	1.4. Artificial, non-agricultural vegetated areas	1.4.1. Green urban areas
		1.4.2. Sport and leisure facilities
2. Agricultural areas	2.1. Arable land	2.1.1. Non-irrigated arable land
		2.1.2. Permanently irrigated land
		2.1.3. Rice fields
	2.2. Permanent crops	2.2.1. Vineyards
		2.2.2. Fruit trees and berry plantations
		2.2.3. Olive groves
	2.3. Pastures	2.3.1. Pastures
	2.4. Heterogeneous agricultural areas	2.4.1. Annual crops associated with permanent crops
		2.4.2. Complex cultivation
		2.4.3. Land occupied by agriculture
3. Forests and semi-natural areas	3.1. Forests	3.1.1. Broad-leaved forest
		3.1.2. Coniferous forest
		3.1.3. Mixed forest
	3.2. Shrub and/or herbaceous vegetation association	3.2.1. Natural grassland
		3.2.2. Moors and heathland
		3.2.3. Scierophyllous vegetation
		3.2.4. Transitional woodland shrub
	3.3. Open spaces with little or no vegetation	3.3.1. Beaches, dunes, and plains
		3.3.2. Bare rock
		3.3.3. Sparsely vegetated areas
		3.3.4. Burnt areas
		3.3.5. Glaciers and perpetual snow
4.Wetlands	4.1. Inland wetlands	4.1.1. Inland marshes
		4.1.2. Peatbogs
	4.2. Coastal wetlands	4.2.1. Salt marshes
		4.2.2. Saline

		4.2.3. Intertidal flats
5. Water bodies	5.1. Inland waters	5.1.1. Water courses
		5.1.2. Water bodies
	5.2. Marine waters	5.2.1. Coastal lagoons
		5.2.2. Estuaries
		5.2.3. Sea and ocean

* The authors suggest visiting www.eea.europa.eu/publications/COR0-landcover, accessed on 10 January 2024, for comprehensive information regarding the CLC codes.

The second layer of information illustrates the administrative boundaries of the municipality of Machico. The Official Administrative Charter of Portugal (CAOP2020) for the Autonomous Region of Madeira was obtained from the National Geographic Information System of Portugal (SNIG), as illustrated in **Figure 3**.

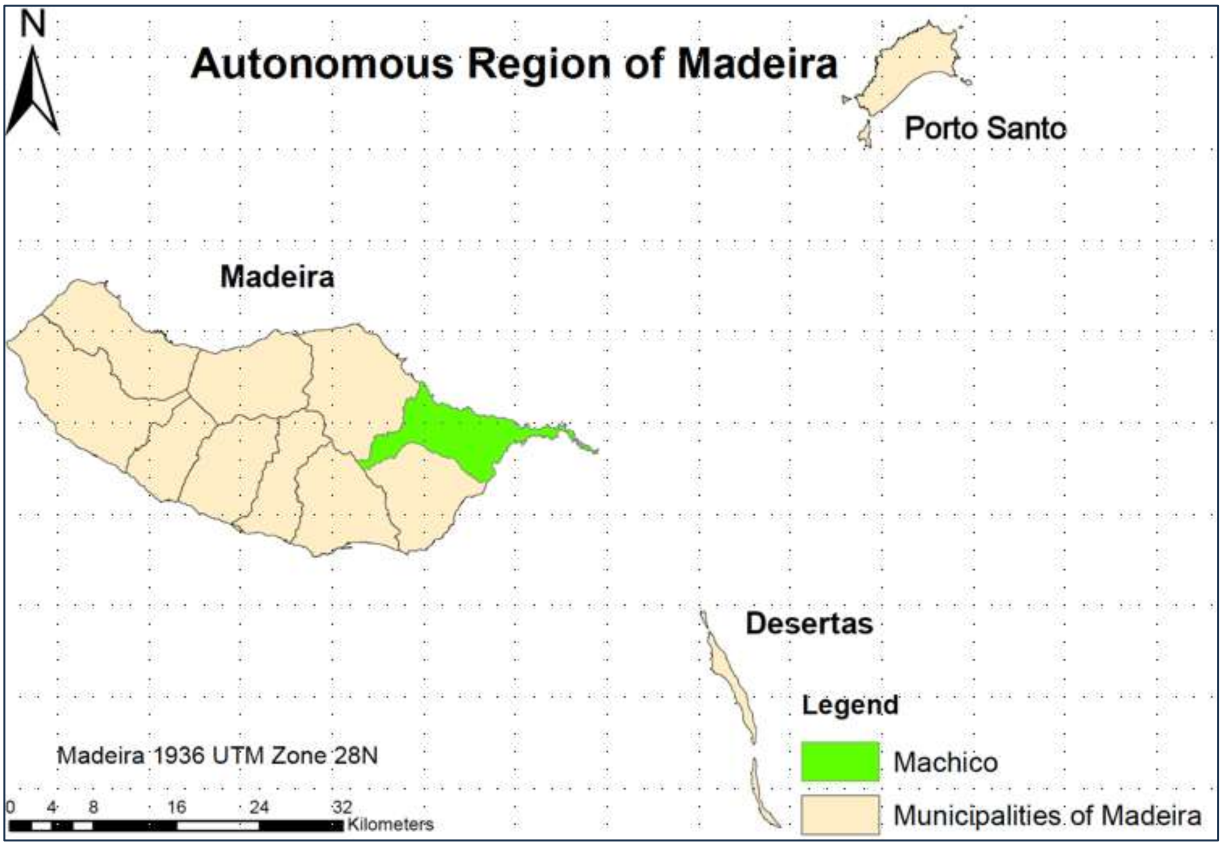

Figure 3. Geographic area under analysis—municipality of Machico.

Subsequently, the ArcGIS 10.5 GIS management software was utilized to process both data layers. Upon the adoption of MapTiler—EPSG:2191 DEPRECATED (GmbH (https://www.klokantech.com/), sem data), as the official coordinate reference system, all information layers underwent conversion to this system through the assignment of a projection in the project (Union, sem data). This approach was employed because the inputs represent the projection of equivalent regions within the territory, forming the basis for EPSG. Consequently, it serves as a standardized system for consistent units throughout Europe, ensuring the uniform representation of analytical and statistical data.

The information about the municipality of Machico was later amalgamated into a unified information layer, and the study's focus was confined to this layer. The boundary of Machico served as the reference layer for the clip tool, applied for each of the considered years (1990, 2000, 2006, 2012, and 2018). Land uses within the municipality were obtained using this methodology, and the geometric measurement and conversion to hectares for each polygon were carried out through the geometry command. As a consequence of that, the total hectares for each polygon, corresponding to the CLC nomenclature's representation of land uses, were determined.

Alphanumeric data from tables for the analyzed years were exported using the export command and imported into a database managed by the Microsoft Access database management program, part of the Microsoft Office 365 suite.

Using Structured Query Language (SQL), selection queries were devised to align with the CLC nomenclature, followed by the addition of another grouping query to the original one. Ultimately, the number of hectares for each type of land use was determined for the years 1990, 2000, 2006, 2012, and 2018.

Thematic maps were generated for each year, considering both numerical and geographic outcomes. This facilitated the identification of areas with the highest land use diversity and those dominated by specific land uses. The data flow outlined in the preceding paragraphs is depicted in **Figure 4**.

Figure 4. Step-by-step of the use of data (source: authors).

A system was devised to enhance comprehension of the employed technique and the criteria used in selecting case studies (**Figure 5**).

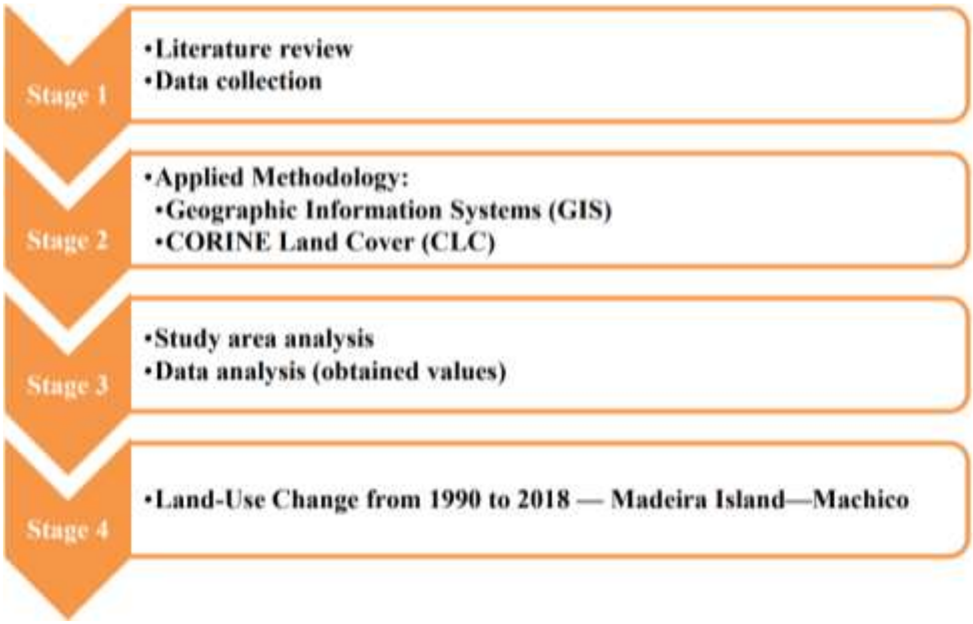

Figure 5. Methodology's four stages.

3. Results

The findings stem from an analysis of land-use changes in the municipality of Machico from 1990 to 2018, as well as in the intervals of 1990 to 2000, 2006, and 2012. Graphs, tables, and thematic maps are employed to present the outcomes. This revealed results typology facilitates the extraction of the most relevant information and delineates the evolution of land use across the 44 soil uses identified by CLC. The data are presented as percentages and detailed in **Table 2**.

Table 2. Division of the municipality of Machico according to level 3 CLC categories.

CLC Nomenclature\Year	**1990**	**2000**	**2006**	**2012**	**2018**
	(%)				
111	0.00	0.00	0.65	0.65	**0.87**
112	7.53	10.77	11.01	11.01	10.22
121	0.00	0.65	0.93	1.05	1.05
123	0.00	0.17	0.17	0.17	0.17
124	0.00	0.31	0.34	0.34	0.34
131	0.00	0.00	0.38	0.38	0.38
133	0.75	0.39	0.67	0.67	0.67
141	0.50	0.50	0.00	0.00	0.00
142	0.00	1.25	1.25	1.25	1.25
222	0.05	0.00	0.00	0.00	0.00
231	0.56	0.00	0.00	0.00	0.00
242	5.54	4.39	4.85	4.85	5.63
243	15.91	13.67	12.57	12.57	12.10
311	16.72	16.72	19.49	19.89	20.50

312	6.51	6.39	6.11	6.25	5.86
313	22.86	23.10	21.83	21.83	21.75
321	9.79	9.01	8.79	8.66	8.57
322	6.02	6.07	5.75	5.35	6.79
324	5.64	5.22	4.27	3.70	2.92
332	0.83	0.83	0.41	0.41	0.41
334	0.00	0.00	0.00	0.44	0.00
523	0.80	0.58	0.52	0.52	0.51

Note: The highest values found are in bold.

To enhance the visualization of area variations based on CLC classification, the graph presented in **Figure 6** was created using percentages.

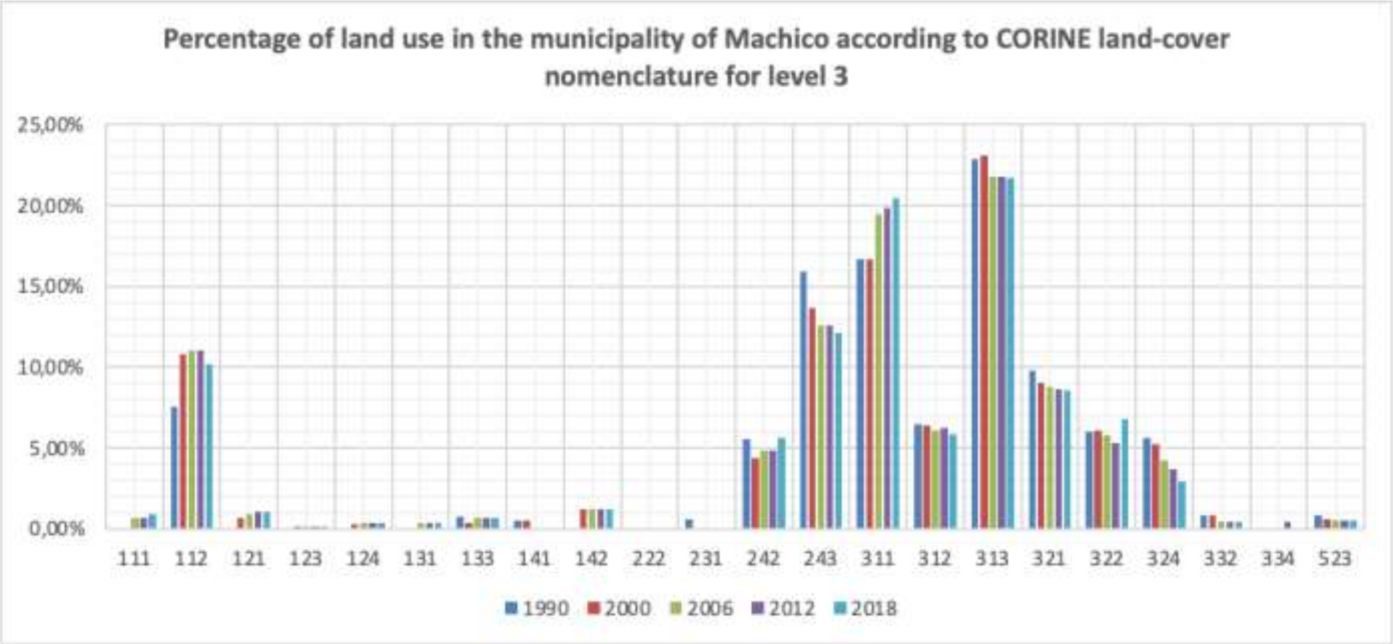

Figure 6. Distribution of the land use in the municipality of Machico.

In order to identify the evolution and difference between the areas of each land use, the percentages calculated and detailed in **Table 3** are presented for each tear.

Table 3. Evolution of each level 3 CLC class in the municipality of Machico.

CLC Nomenclature\ Year Range	**2000–1990**	**2006–2000**	**2012–2006**	**2018–2012**
	(%)			
111	0.00	0.65	0.00	0.22
112	3.24	0.24	0.00	−0.80
121	0.65	0.27	0.12	0.00
123	0.17	0.00	0.00	0.00
124	0.31	0.03	0.00	0.00
131	0.00	0.38	0.00	0.00
133	−0.37	0.29	0.00	0.00
141	0.00	−0.50	0.00	0.00

142	1.25	0.00	0.00	0.00
222	−0.05	0.00	0.00	0.00
231	−0.56	0.00	0.00	0.00
242	−1.15	0.46	0.00	0.78
243	−2.24	−1.10	0.00	−0.47
311	0.00	2.78	0.39	0.61
312	−0.12	−0.28	0.13	−0.39
313	0.24	−1.27	0.00	−0.08
321	−0.78	−0.22	−0.12	−0.09
322	0.04	−0.32	−0.40	1.44
324	−0.42	−0.95	−0.57	−0.78
332	0.00	−0.42	0.00	0.00
334	0.00	0.00	0.44	−0.44
523	−0.22	−0.06	0.00	−0.01

Note: The highest changes values found are in bold.

In order to highlight the differences in the area of occupation of each land use, the differences between percentage areas of different years, **Figure 7** is presented.

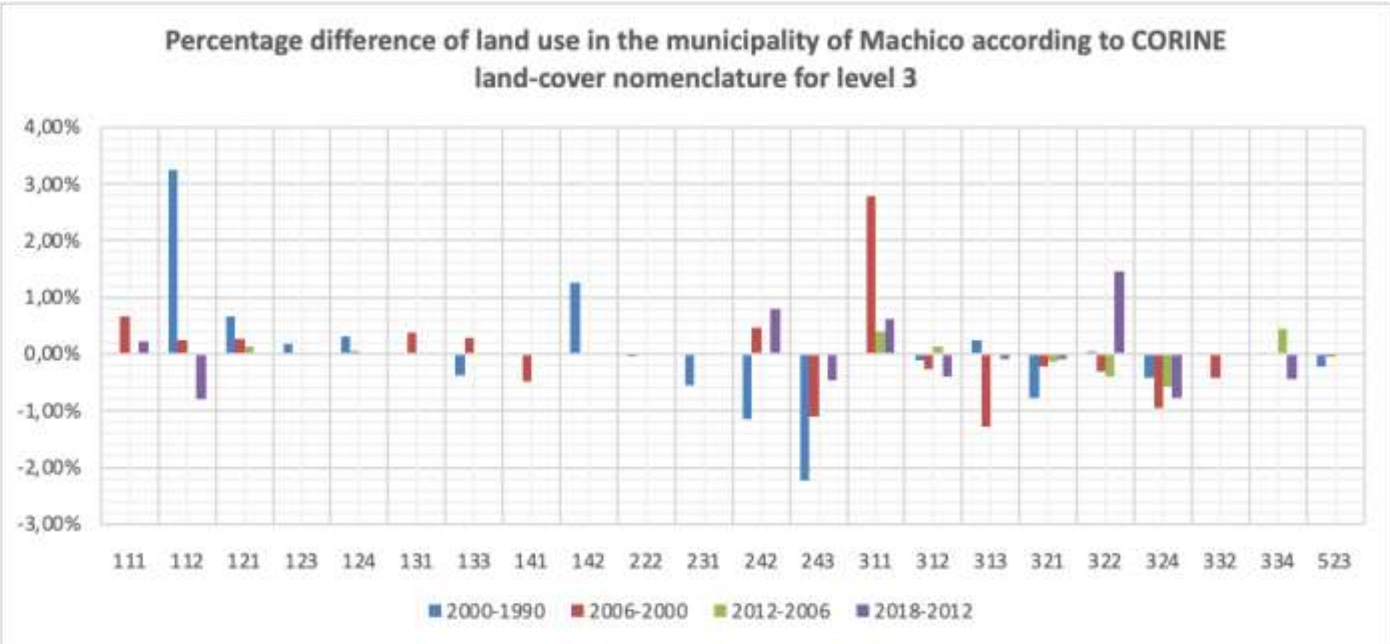

Figure 7. Machico's land use evolution based on level 3 CLC classification (data in percentages).

Furthermore, by utilizing ArcGIS 10.5, GIS software, it became possible to represent in detail the different thematic cartography, aligning with individual CLC ratings and temporal variations for each area, as depicted in **Figures 8–12**.

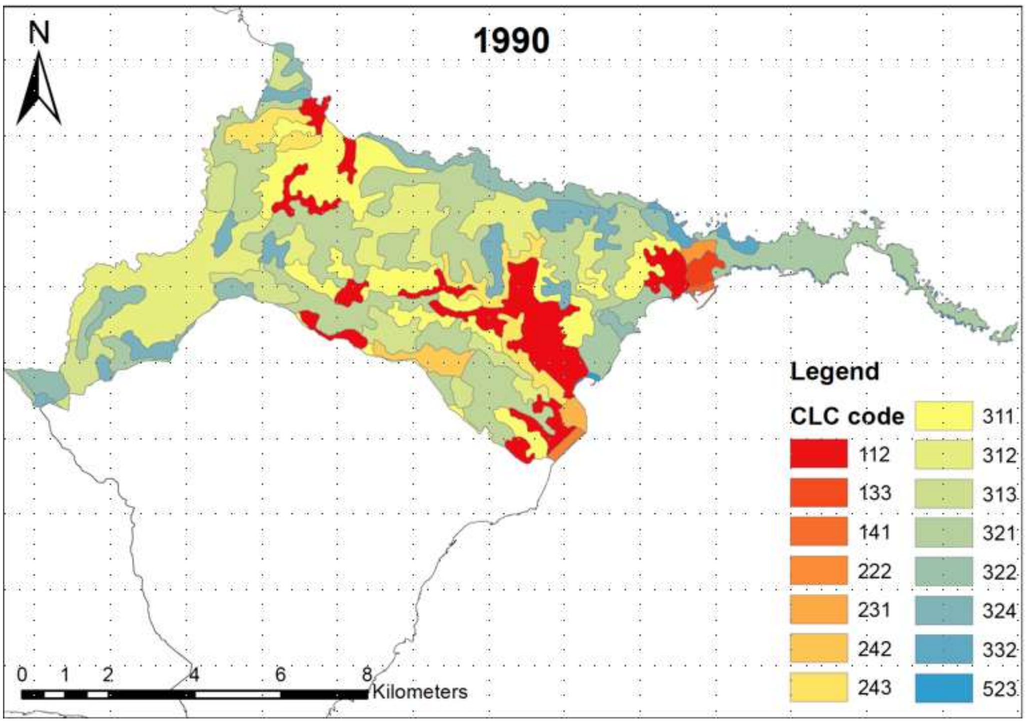

Figure 8. Distribution of land use in Machico according to level 3 CLC classification—1990.

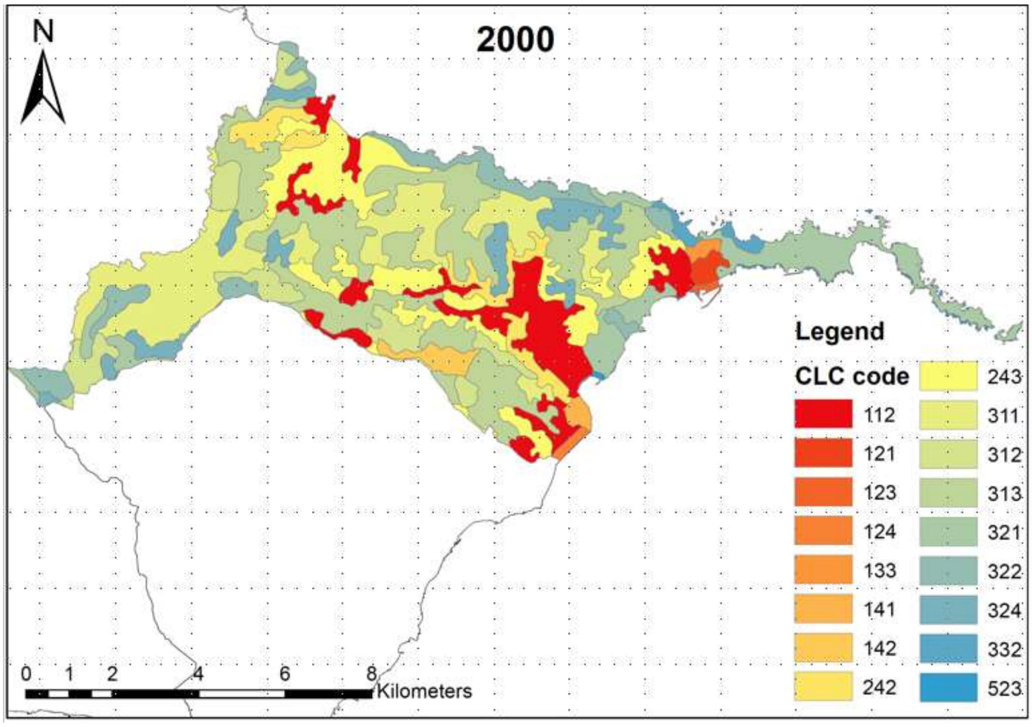

Figure 9. Distribution of land use in Machico according to level 3 CLC classification—2000.

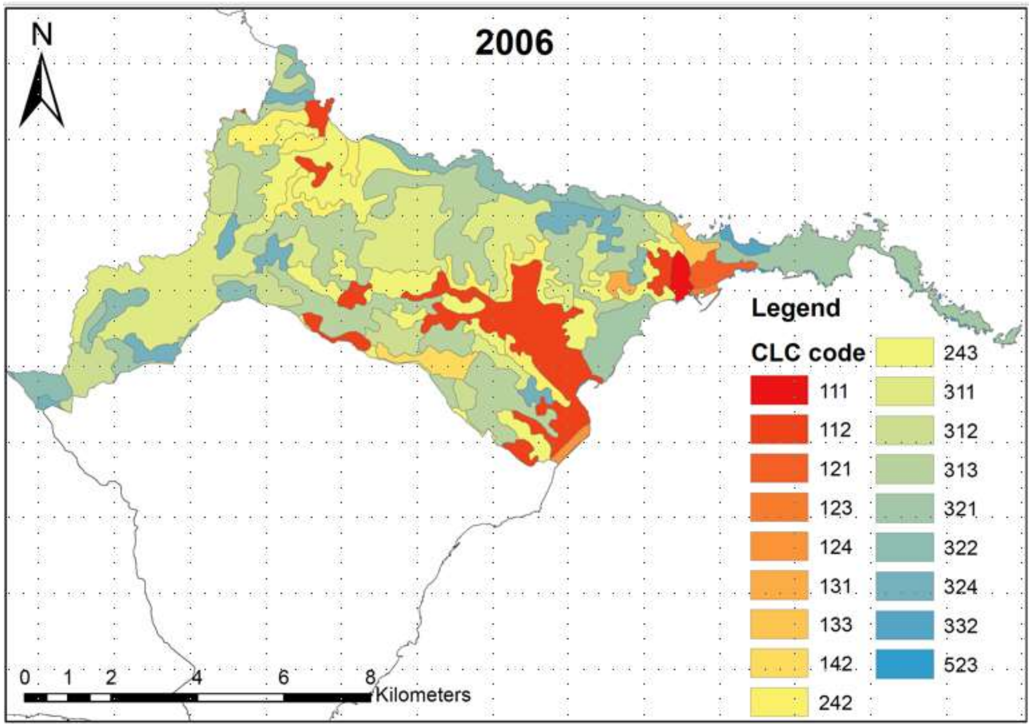

Figure 10. Distribution of land use in Machico according to level 3 CLC classification—2006.

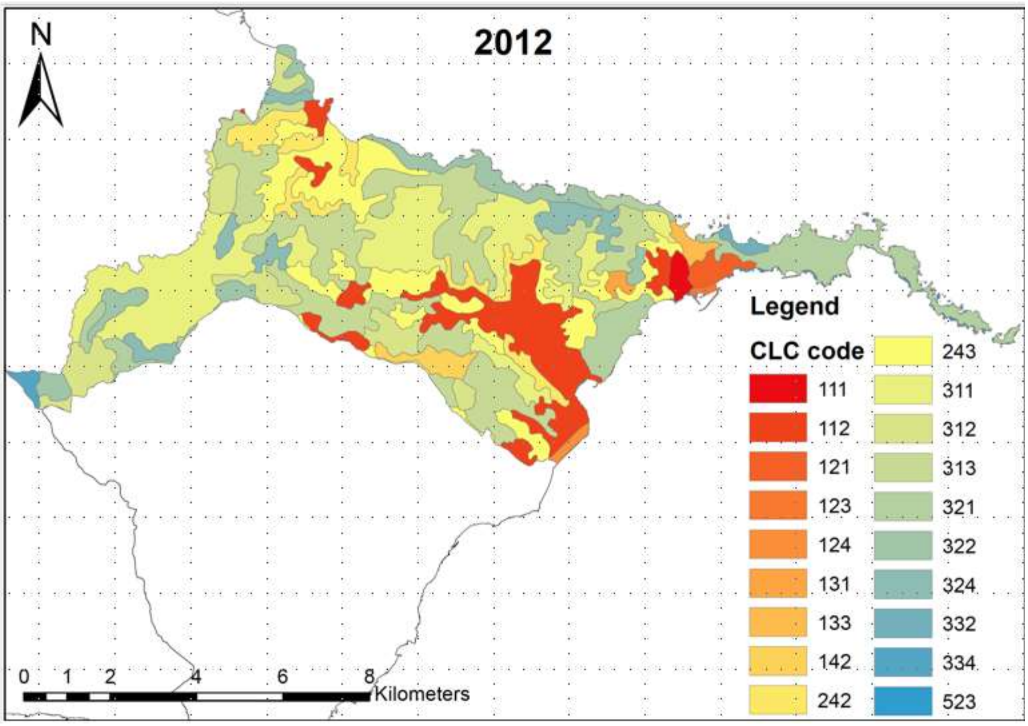

Figure 11. Distribution of land use in Machico according to level 3 CLC classification—2012.

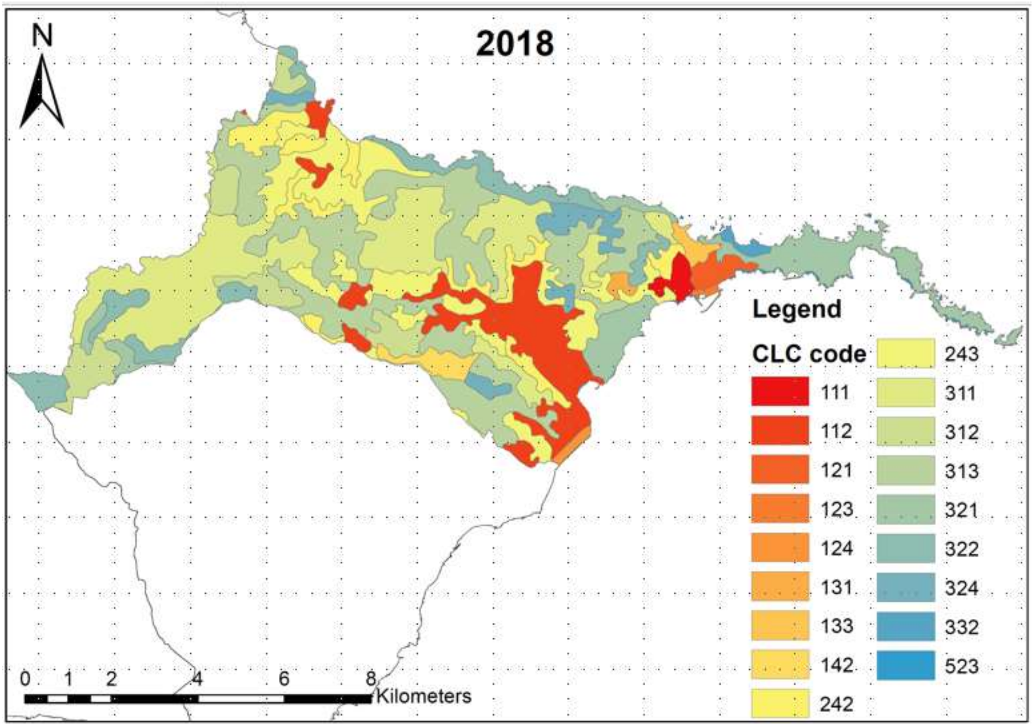

Figure 12. Distribution of land use in Machico according to level 3 CLC classification—2018.

4. Discussion

Following the application of the previously outlined methodology, it becomes feasible to examine each classification based on its respective dynamics (*Home :: Corine Land Cover classes*, sem data). For the case study, the CLC-111 for the municipality of Machico started in 2006 at 0.65%, remained constant until 2012, and increased to 0.87% in 2018. In the case of the CLC-112 increased from 7.53% in 1990 to 11.01% in 2006, remained constant until 2012 and, finally, reduced to 10.22% in 2018. These two parameters indicate that there was no notable rise in the urban fabric, a phenomenon attributed to challenges in construction arising from the irregularity of the terrain, the distance from the island's economic center (i.e., Funchal), and the gradual decrease in population.

Regarding the CLC-121 in the case of Machico, there was a continuous increase from 0.00% in 1990 to 0.65% in 2000, to 0.93% in 2006 and 1.05% in 2012, and remained constant until 2018. Concerning the CLC-123 for the municipality under study, this class increased from 0.00% in 1990 to 0.17% in 2000 and then remained constant until 2018. The CLC-124 increased from 0.00% in 1990 to 0.31% in 2000, and to 0.34% in 2006, and remained constant until 2018. These three parameters belong to the CLC-12 class, as this class corresponds to areas primarily used for industrial activities – namely, manufacturing, trade, finance, and services—and industrial breeding of cattle. It also includes transportation infrastructures such as rail and road networks, airport and port installations, as well as the surrounding areas and access infrastructure that go along with them. Hence, there was merely a slight rise in the number of industrial, commercial, and transport units, sufficient to satisfy local demand. These metrics bear significant importance for the municipality of Machico, as it stands among the most impacted municipalities in the region during flood events across the entirety of Madeira Island (Lousada, 2023). Consequently, regions with limited soil absorption capability undergo rapid saturation, enabling surface runoff (Lousada et al., 2022). This leads to the buildup of water exceeding the runoff capacity of the urban drainage system, potentially causing both economic and humanitarian damage through the complete volume of excess water from intense rainfall (Lousada et al., 2021).

Regarding the CLC-131 in the case of Machico, there was a continuous increase from 0.00% in 1990 and 2000 to 0.38% in 2006, and remained constant until 2018. In turn, the CLC-133 in the case of the municipality under study, a percentage value of 0.75% was reported in 1990, which reduced to 0.39% in 2000, then increased to 0.67% in 2006, and, lastly, remained constant until 2018.

Concerning the CLC-141 for the municipality under study, this class's percentages remained at 0.50% from 1990 to 2000, which reduced to 0.00% in 2006, and remained constant until 2018. The CLC-142 analysis indicates an increase from 0.00% in 1990 to 1.25% in 2000, and remained constant until 2018. Hence, examining the advancement of the CLC-1 classification is crucial for instituting measures to mitigate the impacts of floods in urbanized areas. This applies not only from an administrative standpoint, such as implementing and optimizing the Municipality's Master Development Plan but also from a structural perspective, including the construction of detention basins or enhancing the existing drainage system (Lousada et al., 2022).

Regarding the CLC-222 for the municipality under study, a percentage value of 0.05% was reported in 1990, which reduced to 0.00% in 2000, and remained constant until 2018.

In turn, the class CLC-231 in the case of the municipality under study a percentage value of 0.56% was reported in 1990, which reduced to 0.00% in 2000, and remained constant until 2018.

On the other hand, the CLC-242 in the case of the municipality under study, a percentage value of 5.54% was reported in 1990, which reduced to 4.39% in 2000, then increased to 4.85% in 2006 and 2012, and further increased to 5.63% in 2018. Finally, we analyzed the last classification that belongs to the CLC-2 class found in this study, the CLC-243 data analysis reveals a trend of decreasing percentages for this land occupation type, starting at 15.91% in 1990 and 13.67% in 2006. It subsequently decreased to 12.57% in 2012 and further diminished to 12.10% of the municipality's area in 2018.

To start the analysis of the CLC-3 class, we analyzed the CLC-311 that corresponding to 16.72% of the area occupied in 1990 and 2000, then increased to 19.49% in 2006, then increased to 19.89% in 2012, and further increased to 20.50% in 2018 of the area of the municipality under study. The CLC-312 categorization is not the prevailing type in the municipality of Machico, fluctuating from 6.51% in 1990 to 5.86% in 2018. Primarily situated in the elevated regions of the municipality, this vegetation is influenced by the cold boreal climate of the locality. In turn, the CLC-313 was predominant in the municipality under study with a percentage value of 22.86% in 1990, then increased to 23.10% in 2000; however, its percentage has been gradually reduced and was recorded as 21.83% in 2006 and in 2012 and 21.75% in 2018.

Unlike previous forest classifications, CLC-321 this type of land occupation has gradually reduced, from 9.79% in 1990 to 8.57% in 2018. On the other hand, a classification that has gradually increased its percentage is CLC-322 the analysis carried out in 1990 indicated that this classification was present in 6.02% of the total area of the municipality, increasing to 6.07% in 2000, then decreasing to 5.75% in 2006 and to 5.35% in 2012, and resumed its increase to 6.79% in 2018. Following the same trend as the previous type of vegetation, the CLC-324 for the municipality under study, there was a decreased percentage value between 1990 (5.64%) and 2018 (2.92%).

Regarding the classification CLC-332 for the municipality under study, there was a constant percentage value between 1990 and 2000 of 0.83%, which subsequently decreased to 0.41% in 2006, and ultimately remained constant until 2018. Concerning the classification CLC-334 in the examined municipality, the classification recorded a burned area percentage of 0.00% until 2012, indicating a decline of 0.44% in native vegetation for Machico. This reduction resulted from a significant fire that occurred in Madeira Island in July 2012, purportedly originating from an environmental crime (*PJ detém suspeito de atear incêndio florestal na Madeira - Portugal - Correio da Manhã*, sem data).

Finally, we analyzed the CLC-523 for the municipality under study, the percentages obtained do not vary significantly from 0.80% in 1990, then reduced to 0.58% in 2000, then reduced to 0.52% in 2006 and 2012, and further reduced to 0.51% in 2018.

From a global view, from 1990 to 2018, it can be concluded that 22.80% of the territory of Machico underwent changes. In total, 11.40% of the changes resulted from decreases in a given classification (CLC-133, 141, 222, 231, 243, 312, 313, 321, 324, 332 and 523), while the remaining 11.40% derived from increases (CLC-111, 112, 121, 123, 124, 131, 142, 242, 311 and 322). The most significant changes occurred in the CLC-2 class (agricultural areas), where 3.80% of the CLC-243 classification (land principally occupied by agriculture, with significant areas of natural vegetation) disappeared. The same happens with the CLC-3 class (forests and semi-natural areas), where 2,73% of the CLC-324 classification (transitional woodland shrub) also disappeared. On the other hand, there were increases in terms of land occupation regarding the CLC-1 class (artificial surfaces)—mainly due to the 2.69% increase of the CLC-112 classification (discontinuous urban fabric surfaces)—and the CLC-3 class (forests and semi-natural areas), with a 3.78% growth of the area associated with the CLC-311 classification (broad-leaved forest). The aforementioned cover type plays crucial roles in ecosystem services, particularly in processes such as pollination and the regulation and retention of water flows (Lousada et al., 2022; Sieber et al., 2021).

From the information in **Table 3**, it can be seen that the four greatest differences occurred for the following land uses (according to the land uses identified in **Table 2**—Values in bold corresponding to the higher value founded): CLC-112 between 1990 and 2000 (increased), CLC-243 between 1990 and 2000 (decreased), CLC-311 between 2000 and 2006 (increased), CLC-313 between 2000 and 2006 (decreased), and CLC-322 between 2012 and 2018 (increased).

The land uses for the municipality of Machico were obtained using the previously mentioned methodology, by utilizing ArcGIS 10.5, GIS software combined with the CORINE Land Cover nomenclature. Thus, these will be territorial planning tools, which alone allow decision-makers to add their contribution to municipal and regional planning definitions, without ever failing to consider the concept of sustainable development.

5. Conclusion

This study evaluated alterations in land use and occupation and their regional consequences in the Machico municipality. The analysis revealed that the urban fabric has not expanded significantly, and changes in the prevailing vegetation are largely due to the municipality's morphology. The cessation of artificial surface growth has alleviated the intensity of extreme climatic events, such as the floods and alluvial incidents in February 2010 (Lousada et al., 2022; Lousada et al., 2021). Conversely, this metric could indicate a standstill in both economic and population aspects in the region. Hence, it is apparent that the analysis of the CLC-1 class (artificial surfaces) is indispensable for conducting various assessments on the municipality under scrutiny, encompassing economic aspects as well as urban and social development.

The methodology exhibits notable potential for managing and cataloging main farming activities in the municipality under study, particularly for the CLC-2 class (agricultural areas). This indicator can also imply a shift in priority concerning plantations in the area, potentially altering the entire local economic dynamics.

Concerning the CLC-3 class (forests and semi-natural areas), the adopted methodology demonstrates significant potential for managing and conserving forested areas. It is also effective in inspecting legal activities and identifying illegal practices such as burning or deforestation. The application of this methodology is particularly relevant in regions with dense forests and extensive dimensions, where local quantification may become impractical.

Ultimately, the CLC-5 class (water bodies) was not taken into account (minimally decreased) due to its lack of relevance to the conducted study.

In conclusion, through the scrutiny of models depicting land-use changes (LUC) in conjunction with real-world data about the area and sustainable development guidelines, it becomes feasible to outline various aspects of the Machico municipality. Changes in land uses stand out as clear indicators of human impact on the natural environment (Bertrand and Vanpeene-Bruhier, 2007; Gao et al., 2015). Regarding efficient planning, geographic distribution, territorial administration, and the subsequent implementation of land-use changes take into account numerous essential factors and natural characteristics. These include physiography, slope, relief, soil, vegetation, and others (Gao et al., 2015; Haller, 2014).

Beyond the aforementioned, the absence of proper planning and information leads to the depletion of natural resources, causing a substantial adverse impact on neighboring communities (Arévalo et al., 2005; Çolak et al., 2023; Miklósová and Kozelová, 2023). Indeed, within island territories and specifically in the case of the municipality of Machico, accurately defining and identifying risk areas (while considering the realm of land-use planning and management) are crucial prerequisites for preventing and mitigating the damage inflicted by natural events and hazardous activities (Ishikawa and Akoh, 2023; Vizzari et al., 2018; Wongthongtham et al., 2023). Therefore, this concern becomes even more pertinent in regions characterized by unchecked expansion (Kalfas et al., 2023; Lu & Zhang, 2023; Solís et al., 2023). This poorly controlled expansion is frequently linked to the lack of a proper planning process (Arévalo et al., 2005; Çolak et al., 2023; Miklósová and Kozelová, 2023). Growth should not solely be linked to the municipality's population count, but also to the infrastructure developed from various perspectives to cater to the local population. As stated earlier, urbanized regions contribute to heightened soil vulnerability, increasing the likelihood of natural disasters (Ishikawa and Akoh, 2023; Vizzari et al., 2018; Wongthongtham et al., 2023). Considering local and territorial characteristics, along with the rise in impermeable areas amplifying surface runoff values, built-up areas can lead to issues such as erosion or landslides. This is exacerbated by the diminished capacities of rainwater drainage systems to respond adequately (Kalfas et al., 2023; Lu and Zhang, 2023; Solís et al., 2023). This uncontrolled expansion has frequently been linked to the absence of a proper planning process (Kalfas et al., 2023). As previously mentioned, the development of built-up areas contributes to heightened soil vulnerability, increasing the risk of natural disasters such as erosion or landslides (Kohno and Higuchi, 2023; Merchán et al., 2023; Wei et al., 2023). This risk is amplified when accounting for local and territorial characteristics, along with the expansion of impermeable areas that intensify surface runoff values. This becomes especially critical as existing rainwater drainage systems may no longer possess adequate response capacities (Chen et al., 2023; Li et al., 2023; Zimmermann et al., 2016). As delineated earlier, this scenario can give rise to substantial challenges impacting the residents of the mentioned municipality of Machico, the environment, and consequently, the local economy, potentially resulting in a decline in tourism. In this context, taking into account both urban and spatial planning criteria and the limitations associated with urban growth, including natural disasters, as evidenced by past occurrences in the municipality of Machico, it ends up being reinforced the necessity to define land-use classes (Lousada et al., 2022; Siangulube et al., 2023).

Moreover, in a relevant context, the topography can influence urban expansion and development, compelling the city to either sprawl or become somewhat disorganized, ultimately resulting in urban voids. In these cases, it functions as a topographic barrier, acting as a natural hindrance to urban expansion and, to some degree, maintaining the fragmentation of natural habitats. This scenario is frequently linked to areas located in hilly regions, marked by substantial variations in altitude and steep slopes (Hassan, 2017; Mansour et al., 2023). The alteration of land uses in Machico municipality is ultimately significantly impacted by this situation. Despite the constraints imposed by the local topography, barriers like those previously mentioned might potentially benefit the municipality from an environmental perspective. Such enhancement could foster social and economic development, along with the promotion and use of local natural resources. Hence, fostering a collaborative connection between economic pursuits and the environment is imperative to instigate sustainable expansion in this area. With its distinctive natural resources, ecosystems, and landscapes, there are abundant prospects to encourage sustainable development in this municipality. Moreover, a notable effort should be made to progress agriculture, capitalizing on the robust cultural heritage not just in Machico but across Madeira Island, especially concerning crops like bananas, sugar cane, and vines. This emphasis is in line with strategies for sustainable development.

Hence, evaluating the recognized challenges within the Machico municipality, the focal point of this case study, allows for the measurement of the adoption of sustainable development policies by all pertinent stakeholders and the community.

The study not only allowed an examination of the dynamics of land-use changes in this region but also facilitated an understanding of the impacts of these changes on the municipality. Moreover, by integrating the results obtained from this study with empirically gathered information from the area, it became possible to pinpoint opportunities and challenges related to the sustainable development of Machico. Concerning challenges, these can be perceived as intricate, in the sense that they demand attention to the physical spatial dimensions of the municipality and the difficulties associated with promoting a reconversion of land uses. Thus, policymakers must formulate an appropriate set of actions that consider the particular nature of the county, recognizing the significant impacts such policies could have on long-term sustainable development and the population's quality of life.

So, investigations into patterns of land-use variation are crucial for understanding regional dynamics and trends, thus providing essential guidance to decision-makers in terms of sustainable development for the region.

In conclusion, land uses can be regarded as a valuable framework for comprehending the county by assessing its past and envisioning its future.

Author contributions: Conceptualization, SL, JMNG and MF; methodology, SL, RA, MR and JMNG; software, SL and JMNG; validation, MR, RA, SL, JMNG and MF; formal analysis, SL; investigation, SL and MR; resources, SL; data curation, SL; writing—original draft, SL and MF; writing—review and editing, SL, RA, MF and MR; visualization, SL, RA, JMNG and MF; supervision, SL, DJ, RA, MR and JMNG; project administration, SL and DJ. All authors have read and agreed to the published version of the manuscript.

Funding: This publication has been made possible thanks to funding granted by the Consejería de Economía, Ciencia y Agenda Digital from Junta de Extremadura and by the European Regional Development Fund of the European Union through the reference grants GR21135.

Conflict of interest: The authors declare no conflict of interest.

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