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Research article

Mapping environmental crime to characterize human impacts on islands: an applied and methodological research in Canary Islands.

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ABSTRACT

Environmental crimes are a global issue due to the damage they cause to landscapes and ecosystems. This study focused on characterizing environmental crimes in the Canary Islands (Spain). Four categories of environmental crimes related to construction, mining and tilling, solid waste, and liquid waste) were defined and analysed. A total of 28 databases were generated, corresponding to each of the 7 major islands and each environmental crime typology. Each database was linked to information on land use and the socioeconomic and physical characteristics of the territory. For each database, firstly a descriptive statistical analysis was conducted, followed by the generation of a regularized Random Forest model with the aim of identifying characteristics that may be related to the location of environmental crimes. The results showed that, in most cases, proximity to residential accommodations, agricultural areas and industrial zones act as the main explanatory features of the distribution of environmental crimes. Furthermore, a marked pattern of concentration of environmental crimes in the coastal belt of the islands was observed, mainly associated with urban-tourist development since the 1960s and 1970s.

1. Introduction

Public administrations in most countries have enacted laws for the classification and reporting of environmental crimes. The growing social awareness of the environmental impacts of human activities is due to a greater understanding of the value of ecosystems services (Costanza et al., 2017; Lee et al., 2015). Nowadays, public administrations in most countries actively work to prevent environmental crimes, and the establishment of surveillance and alert systems has become a necessary tool for territorial management (Anderson and Thompson, 2004). Collaboration between administration and civil society has been shown to be a guarantee for the protection of natural heritage when it is threatened by private interests that put biocenosis at risk (Truelove and Gillis, 2018).

Public authorities face the challenge of defining what types of actions should be considered environmental crimes. The concept of environmental crime emerged in the second half of the 20th century (Winter, 2001) and mainly applies to behaviours that violate legal provisions enacted to protect the physical environment (Clifford and Edwards, 1998; Mitsilegas et al., 2015; EPA, 2020). However, environmental impacts encompass more actions than those legally considered as criminal, and therefore the concept has been extended to any act that may cause severe damage to air quality (Fuller et al., 2022), soil or subsoil (Petrie et al., 2015; Wu et al., 2022), surface or groundwater (Hoogesteger and Wester, 2015), people (Cardinale et al., 2012), plants and forests (Watson et al., 2018), or animals (McKinney, 2006). Environmental crimes are generally caused by actions such as illegal constructions and buildings (e.g.,Marzouk and Azab, 2014), illegal mining and tilling of soils or subsoils (e.g., Bueno et al., 2020) dumping solid land waste (e.g., Marzouk and Azab, 2014; Quesada-Ruiz et al., 2019b), discharging liquid waste on land or into the sea (e.g., Reinold et al., 2021), or the trafficking, trading, and mutilation of protected species (e.g., Cunha et al., 2017).

The registration of environmental crimes is crucial for assessing and preventing anthropogenic disturbances to ecosystems and landscapes. In this context, environmental agencies play a pivotal role as entities capable of collecting and storing information on potential environmental impacts caused by human activities (Mitsilegas et al., 2015). The European Environment Agency (EEA) and the United States Environmental Protection Agency (EPA) are two notable examples in this area. At the national level, various countries have established agencies responsible for environmental and territorial protection (e.g., Istituto

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Superiore per la Protezione e la Ricerca Ambientale -Italy-, Office central de lutte contre les atteintes à l'environnement et à la santé publique -France-, Federal Environment Agency -Germany-, Environment Agency -United Kingdom-). In countries like Italy or Spain, regional environmental protection agencies play a significant role in centralizing and transferring this type of information (Biotto et al., 2009; Uricchio et al., 2010). Environmental crime data is often biased to more populated areas, where recording is higher because of greater vigilance (Troisi and Alfano, 2021). However, the registration of environmental crimes can provide a solid foundation for the development of environmental diagnostic tools, as well as serve as a reference for the creation of territorial planning policies that mitigate the impact of human activities on the environment. Furthermore, it can help identify areas that require increased monitoring and control of damage to the environment and landscapes.

In overpopulated island territories, the development of environmental control strategies becomes especially important (IPCC et al., 2021; Satumanatpan et al., 2017; Sealey et al., 2014). This is due to factors such as excessive urban densification and pressure on the landscapes (Sealey et al., 2014; Tassi and Gil, 2020), dependence on mass tourism (Garau-Vadell et al., 2018; Satumanatpan et al., 2017), reliance on limited natural resources (Mimura et al., 2007; Pörtner et al., 2022), especially water resources (Lal and Datta, 2019; Rabassó and Hernández, 2015), or the presence of high levels of biodiversity and sensitive ecological niches (Foo et al., 2021; Richmond et al., 2015).

Overall, few studies have published on the analysis of geospatial information on environmental crimes. The current challenge lies in applying analytical methods to understand and map the actual and potential distribution of environmental crimes for prevention purposes (Winter, 2001). Through this concern, the general objective of this study is to characterize recent environmental impacts in the Canary Islands through the study of the occurrence of environmental crimes between 2001 and 2020. For this, the following three specific objectives were established: i) to analyse the spatio-temporal evolution of environmental crimes in the Canary Islands; ii) to explore the potential explanatory relationships between their geographical distribution and land uses and different socio-economic characteristics of the territory; iii) to provide useful information for territorial planning and the prevention of environmental impacts which enable geoconservation in the region.

2. Study area

This study focuses on the Canary Islands. This archipelago is one of the 16 autonomous regions of Spain and has been designated an Outermost Region of the European Union due to its location northwest of the African continent, at a distance of 1400 km from the Iberian Peninsula (Fig. 1). Canary Islands is composed of seven major islands (La Palma, La Gomera, El Hierro, Tenerife, Gran Canaria, Fuerteventura, and Lanzarote) and five smaller ones, with a total combined area of 7447 km^2. Of the major islands, Tenerife is the largest (2034 km^2) and El Hierro the smallest (268.7 km^2).

The natural environment of the Canary Islands is characterized by its subtropical climate, volcanic geology and biological endemism. Steeply rising slopes and exposure to the prevailing trade winds are two of the factors that result in sharp temperature and precipitation contrasts both between islands and often within the same island (AEMET, 2012). The volcanic origin of the Canary Islands has resulted in very high levels of natural diversity. The climatic and geomorphological diversity has generated a wide variety of landscapes, ecosystems, and natural environments. The Canary archipelago is also recognized as having one of the highest concentrations of endemism in the world due to adaptive radiation and speciation generated by geographic isolation from Africa (Aguilera et al., 1994). The terrestrial vascular flora includes a total of 1995 species, of which 511 are endemic (BOC, 2014). This is reflected in the presence of 146 natural areas, covering 40% of the islands' surface. Among them are 4 National Parks (MAPAMA, 2015). Additionally, all the islands have been catalogued, in whole or in part, as a World Biosphere Reserve by UNESCO (UNESCO, 2023).

In demographic terms, the Canary Islands is characterized by high levels of human pressure. The most populated islands are Tenerife (970,000 inhabitants) and Gran Canaria (876,200 inhabitants), and the least populated La Gomera (21,798 inhabitants) and El Hierro (11,423 inhabitants) (INE, 2022a). The average population density in the Canary Islands is significantly higher compared to the rest of Spain (292.19 inhabitants/km^2 compared to 93.55 inhabitants/km^2). However, high densities are found in Gran Canaria (548.41 inhabitants/km^2) and Tenerife (456.54 inhabitants/km^2), while the rest of the islands show significantly lower densities. In general, the population of the islands is concentrated in coastal areas, where the most important cities and ports are also located (Fig. 2).

Currently, tourism is the main economic activity in the Canary Islands and is essentially based on the so-called 'sun and beach' type (Hernández Martín and Santa Talavera, 2010). The Canary archipelago received more than 14 million tourists in 2022 (INE, 2022b), mainly concentrated on the islands of Tenerife, Gran Canaria, Fuerteventura and Lanzarote. In contrast, El Hierro, La Gomera and La Palma offer a more minority 'rural' and 'nature' type tourism (Hernández Martín and Santa Talavera, 2010). All are well established tourist destinations at national and international level. The growth of tourism, which began in the 1960s, generally replaced the traditional agrarian economic model although it is still important today in some rural areas. At the beginning of the 21st century, an expansive economic cycle (1998–2008) produced a new impulse to the growth of tourist and residential uses (García-Cruz,

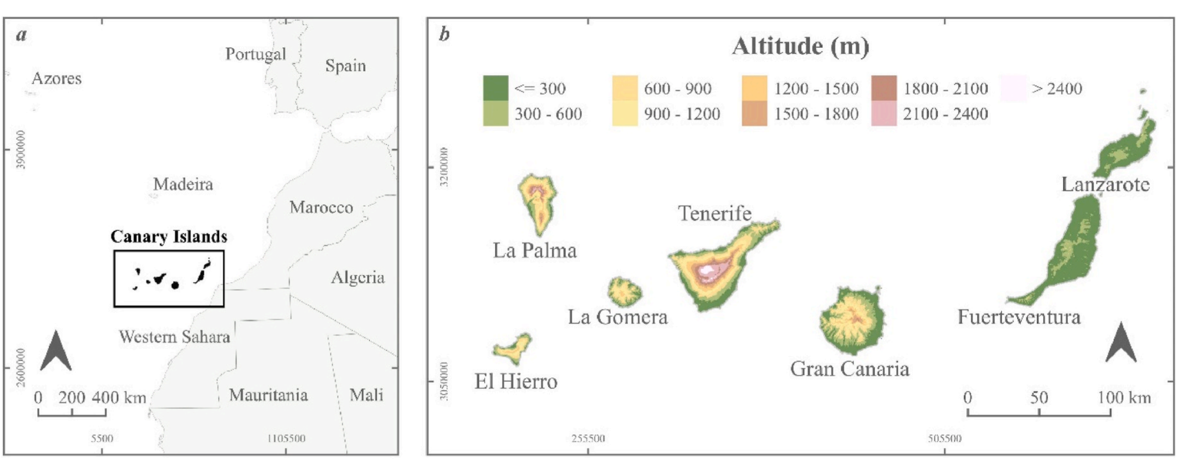

Fig. 1. Study area.

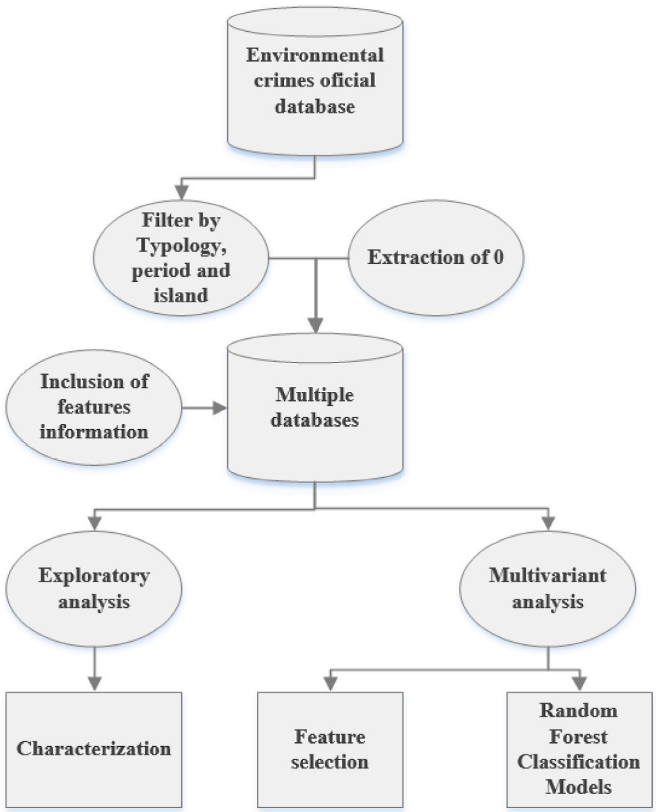

Fig. 2. Flowchart of this research.

2016), which ended in 2008 with the mortgage crisis (Cruz, 2014; García-Cruz, 2016). The sudden drop in demand led to the non-completion of some planned developments and residences (Cruz, 2014; García-Cruz, 2016). In recent years, after the economic recovery and in the post-Covid-19 period, many of these urbanizations have been completed, while the high demand from foreign buyers has increased real estate pressure on the territory. Despite the significant economic activity of the entire archipelago, based on mass tourism, a powerful construction sector (Hernández Martín and Santa Talavera, 2010; García-Cruz, 2016) and intense commercial and port activity in the capital cities (which have two of the busiest cargo ports in the Atlantic Ocean), unemployment hovers around 15% and GDP per capita in 2021 was 18, 990 € (INE, 2022a), which was second to last in the national ranking.

3. Materials and methods

3.1. Database construction

3.1.1. Environmental crime data

In this study, we approached the spatial analysis of recent environmental impacts mainly based on geo-referenced information of environmental crimes. The environmental crime data for the Canary Islands were provided by the Agency for the Protection of the Natural Environment of the Canary Islands Government (APMN for its initials in Spanish). The data, collected from 1987 to 2022, cover a total of 59,633 environmental crimes, which were mainly reported by private individuals, the Nature Protection Service of the Civil Guard (SEPRONA for its initials in Spanish), or the environmental agents of the APMN. This diverse sourcing helps to ensure a comprehensive and accurate capture of environmental crime incidents. The data provided by the APMN mostly correspond to the period after the year 2000 and distinguish between various types of environmental crimes including, among others, the dumping of hazardous waste, urban planning violations, abandoned vehicles, coastal law violations, extraction of aggregates and discharges into the sea. The database includes a detailed description of each violation.

For analytical purposes, the database was cleaned up, grouping the crimes based on their main typology and the keywords found in the observations of the police reports. In the initial structure of our data, certain categorizations of environmental crimes were overly specific and, at times, indirectly related to location such as being situated in urban or coastal areas. An example of this is in the solid waste classification, where 'hazardous waste' and 'end-of-life vehicles' were originally considered separate categories. However, in our analysis, we recognized a need to streamline these categories in order to focus on the primary environmental harm caused rather than the specific type of waste or location. In this way, environmental crimes were reorganized into four categories (Table 1): solid waste, liquid waste, buildings and constructions, and mining and tilling. The period chosen for this study was the time span between 2001 and 2020, which covers the main recent periods of economic changes in the world economy. Once the typologies of the database had been reclassified and the study period filtered, the total number of environmental crimes proposed for analysis was 38,711 cases (see Fig. 2).

3.1.2. Socio-environmental data

The database includes multiple territorial features, including physical, socioeconomic and land use characteristics, which were obtained from various sources (see supplementary material, Table 1). Physical features mainly include information on forested areas, protected natural spaces, topographic features (altitude, slopes) and a normalized difference vegetation index (NDVI) obtained from Sentinel-2 images for the summer of 2019. Socioeconomic features include information extracted from the National Institute of Statistics (INE for its initials in Spanish) at the census section level, on income level, employability, population structure, per capita income, Gini coefficient and average age of the population, among others. The distribution of the population and land uses mostly comes from the socioeconomic cartographic base of the PIMA ADAPTA Costas project (Ferrer-Valero et al., 2017). Each of the characteristics was standardized, rasterized and resampled to a spatial resolution of 100 m. For each location of an environmental crime, the values of all characteristics were extracted. To analyse the contribution of land uses to environmental crimes, density and different Euclidean distances were performed in relation to various type of land use. To complement the database, a random sample of 0s was added with the purpose of providing statistical validity to the multivariate analyses. Additionally, the inclusion of these 0s serves the purpose of distinguishing the behaviour of areas affected by environmental crimes from those that are not. This sample was obtained individually for each island and type of infringement following the criteria proposed by Carranza et al. (2008) and Quesada-Ruiz et al. (2019a): i) dissimilarity in the multivariate information with the locations of the recorded environmental crimes; ii) distances greater than 90% probability that an environmental crime will not occur, considering the minimum distance between the locations of environmental crimes for each typology and island; iii) an equal number of positive and negative occurrence zones. Finally, 28 different databases were generated, corresponding to each of the major Canary Islands and each type of environmental crime for the period between 2001 and 2020.

3.2. Statistical analysis

3.2.1. Descriptive multiscale analysis

To understand the evolution and status of environmental crimes in the Canary Islands, a multi-scale descriptive approach was applied that analysed and compared individual environmental crime types and their occurrences by island (Fig. 2). Additionally, cluster analysis using the Ward method was employed to examine from an evolutionary point of view the distribution of environmental crimes on each island. In this

Table 1
Mainly environmental crimes considered based on the primary data and legislation.

	Infringement type	Keywords	Main impacts	Applicable legislation (Canary Islands)
B	Constructions and buildings	Building, construction, expansion, installation, renovation or works of: residential units, enclosures, fences, structures, rooms or garages	Landscape, landforms, wooded areas	- Directive 2008/99/EC - Directive 2004/35/EC - BOE-A-2015-11,723 - BOE-A-2017-10,295
M	Mining and tilling	Clearing, tilling, movements, extraction, excavation or opening of the terrestrial substrate	Terrestrial substrate, landscape	- Directive 2008/99/EC - Directive 2004/35/EC - BOE-A-2015-11,723 - BOE-A-1973-1018 - BOE-A-2017-10,295 - BOC-L14/2014 - BOC-4/2017
S	Solid waste	Discharge, accumulation, deposit, abandonment or transportation of: soil, debris, vehicles, scrap, solid waste or hazardous waste	Soil quality, landscape, habitability	- Directive 2008/99/EC - Directive EU/2018/851 - BOE-A-2022-5809 - BOC-A-2022-009-148 - BOC-L14/2014 - BOC-4/2017
L	Liquid waste	Discharge into surface waters, beaches or the sea of liquid waste related to sewage, brine, stormwater or hazardous waste.	Water quality, subsurface and marine ecosystems	- Directive 2008/99/EC - Directive 2000/60/EC - BOE-A-2022-5809 - BOE-A-2001-14,276 - BOC-L14/2014 - BOC-4/2017

*BOE = Boletín Oficial del Estado (Spain's Official State Gazette), BOC = Boletín Oficial de Canarias (Official Canary Islands' Gazette).

way, because the Ward method is a hierarchical cluster analysis technique that groups data into compact and homogeneous subsets (Ward, 1963), the intention was to understand on a regional scale how different types of environmental crime have been occurring and to obtain, at least, inter-island linkages through cluster groupings. For this reason, characteristics such as the number of environmental crime types occurring each year and on each island were added to the cluster analysis.

3.2.2. Factor modelling

To study the causes of environmental crimes, the Random Forest (RF) artificial intelligence algorithm (Breiman, 2001a) was employed using the R MLR package (Amat, 2010). RF is a parallel ensemble algorithm that can be used for both classification and regression tasks (Tuv, 2009). With RF, uncorrelated decision trees are combined, where each tree is constructed using a different subset of observations and a fixed number of random features. The final output of RF is obtained by averaging for regression models and by calculating the mode of multiple classification predictions. Different studies have applied RF as an embedded feature selection method, using a threshold of feature importance or by setting the number of features a priori (Rodriguez-Galiano et al., 2014). RF wrappers such as regularized Random Forest (RRF) use regularization for feature selection more exhaustively (Deng and Runger, 2013). In this study, we used RRF to select land use features that have a greater a priori influence on the occurrence of each type of environmental crime and for each island (see Fig. 2). To validate the models, a training sample (75% of the cases) and a test sample (25% of the cases) were separated in each database. Overall accuracy served as a metric for evaluating the precision and performance of the RF models.

4. Results and discussion

4.1. Temporal patterns of environmental criminality

During the period from 2001 to 2020, a total of 38,711 environmental crimes were recorded in the Canary Islands (Fig. 3). The most common type involved buildings and constructions (45.93%), followed by solid waste (45.05%). Crimes related to mining and tillage, and liquid waste represented only 5.79% and 3.17%, respectively (Fig. 4).

In general terms, the evolution of environmental crimes followed a sharp increase until 2008 (the "real estate boom" period), followed by a clear decline between 2008 and 2012 (the economic crisis period), a relative stabilization between 2012 and 2017 (the economic stagnation period), and a slight increase from 2017 onwards (the economic recovery period) (Baker, 2008; Antoshin et al., 2017; García-Mayor et al., 2021). In contrast to this general trend, the evolution patterns in the islands of La Gomera and El Hierro were much more stable, with similar numbers throughout the entire period (Fig. 5). For all the islands, the maximum was reached in 2008, with up to 3600 environmental crimes recorded, while the average annual figure for the period was 1934. It should be noted that the decrease in the number of registered environmental crimes was not a reflection of increased concern on the part of the infringers, as only 46.8% of environmental crimes cases have been resolved and closed administratively.

4.1.1. Constructions and buildings

The high number of environmental crimes associated with construction and buildings during the period between 2001 and 2008 can be attributed to exceeding the permitted surface area for construction, non-compliance with urban planning regulations, illegal construction and renovation work, construction of buildings in unauthorized spaces and malpractice and corruption by public agents (Hortas-Rico, 2014; Quesada et al., 2013). The international economic crisis and the tightening of urban planning laws as a result of the 2007 Land Law (Government of Spain, 2007) could have contributed to the gradual decrease in this type of crime from the year 2007–2008 onwards. The decreasing trend continued until 2019, when the slight economic recovery from that year seems to have halted the decline. A higher density of environmental crimes related to illegal buildings can be observed in urban outskirts or interior zones (see supplementary material Fi g. 1), which is related to urban expansion. These behaviours could be explained by Lapointe et al. (2021), who highlighted new populations as generators of damage

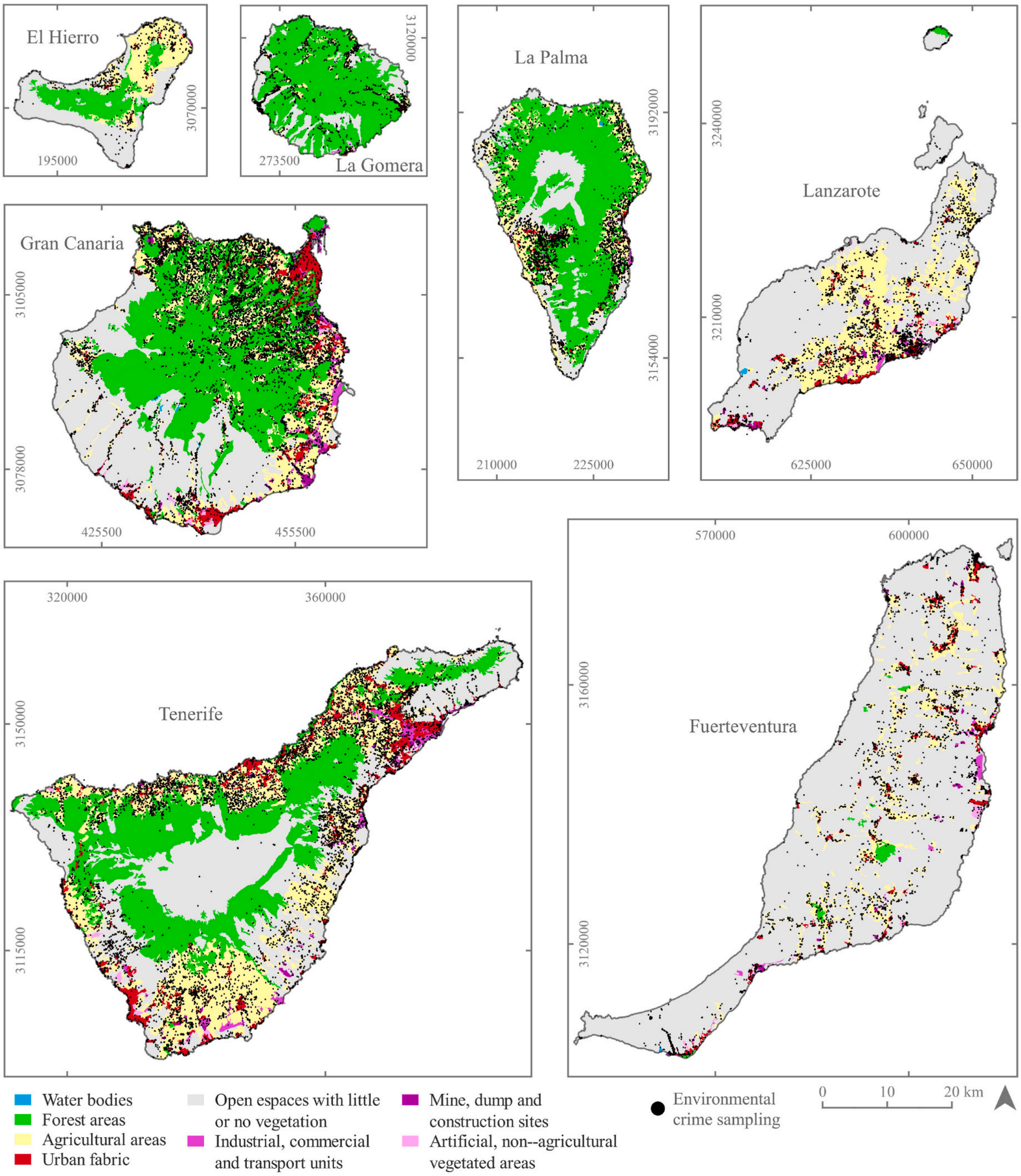

Fig. 3. Location of environmental crimes overlaid on Corine Land Cover 2022 in the Canary Islands.

against the environmental due to urban exodus and less concern for the value of ecosystem services.

The Canary Islands, like many European cities, have relied on urban expansion as a source of economic growth, but this expansion has also had significant environmental impacts (Turner et al., 1990). Residential construction has been disproportionately high compared to declining population trends, with most of this growth consisting of single-family homes characterized by patterns of urban sprawl, particularly in low population density areas (Salvati and Sabbi, 2011; Salvati, 2013; Colantoni et al., 2016). In line with the rest of Spain, the Canary Islands experienced a real estate boom during the late 20th and early 21st centuries, resulting in a process of urban surface expansion (Quesada et al., 2013).

4.1.2. *Mining and tilling*

Environmental crimes related to mining and tilling decreased during the study period, but at a slower rate than the other types of crimes, going from 253 crimes in 2001 to 24 in 2009. The highest number of cases coincides with the real estate boom period, which may be due to a greater need for building materials in the construction sector. The illegal extraction of materials in unauthorized areas as well as the over-exploitation of quarries can generate serious environmental impacts. For its part, the illegal tilling of land often involves the movement of large amounts of soil.

4.1.3. *Solid waste*

A significant portion of environmental crimes related to solid waste involves the illegal disposal or dumping of debris, urban waste and end-

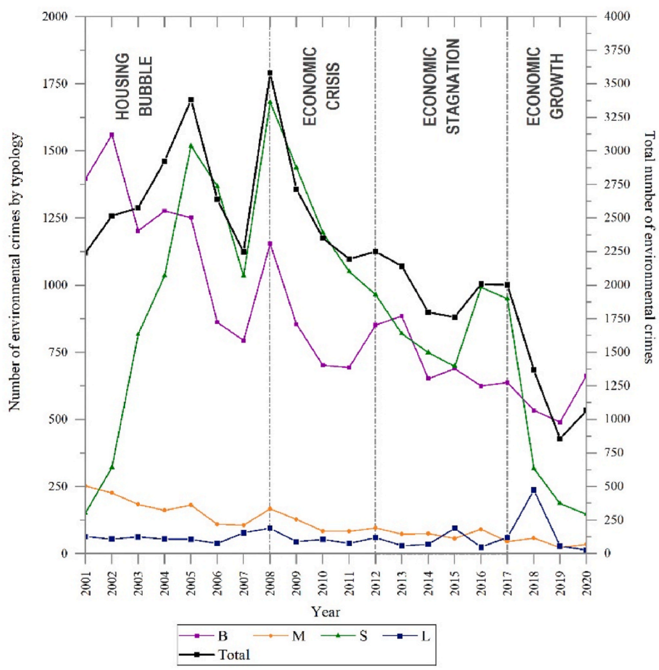

Fig. 4. Evolution of the number of environmental crimes in the Canary Islands between 2001 and 2020 by typology: buildings and constructions (B), mining and tilling (M), solid waste (SL) and liquid waste (LL).

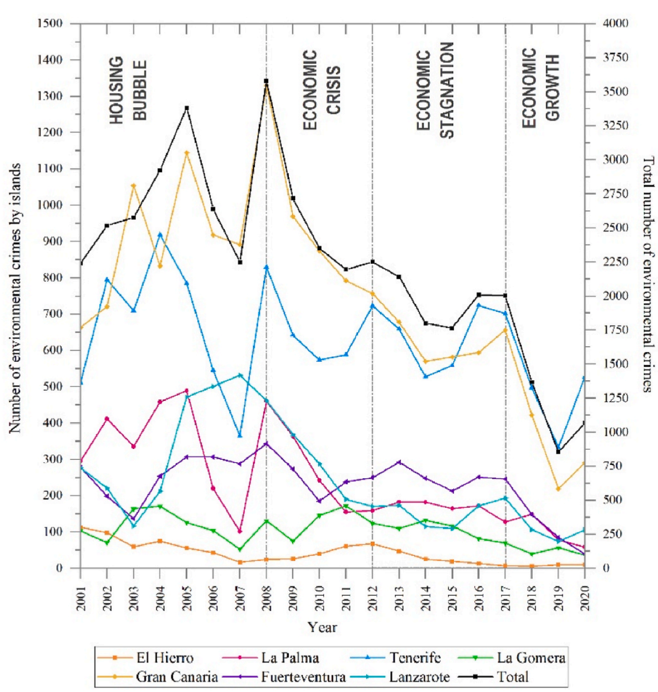

Fig. 5. Evolution of the number of environmental crimes in each of the Canary Islands between 2001 and 2020.

of-life vehicles. The evolution of this type of environmental crime in the Canary Islands showed a considerable increase between 2001 and 2008 before gradually decreasing until the end of the series. The initial increase could be related to the observed trend of construction and building crimes, given that the larger number of constructions and buildings may have generated a higher amount of waste and illegal dumping, as noted by Quesada-Ruiz et al. (2019b). Similarly, the demolition of old buildings to make way for new constructions, the paralysis of urban projects and the increase of interior renovations may have also contributed to the increase in waste dumping incidents. The period of economic growth may have also been a contributing factor, as access to new goods and properties by companies and households increased leading to the disposal of older items without consideration for waste management measures. These trends suggest that a decrease in the economic capacity of companies and individuals results in a reduction in the use of waste treatment centres, and that improvements in waste treatment centre access policies help reduce waste dumping.

4.1.4. Liquid waste

The evolution of liquid waste environmental crimes maintained a relatively stable trend throughout the time series, with peaks in 2008 (95), 2015 (95), and 2018 (238). The significant increase recorded in 2018 can be attributed to the census of oceanic waste dumping that was carried out by the Government of the Canary Islands and which identified mainly urban wastewater discharges related to the lack of adequate sanitation systems. Such was the severity of the situation that, in 2004, the European Union denounced Spain for not complying with the regulations on the treatment and purification of urban wastewater in the Canary Islands and other regions of the country. Liquid waste dumping represents a significant environmental problem in the Canary Islands, and its monitoring and control is of the utmost importance to preserve and maintain the health of the islands' marine and coastal ecosystems.

4.2. Spatial patterns of environmental criminality

4.2.1. Inter-island patterns

During the study period, Gran Canaria and Tenerife recorded the highest number of environmental crimes, with 12,500 and 10,946, respectively, accounting for 60.60% of the total (Table 2). La Palma (4,443), Lanzarote (4,231) and Fuerteventura (3,903) had similar numbers of crimes, representing 32.51% of the total. In contrast, La Gomera and El Hierro, with 1908 and 757 crimes respectively, were the islands with the lowest number of recorded environmental crimes (6.89%). In terms of the number of inhabitants, the smallest islands (La Gomera and El Hierro) recorded the highest number of environmental crimes, with 863.3 and 678.7 crimes per 10,000 inhabitants, respectively. The islands with the largest populations, Gran Canaria and Tenerife, recorded much lower ratios of 144.4 and 115.3, respectively. However, the island of Gran Canaria had the highest ratio of environmental crimes per km2, with 8.0, followed by La Palma with 6.3. Fuerteventura and El Hierro had the lowest ratios, with 2.4 and 2.8 environmental crimes per km^2, respectively. More specifically, in Gran Canaria, densities of environmental crimes exceeding 10 crimes/km^2 were recorded in 28.23% of its surface area (densities higher than 50 crimes/km^2 were recorded in an area of 15.28 km^2 of the island, reaching up to 100 crimes/km^2 in a portion of 1.27 km^2). In addition, approximately 20% of the territory of La Palma and Tenerife recorded densities of environmental crimes higher than 10 crimes/km^2. In Lanzarote a particularly pressured area of 2.97 km^2 was found, with more than 100 crimes/km^2. In total, the Canary Islands had a total area of 1263 km^2 with average densities of environmental crimes exceeding 10 crimes/km^2 (see Table 3).

The cluster analysis shows four groups of islands according to the evolution of environmental crimes per island (Fig. 6). Group 1, consisting of La Gomera and El Hierro, are the islands with the lowest number of crimes but with the highest number of environmental crimes per inhabitant and where the land uses that most occupy the territory are associated with the agricultural sector, whether it is currently active or abandoned. Group 2, defined as an intermediate group, is composed of Lanzarote, Fuerteventura and La Palma. These islands have a similar behaviour regarding the number of environmental crimes, even in terms of environmental crimes per 10,000 inhabitants, and are where the predominant land uses are associated with the tourism and services

Table 2
Number of environmental crimes by island and per inhabitant and km^2.

	No. Of environmental crimes	%	Inhabitants	Area (km^2)	Environmental crimes per 10,000 inh.	Environmental crimes per km^2
Gran Canaria	12,500	32.3	865,756	1560.1	144.4	8.0
Tenerife	10,946	28.3	949,471	2034.38	115.3	5.4
Palma (La)	4443	11.5	84,793	708.32	524.0	6.3
Lanzarote	4231	10.9	150,998	845.9	280.2	5.0
Fuerteventura	3903	10.1	122,629	1659	318.3	2.4
Gomera (La)	1908	4.9	22,100	369.76	863.3	5.2
Hierro (El)	757	2.0	11,154	268.71	678.7	2.8

Table 3
Percentage of surface area affected by different numerical ranges of environmental crimes.

	Area (km^2)	(0–10)	(11–50)	(51–100)	(101–150)	>150
El Hierro	1560.1	91.88%	7.80%	0.28%	0.04%	0.00%
La Palma	2034.38	79.29%	19.51%	1.16%	0.04%	0.00%
La Gomera	708.32	86.73%	11.65%	1.57%	0.05%	0.00%
Tenerife	845.9	80.43%	19.37%	0.17%	0.02%	0.01%
Gran Canaria	1659	71.77%	27.24%	0.90%	0.06%	0.02%
Fuerteventura	369.76	94.05%	5.74%	0.15%	0.03%	0.02%
Lanzarote	268.71	86.01%	12.77%	0.85%	0.33%	0.04%

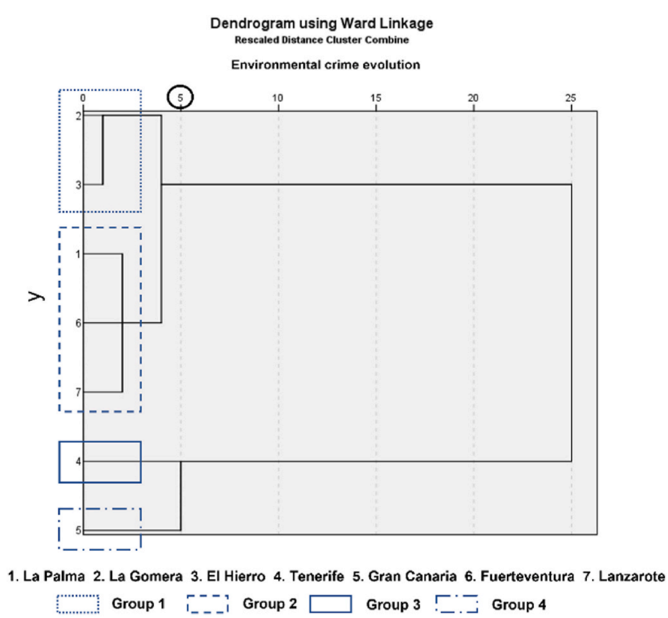

Fig. 6. Cluster analysis of environmental crime evolution and land use density across the islands.

sector. Finally, Groups 3 and 4 are formed by the two capital islands. Group 3 is composed solely of Tenerife, which is the island with the second highest number of environmental crimes registered, and Group 4 of Gran Canaria, which has the highest number of environmental crimes per km2, and where the most important land use is associated with residential urban development. In this sense, this information and these groupings could also facilitate environmental management at the regional level by classifying the islands according to their characteristics associated with the occurrence of environmental crimes.

4.2.2. Urban-rural patterns

In general terms, it was observed that environmental crimes in the Canary Islands were mainly concentrated in the inland or peripheral areas of urban centres with less than 50,000 inhabitants, with density values ranging between 10 and 50 environmental crimes per km^2 (Fig. 7). In contrast, depopulated areas or those located within protected natural areas had very low densities of environmental crimes, accumulating only 11.19% of the total registered crimes. Additionally, it was observed that highly dense urban areas, such as capital cities or major tourist centres on the islands, had density values of environmental crimes below 10 crimes per km^2 compared to the rest of the territory. However, urban areas concentrated high densities of environmental crimes in their periphery. In this sense, our analysis revealed notable disparities in the incidence and nature of environmental crimes between urban and rural areas. In urban settings, crimes related to illegal construction and solid waste littering were more prevalent, accounting for 53.6% and 54.9% of cases respectively, compared to 46.4% and 45.1% in rural regions. In contrast, environmental crimes associated with mining extraction and liquid waste littering were more common in rural areas, where they constituted 64.7% and 62.6% of reported cases respectively. These findings underscore the complex spatial dynamics of environmental crime and highlight the need for differentiated strategies in tackling these issues across diverse geographic contexts.

On the other hand, the environmental crimes strongly concentrated in tourist urban areas are likely related to the construction boom caused by the increase in tourism activity (Hortas-Rico, 2014) (Fig. 8A). The creation of residential spaces for workers in the tourism industry and the expansion of tourist areas may have increased the occurrence of environmental crimes related to illegal buildings (Quesada et al., 2013). This phenomenon is particularly notable in the southern regions of Gran Canaria and Tenerife, as well as in the western region of La Palma (see supplementary material Fig. 1). The distribution of environmental crimes relat ed to illegal mining and tilling, probably associated with agricultural and construction activities, shows a similar pattern (Fig. 8B). The extraction of materials used in construction and the preparation of urban areas, as well as the need to make infertile surfaces productive for agriculture, could have caused an increase in environmental crimes in these areas (se e supplementary material Fig. 2). On the other hand, the density of solid waste environmental crimes was concentrated in the interior or in the vicinity of well-connected urban centres (Fig. 8C), which may suggest a higher likelihood of these crimes occurring in more populated areas (see supplementary material Fig. 3). At the same time, the high density of environmental crimes related to the discharge of liquid waste into the sea in almost all the heavily touristic areas of the islands (Fig. 8D; see supplementary material Fig. 4) may suggest a lackof adequate wastewater treatment and sewage systems.

4.2.3. Inland-coast patterns

The concentration of environmental crimes in coastal areas is a prevalent trend in the Canary Islands (Fig. 9). This pattern is consistent

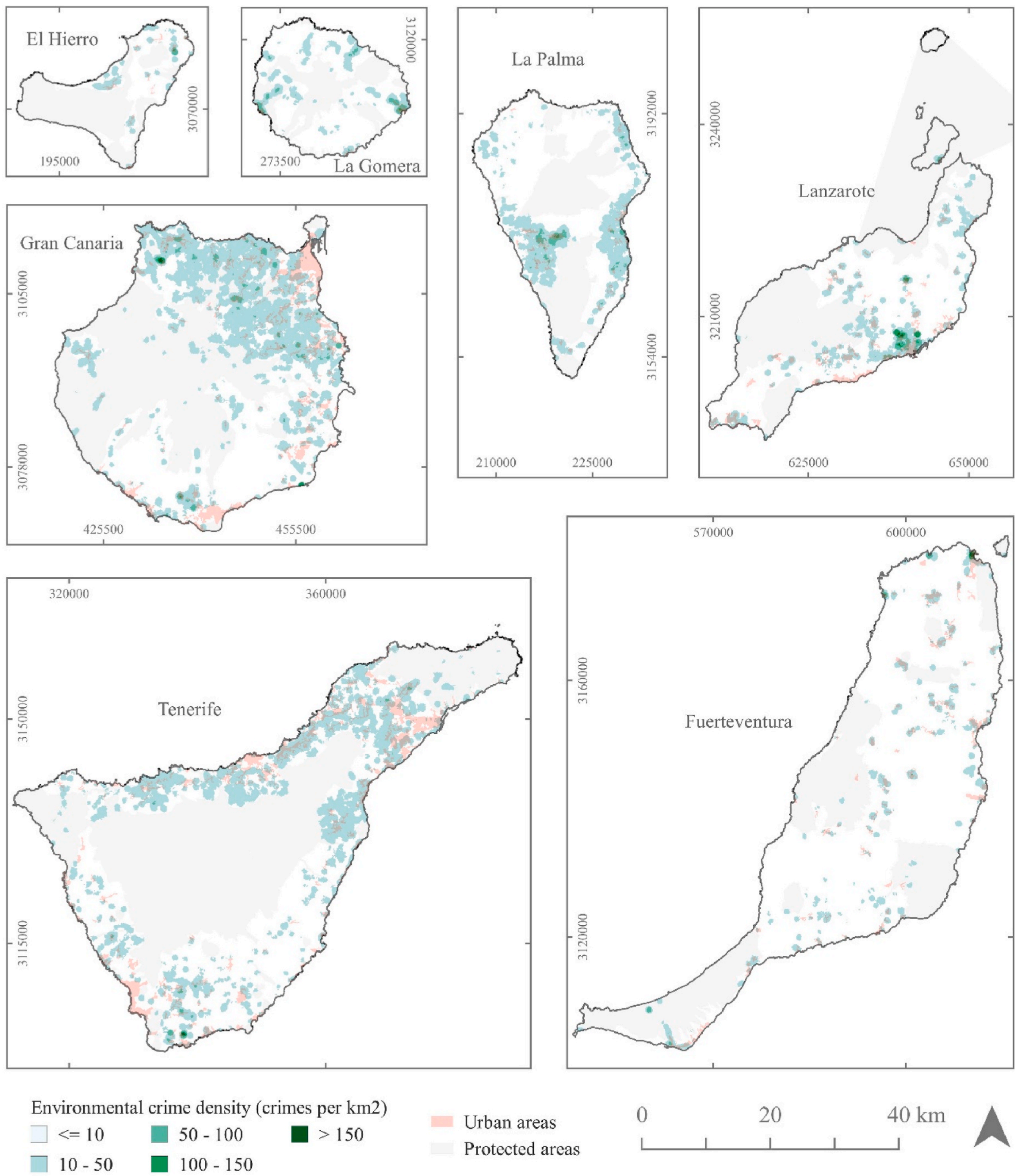

Fig. 7. Environmental crime density in the Canary Islands for the period 2001–2020.

across all islands, with almost all crimes related to liquid waste occurring near the coast and more than half of the solid waste crimes occurring within 2.5 km of the coast. Additionally, half of the crimes related to illegal buildings and land use changes were located within 3.5 km of the coast. These findings align with previous research indicating that the natural resources and coastal ecosystems of the Canary Islands are under significant pressure from human activities, particularly from urban-touristic development (Garcia-Romero et al., 2016; Ferrer-Valero et al., 2017). Furthermore, the findings of this study alert to the relationship between environmental crimes and urban uses, particularly in the coastal areas of insular environments, a discovery that could be essential for environmental management in other similar regions.

4.3. *Environmental crimes and land use relationships*

The statistical models generated with RF showed that all types of environmental crimes are highly related to residential land use (based on the distance to residential accommodations) (Table 4), being the most determining characteristic in the case of construction and building crimes and solid waste crimes. In the case of mining and tilling crimes, the distance to agricultural areas was the most determining characteristic, and, in all cases, the distance to industrial areas was also a determining characteristic. These results indicate that, although environmental crimes could occur in areas far from these land uses, ultimately these were the areas most affected by the activities that sustain them. In the particular case of solid waste crimes, it was observed

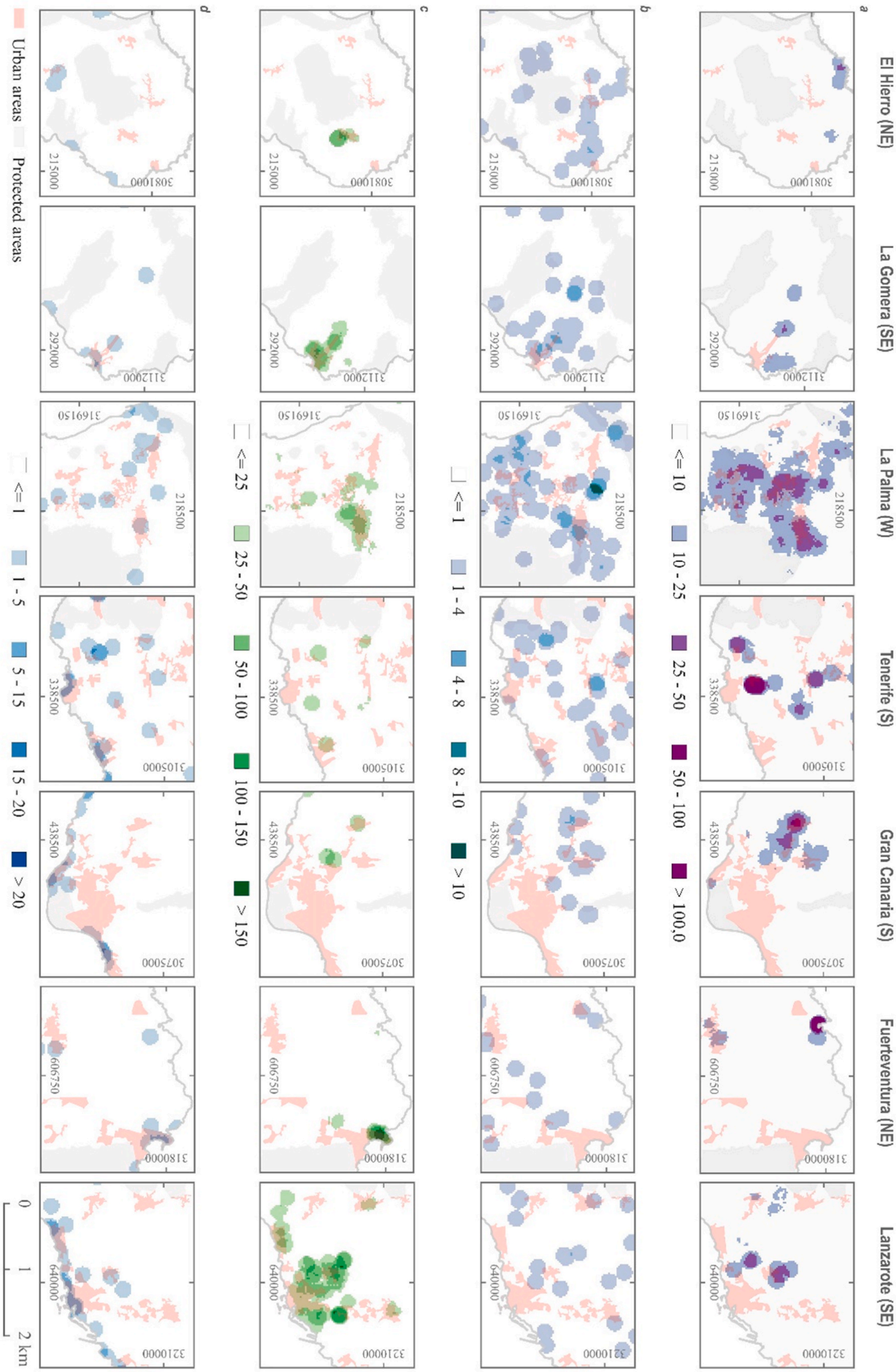

Fig. 8. Density of environmental crimes (km^2) in the main tourist areas of each island: a) constructions and buildings; b) mining and tilling; c) solid waste; d) liquid waste.

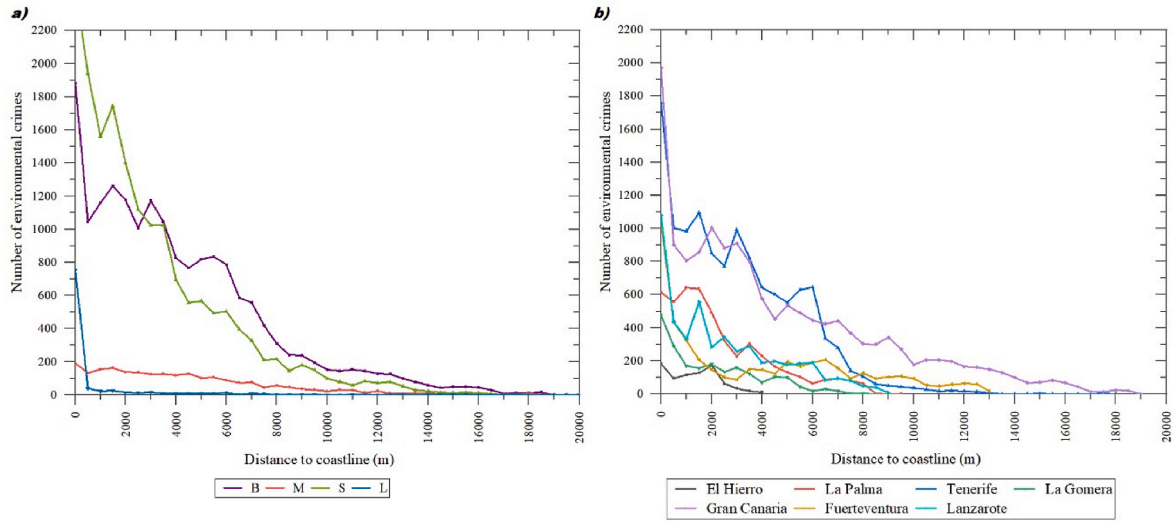

Fig. 9. a) Distance to coastline from the environmental crimes by typology: 1) buildings and constructions (B); 2) mining and tilling (M); solid waste (S); liquid waste (L). b) Distance to coastline from the different environmental crimes by island.

Table 4
Main features selected by the Random Forest model considering all islands: 1) construction and buildings (B); 2) mining and tilling (M); solid waste (S); liquid waste (L).

B	M	S	L
ED to residential areas	ED to agricultural areas	ED to residential areas	ED to coast
ED to agricultural areas	ED to residential areas	ED to industrial areas	ED to protected areas
ED to industrial areas	ED to industrial areas	ED to services areas	ED to residential areas

ED = Euclidean distance.

that service areas and industrial hubs had a high influence on their location and occurrence. Finally, proximity to the coast and residential areas was shown to be a determining characteristic in the occurrence of liquid waste crimes.

Table 5
Main features selected by island and environmental crime typology: 1) construction and buildings (B); 2) mining and tilling (M); solid waste (S); liquid waste (L).

	Feature selected			
	B	M	S	L
Lanzarote	ED to residential areas	ED to agricultural areas	ED to services areas	ED to restauration areas
Fuerteventura	ED to residential areas	ED to residential areas	ED to residential areas	ED to touristic residences
Gran Canaria	ED to residential areas	ED to residential areas	ED to manufacturing and storage areas	
Tenerife	ED to residential areas	ED to agricultural areas	ED to industrial areas	ED to roads
La Gomera	ED to residential areas	ED to industrial areas	ED to residential areas	ED to roads
La Palma	ED to agricultural areas	ED to residential areas	ED to residential areas	ED to roads
El Hierro	ED to residential areas	ED to agricultural areas	ED to residential areas	ED to agricultural areas

In the case of Lanzarote and Fuerteventura (Table 5), the proximity to tourist and food service industry areas may largely explain the occurrence of environmental crimes, suggesting a strong association with tourism. The effects of tourism on the coast are often associated with a drastic change in land use, which can have negative effects on the environment by replacing natural ecosystems with infrastructures necessary for the tourism industry (Benseny, 2006; Zibaoui, 2011). The growth of coastal area development and the lack of sanitation infrastructure to prevent illegal discharge into the sea are key factors in the occurrence of environmental crimes in coastal areas. In Spain, around 600,000 homes were built annually between 2000 and 2006, of which 30,000 were built in the Canary Islands, with 50% of them located in coastal tourist areas (Cuadrado-Ciuraneta et al., 2016).

The environmental crimes related to illegal buildings and constructions were also concentrated in proximity to agricultural areas (Fig. 10A). Half of the mining and tilling crimes, and of solid waste crimes, occurred within 100 m of agricultural spaces. This could be due to the process of converting agricultural buildings, such as barns or storage sheds, into residential areas, or the direct conversion of agricultural land into constructed areas. Similar problems have been reported in other parts of the world, such as the United States, due to the construction of housing developments on agricultural land and the conversion of agricultural land into urban and suburban areas (Cook, 2011). These areas are typically located away from urban centres and may become dumping grounds for solid waste due to a lack of surveillance or the activity of illegal dumping. However, liquid waste dumping mainly occurred in coastal and touristic areas, which are often some distance from agricultural activities.

Regarding the proximity of environmental crimes to industrial areas, most of them were found to occur within 200 m of such areas. Specifically, solid waste crimes tended to occur in close proximity to industrial areas, suggesting a strong relationship between them (Fig. 10B). However, industrial activities appeared to be less associated with liquid waste or construction and buildings crimes. Finally, tertiary or service activities areas had significant numbers of liquid waste crimes, which may be related to touristic activities (Fig. 10C). Solid waste crimes were also found at a distance of less than 300 m, which may be related to construction activities in these areas.

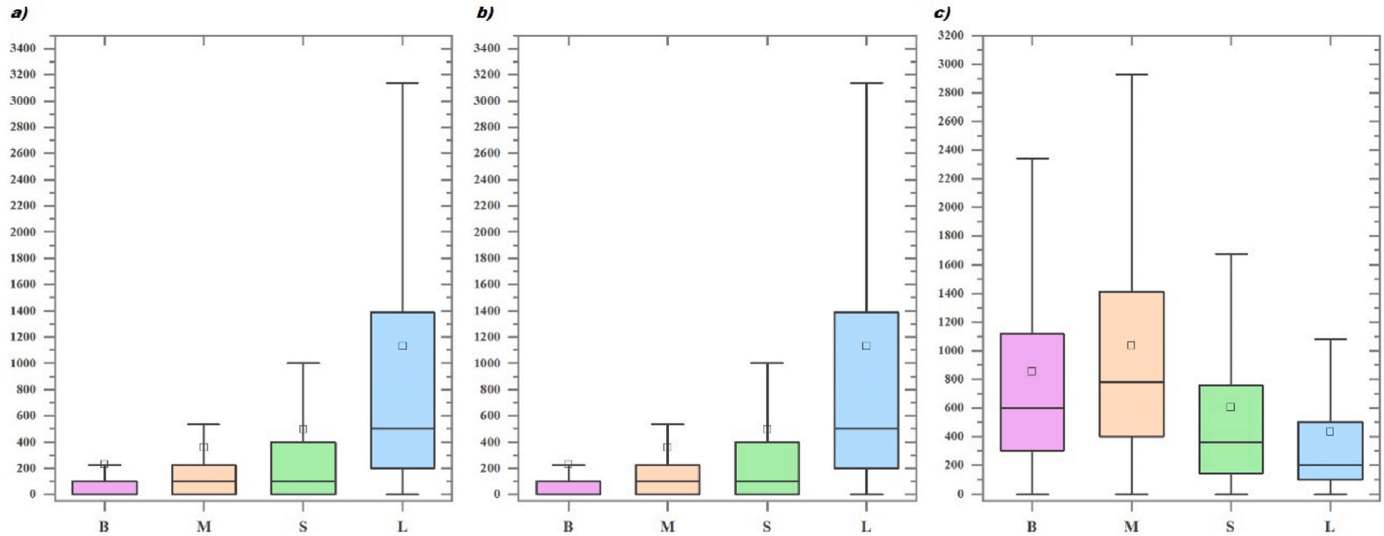

Fig. 10. Boxplot illustrating distances (in meters) to different land uses for the different types of environmental crimes: construction and buildings (B), mining and tillage (M), solid waste (S), and liquid waste (L): a) Distance to agricultural areas; b) Distance to industrial areas; c) Distance to service areas.

4.4. Methodological contributions

4.4.1. The usefulness of georeferenced information of environmental crime

Although the environmental impacts are not reducible to crimes (in a legal sense), the present study shows the valuable insights that georeferenced information on environmental crimes can provide. It allows for precise depiction of the damages inflicted on the territory and landscape and enables the analysis of the impacts and scope of human activities on the land, thereby facilitating the prioritization of the territory according to levels of urgency (Araneo and Bartolucci, 2021). Nevertheless, despite the accuracy of our data we acknowledge that certain inherent biases may exist. Such biases could include the uneven distribution of the population and the specific routines of environmental agents conducting the surveillance. Although numerous studies have been conducted on indicators for environmental impact assessment and landscape quality, to date no specific methodology has been developed to transform information related to environmental crimes into quantifiable indicators. Previous works include the exhaustive environmental impact analysis conducted by Toro et al. (2010) or the quantification of global human interventions through unitary and total environmental impact by Pereira et al. (2019). Other studies have applied an environmental impunity index from the perspective of corruption and organized crime (Le Clercq and Cedillo, 2022) and models to evaluate regional vulnerability through the integration of ecological and economic indicators of land degradation (Salvati and Zitti, 2009). However, none of the aforementioned studies included analyses of official data on actual environmental crimes, limiting their retrospective and prospective capacity.

This study opens up the possibility of generating a specific indicator in the future that allows for the measurement and quantification of environmental crime in a unified manner, taking advantage of the information available from public administrations. However, before proposing any indicator, it is essential to consider relevant aspects such as the scope and severity of each type of environmental crime, their recurrence, extent and combinations with other typologies of crimes. For example, in the case of construction and buildings crimes, it would be convenient to know the surface area of new construction and the impacts on the subsurface. For solid waste crimes, both the surface area and volume of waste should be considered, while for liquid waste crimes, the total volume of water affected and the marine species in the area should be taken into account. In the case of mining and tilling crimes, the volume of land substrate affected should be known to make a full diagnosis of the extent of the crime. Moreover, we fully acknowledge these potential limitations in our study and have endeavoured to mitigate any undue influence on our findings by employing robust statistical techniques. Our data analysis methods were carefully selected to control for possible skewing effects. Therefore, future databases and information collection systems should include information on the extent, volume and recurrence of crimes to improve underlying analyses (see Table 5).

4.4.2. The suitability of the analytical approach

The analysis of databases using the RF method allowed the investigation of the implication of certain human land uses in the occurrence of environmental crimes and the possible socioeconomic determinants that explain the distribution of these crimes. The RF method offers several advantages for the analysis of geolocated environmental crimes, as it is relatively robust in terms of outliers, and provides information on the relative importance of different input features of the model, which helps to better understand the model and reduce its dimensionality. In addition, the parameterization of RF is simple and computationally lighter than other machine learning methods, such as neural networks or support vector machines (Rodriguez-Galiano and Chica-Rivas, 2012). RF has already been applied in land cover classification (Breiman, 2001a; Pal and Foody, 2010; Rodriguez-Galiano et al., 2018) and in many other environmental, water and mineral resource, and public health problems (Arabameri et al., 2019). Likewise, the RRF method has been applied in genetic research (Deng and Runger, 2013), land cover classification (Izquierdo-Verdiguier and Zurita-Milla, 2020) and the recovery of biophysical parameters (Izquierdo-Verdiguier and Zurita-Milla, 2018). This work represents a novel application of the RF method to the analysis of the distribution of environmental crimes. The analysis of the overall accuracy of the RF models (Table 6) shows a high degree of precision,

Table 6
Overall accuracy of each Random Forest model: buildings and constructions (B), mining and tilling (M), solid waste (S), liquid waste (L).

	B	M	S	L
Lanzarote	93.93	86.08	92	95.71
Fuerteventura	93.36	83.33	93.2	87.88
Gran Canaria	88.39	89.89	92.7	27.62
Tenerife	92.78	90.83	89.3	97.59
La Gomera	97.28	92.74	95.1	84.62
La Palma	92.62	83.46	93.7	88.89
El Hierro	97.34	92.59	94.5	87.50

with percentages that mostly exceed 90% (Quesada-Ruiz et al., 2022). This accuracy indicates the relevance of incorporating features related to land use in the evaluation of environmental crimes. Despite the notable performance attributed to the application of RF (Breiman, 2001a), it would be advisable to further explore the identification of causes, contrasting the analyses carried out with other multivariate analysis approaches. Given the global accuracy of 27.62% obtained in the RF model applied to the liquid waste database in Gran Canaria, it would be appropriate to reconsider its implementation in this context. The relatively low effectiveness of this model could be related to the massive occupation of coastal spaces in Gran Canaria, which could generate a certain degree of randomness in the location of waste dumping. To optimize this and other feature selection models, it would be useful to complement the features associated with land use with socioeconomic and productivity indicators (Riahi et al., 2017). In this regard, it was observed that the scale of disaggregation of socioeconomic characteristics is quite high (Ferrer-Valero et al., 2017), although they were not included among the 10 most relevant features in most of the RF models. However, these features could be reused in future predictive models of the occurrence of environmental crimes, considering the probability of occurrence as a proper indicator to assess the vulnerability of the territory to the incidence of environmental crimes.

This approach represents a first step towards differentiating between areas with a higher incidence of environmental crimes based on density calculations, while raising questions about the usefulness of analysing environmental crimes separately or together. It is also worth considering whether the rate of surface area affected by different ranges of environmental crime densities or the rate of environmental crimes per 10,000 inhabitants could constitute appropriate metrics for developing an indicator to rank different zones. In the case of the Canary Islands, using territorial demarcations, it would be interesting to rank the territory according to these densities and assign scores to sections with higher or lower densities of environmental crimes. This research highlights the need to establish clear and rigorous methodologies for transforming information related to environmental crimes into cartographic products that can enrich and guide territorial planning. The incorporation of additional information and the performance of complementary analyses would allow for a deeper and more nuanced understanding of the relationship between environmental crimes and socio-economic and territorial characteristics. For example, the analysis of spatial and temporal correlations could provide valuable information on the dynamics of environmental crimes and help identify patterns of occurrence and areas of higher risk. This research also has the potential to make a significant impact on how decision-makers address environmental crimes, whether in the Canary Islands or in similar locations worldwide. The understanding and portrayal of environmental crime occurrences, as an indicator of anthropogenic influence on a region, substantially hinge on the availability of a vast array of georeferenced socio-environmental characteristics. The robustness of the models employed directly corresponds to the quantity of these characteristics. The practical implementation of this study emerges in the context of current territorial monitoring and control measures (which involve registration, georeferencing, and characterizing based on environmental criteria). Essentially, the research would necessitate the following: i) georeferenced data pertaining to environmental crimes; ii) a rough delineation of land use (for example, an adaptation of the Corine Land Cover for European contexts); iii) an assortment of georeferenced socio-environmental characteristics to provide a more precise depiction of the milieu wherein environmental crimes transpire; iv) application of RF. Hence, in future research, it would be appropriate to evaluate the applicability and robustness of predictive models of environmental crimes in different geographic and socio-economic contexts, which could improve the generalization and transferability of the results. It would also be of interest to examine the influence of political, institutional and cultural factors on the occurrence of environmental crimes, as well as to consider the interaction between these factors and the territorial and socio-economic features analysed.

5. Conclusions

Environmental crimes, understood as transgressive actions of legislations enacted to safeguard the natural environment, are committed in many countries and monitored by regional and state agencies responsible for environmental protection. However, the information collected is rarely subject to thorough scrutiny, largely due to the lack of clear and rigorous methodologies for analysis beyond descriptive statistics. In this context, the causes of environmental crimes could be elucidated through comparative studies with socioeconomic characteristics, especially those related to land use. The present research addressed environmental crimes that occurred in the Canary Islands archipelago over the 2001–2020 period, demonstrating how the cross-referencing of geolocated environmental crime data can help uncover the relationship between environmental crimes and various physical and socioeconomic characteristics of the territory. In the spirit of research transparency, we have made clear the potential biases in our data. We continue to explore avenues for refining our data collection and analysis methods in order to enhance the credibility and validity of our findings in future research.

This study presents, for the first time, density maps corresponding to each environmental crime typology, thus contributing to the identification of "hotpoints" in the territories. Through density calculations for each type of crime, we provide a first cartographic proposition, a useful tool that can be adapted and applied to different geographic and crime contexts. Throughout the studied period, the Canary Islands recorded a total of 38,711 environmental crimes, with construction and building violations (17,780) and solid waste dumping (17,442) being predominant. The evolution of the number of crimes appears to be conditioned by urban expansion during the "real estate boom" period. Thus, a high density of environmental crimes related to illegal building was observed in areas of continuous urban sprawl, associated with tourism and residential uses.

While our study is centred on the Canary Islands, the methods we use can be applied anywhere, providing a valuable framework for understanding the correlations between land use and environmental crimes, as well as the factors that may influence the incidence of environmental crimes. The results obtained in this study show that the analysis of environmental crimes is related to certain land uses and socioeconomic characteristics of the analysed spaces, allowing for the identification of patterns and specific activities responsible for a particular environmental crime. Our research methodology offers a fresh perspective on characterizing environmental crimes and identifying associated characteristics of their occurrence, with its relevance extending beyond the Canary Islands and being applicable to a variety of geographical contexts. The feature selection models using Random Forest applied to each island and environmental crime typology revealed a substantial correlation between the proximity of residential areas and construction and building crimes, as well as solid waste crimes. There is a lack of specific methodologies to generate quantifiable vulnerability indicators from environmental crime information. Consequently, it is proposed for future research to develop a specific indicator that allows the measuring and quantification of environmental crimes in a unified manner. Finally, it is suggested to consider the rate of surface area affected by different ranges of environmental crime densities or the rate of environmental crimes per 10,000 inhabitants as possible metrics for developing an appropriate indicator aimed at ranking environmentally stressed areas. Additionally, the creation of predictive models that can be employed for this purpose is proposed, contributing to a deeper understanding and more efficient management of the issues associated with environmental crimes.

Credit author statement

LQR conceptualized and devised the process. All authors supervised the work. All authors discussed the results. LQR wrote most of the original draft. All authors reviewed and edited the manuscript.

Compulsory brief authorship statement

All authors conceptualized and devised the review process. All authors supervised the work. All authors discussed the results. LQR wrote most of the original draft. All authors reviewed and edited the manuscript.

Declaration of competing interest

I would like to submit the manuscript entitled "Mapping environmental crime to characterize human impacts on islands: an applied and methodological research in Canary Islands" by Quesada-Ruiz. L.C., Garcia-Romero, L. and Ferrer-Valero, N. to be considered for publication as an original review article in *Journal of Environmental Management*.

We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We know of no conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome. As corresponding Quesada-Ruiz, L. I confirm that the manuscript has been read and approved for submission by all the named authors.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118959.

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