Journal of Hazardous Materials 468 (2024) 133843

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Research Paper

Anthropogenic and environmental factors partly co-determine the level, composition and temporal variation of beach debris

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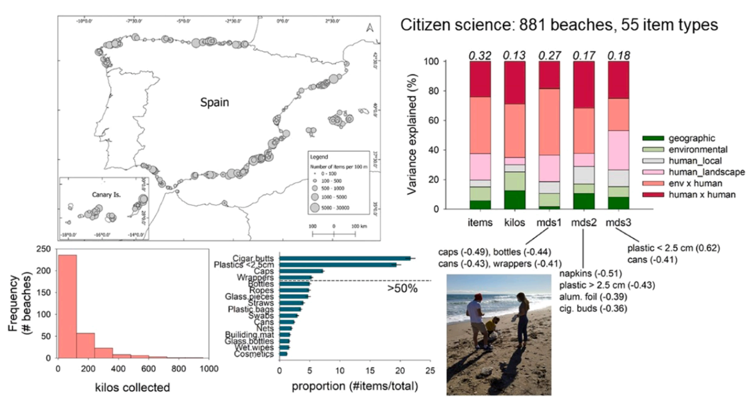
HIGHLIGHTS

- Citizen science provided 881 collections from beaches in Spain during 10 years.
- Land-originated single-use items dominate beach debris.
- Environmental and anthropogenic factors co-determined beach debris composition.
- Temporal variation is large and influenced by anthropogenic pressures.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Citizen science
Marine litter
Marine pollution
Protected areas
Plastic pollution

ABSTRACT

The accumulation of human-derived waste on our coasts is an escalating phenomenon, yet the relative importance and potential interactions among its main drivers are not fully understood. We used citizen-science standardized collections to investigate how anthropogenic and environmental factors influence the level, composition, and temporal variation of beach debris. An average of 58 kg and 803 items/100 m, dominated by single-use items of land (rather than sea) origin, were collected in the 881 beaches sampled. Interactions between anthropogenic and environmental factors (e.g., human use × beach substrate) were the strongest predictors of beach debris, accounting for 34% of the variance explained in its amount and composition. Beach debris showed a highly stochastic temporal variation (adjusted $R^2 = 0.05$), partly determined by interactions between different local and landscape anthropogenic pressures. Our results show that both environmental and anthropogenic factors (at the local and landscape scale) co-determine the level and composition of beach debris. We emphasize the potential of citizen-science to inform environmental policy, showing that land-originated single-use items dominate beach debris, and the importance of considering their multiple anthropogenic and environmental drivers to improve our low predictive power regarding their spatio-temporal distribution.

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https://doi.org/10.1016/j.jhazmat.2024.133843
Received 5 December 2023; Received in revised form 14 February 2024; Accepted 18 February 2024
Available online 20 February 2024

1. Introduction

The amount of debris arriving to our oceans and beaches constitutes an environmental problem that is growing exponentially [1–5]. These residues not only have a landscape impact that can affect the tourism sector and other commercial activities such as fishing or navigation, but their presence influences water quality, marine fauna and flora, ecosystem functioning and human health [e.g., 1–5]. There is thus an urgent need to understand the main factors determining the level and composition of the debris reaching our beaches to apply environmental policies and management tools that limit its main sources. However, we lack large scale and standardized data across habitats and time to do so (but see [5]) which prevents comprehensive evaluations of the relative importance of the different known anthropogenic and environmental drivers in the level, composition, and temporal dynamics of beach debris [4,6–9].

Amongst the factors that can affect the level and type of beach debris are the accessibility and use of the beaches, with more items collected on urban or highly frequented beaches [7,10,11]. Human activities at larger (landscape) scales can also play a role, with nearby greenhouses or industrial activities increasing the inputs of large plastic, wood, metal or textile waste [1,12], and areas undergoing heavy ship traffic or intense fishing or aquaculture activities being commonly enriched in plastic residues [10,11,13]. In addition to anthropogenic factors, environmental variables such as the type of beach substrate (sand vs. pebbles or rocks), the direction and strength of the dominant sea-wind, or the presence of nearby river mouths, also affect the level and composition of marine litter [6,13,14].

With very few exceptions [e.g., 7], most studies on the drivers of the spatio-temporal distribution of human-derived consider either

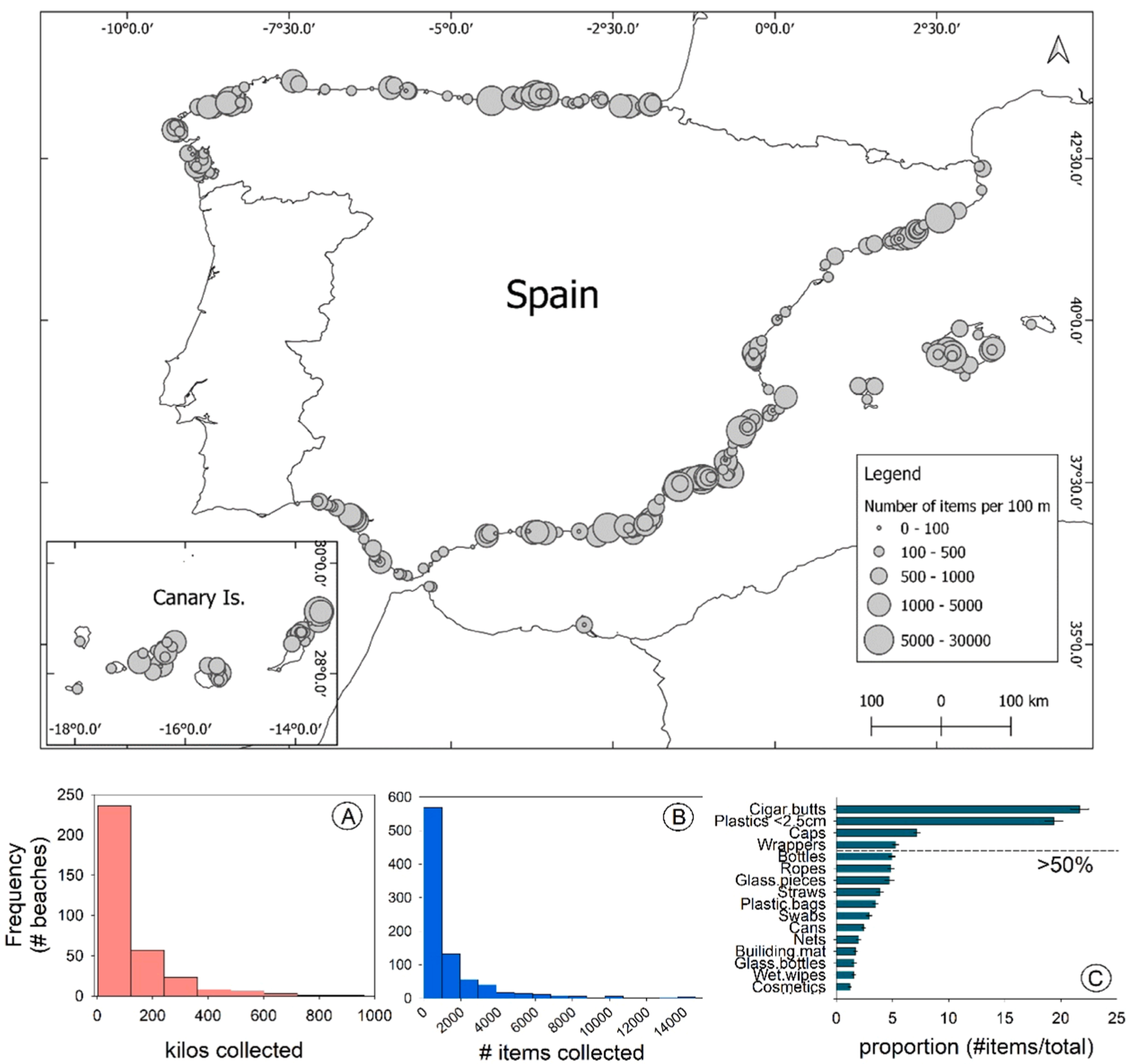

Fig. 1. Spatial distribution of the beach debris database used across the Spanish coast, showing the number of items (log-transformed) collected at each location. Frequency distributions (as in number of beaches) according to the number of kilograms (A) and items (B) collected are also shown. Finally, the most dominant types of items collected (number of items of that particular category × 100/number of total items found) is shown (C), with those above the dashed line representing over 50% of the items recovered across the 881 beach collections.

environmental or anthropogenic factors, and analysed them individually. However, there is strong potential for interacting effects between environmental and anthropogenic factors, or between different categories of the latter, in driving spatio-temporal variation in beach debris. For example, beaches close to a river mouth or more exposed to dominant sea-winds could accumulate larger amounts of debris if surrounded by a dense population or greenhouse/industrial land uses. In addition, the composition of beach debris could importantly change if multiple anthropogenic pressures co-occur (e.g., shipping traffic, industrial and greenhouse uses, and/or high affluence of public) regarding that of beaches surrounded by more homogeneous landscapes. These interactions between environmental and anthropogenic factors have - to the best of our knowledge- received very little attention so far.

Another potential, yet poorly studied factor [but see 15], determining accumulation of debris on our beaches is that of environmental protection of natural areas of conservation interest. Previous studies have measured the amount, composition and sources of beach debris in protected areas or remote environments [12,13,16,17]. However, we still lack comprehensive comparisons as to whether such level of environmental protection drive change in beach debris ́(amount or composition) in comparison to similar but unprotected areas. Marine and coastal protected areas could reduce the presence of marine debris and affect the composition of marine litter via three main mechanisms: i) environmentally aware visitors, ii) low accessibility, or iii) limited anthropogenic activities nearby. However, it is unknown the degree to which these environmental and anthropogenic factors -and their interactions- determine the level and composition of debris found on our beaches.

To understand all the above-mentioned factors and their interactions, datasets covering large spatio-temporal scales are necessary to perform a robust analysis. Citizen science engage society actively in science and can contribute to scientific studies by allowing the acquisition of large and reliable datasets [18–20]. Here, we analyze a large citizen science dataset, including the weight, number and type of items collected between 2011–2020 in 881 beaches across the entire Spanish coast (Fig. 1). We evaluated the effect of geographic (latitude, longitude, region/demarcation), environmental (type of substrate, distance to the nearest river, degree of exposure to the dominant sea-wind), and anthropogenic (local and landscape use types and intensities, environmental protection) factors, and their interactions, on beach debris level, composition and temporal dynamics. We tested the following hypotheses: i) anthropogenic factors, and amongst them those related to terrestrial rather than sea uses, are more important than environmental factors to determine the level and composition of beach debris, ii) the environmental protection of an area effectively reduces the amount of litter on our beaches, iii) both the effects of the anthropogenic influence and the degree of protection are partly modulated by the environmental characteristics of each beach, mainly those related to type of substrate and water dynamics.

2. Materials and methods

We analysed the information on beach debris gathered by a large citizen science effort conducted by two NGOs "Ambiente Europeo" [19] and "Surfrider", together with the "MARNOBA" [20] platform. Together, these databases agglutinate information gathered by more than 20,000 volunteers, who collected, quantified, and classified systematically beach debris in a total of 881 collections from beaches throughout the Spanish coastline between 2011 and 2020 (Fig. 1). For all these collections, there is available information on their geographical coordinates and number of items collected, which allowed us to integrate in situ observations with satellite information, as recommended [15]. Beach debris was classified following the standards of the Spanish Ministry for the Ecological Transition and the Demographic Challenge [21], in the case of the Ambiente Europeo database, and those of OSPAR [22] in the case of Surfrider and MARNOBA. For this work, we homogenized these two classification schemes into a single common one (Suppl. Table S1). As commonly done [23,24], we calculated number of items as a proportion of the length covered in each collection (number of items/ 100-m).

The Ambiente Europeo database ($N = 350$) also included the weight of the waste collected, as well as the number of participating volunteers. In some cases ($N = 120$ beaches), data were collected from the same beach at different dates. In these cases, we only took the first collection to feed our main database (Section 2.1), but used all sampling times to analyse their temporal dynamics and its drivers (Section 2.2). Those beaches that we only sampled once provide a sound space-by-time substitution effort to analyse the effects and relative importance of the different drivers of beach debris ́accumulation, comparable to previous efforts [6,25]. First, because the different collections took place over different seasons (Suppl. Table S2) and over 10 different years, implicitly accounting for temporal variation in beach debris ́accumulation. Second, because it is very unlikely that most of the environmental and anthropogenic drivers included (see below) vary across relatively short time periods, such as the ones covered by our sampling.

2.1. *Anthropogenic and environmental drivers of beach debris*

2.1.1. *Environmental drivers*

From the coordinates, we obtained the corresponding marine demarcation of each beach sampled according to the Spanish law 41/2010 (three in the Atlantic: 1. North Atlantic, 2. South Atlantic and 3. Canary Islands; and two in the Mediterranean: 1. Straits and Alborán, and 2. Eastern and Balearic), together with information if the beach was located in an island or in mainland. We also obtained the type of beach substrate (re-organized in this study as sand, pebbles/rocks or mixed) from the website of the Spanish Ministry for the Ecological Transition and the Demographic Challenge [26]. We also measured the distance to the mouth of the nearest river from Google Earth, since debris is often dragged into rivers and eventually deposited on the neighboring beaches. Finally, the degree of exposure of the beach to dominant sea winds could greatly modulate debris accumulation [e.g., 7,27]. To measure this exposure, some studies use the relative exposure index (REI). However, we aimed to use an index of exposure that took into consideration mainly the degree of exposure of the beach to the *dominant* sea wind, as we thought that it could be more correlated with litter accumulation than indices such as REI [28–30], which use the average of all winds, regardless of their dominant direction. In consequence, we developed the Shoreline Exposure Index (SEI):

$$SEI = \sum_{i=m} (1 - |\frac{D_m - Or}{Or}|) * S_m$$

where, D_m is the dominant direction of the wind (value range: 0–360°) for a given month (m), Or is the orientation of the beach towards oceanographic factors (value range: 0–360°), and S_m is the average speed for a given month (value range: 0–1.18 m/s). The monthly dominant direction and average speed of the sea-wind was obtained from the Copernicus database [30] for the year 2019 (chosen randomly). Therefore, SEI is the monthly sum of the corresponding speed of the wind multiplied by a factor (value range: 0–1; 1 direction of the wind fully perpendicular to the orientation of the beach and 0 fully parallel) that aim to reflect the exposure to the dominant wind. We chose 2019 as a representative year due to the large number of years covered in our sampling (2011–2020), since choosing specific time spans for each collection would render this as a non-comparable predictor, and choosing the time window that would specifically affect beach debris accumulation was not straightforward in such an intensive and large-scale sampling [see 31,32 for similar approaches]. Since intra-annual wind variation is often larger than inter-annual wind variation [33], integrating one representative year should provide us the prevalent wind direction and intensity we have in a specific beach.

Overall, our environmental predictors included beach geographical distribution (coordinates and demarcation), whether the beach was located in an island or mainland, the type of substrate, distance to the nearest river, and the shore exposure index (direction and speed of the main sea-wind).

2.1.2. Anthropogenic drivers

Information on anthropogenic pressure exerted at the *local* scale was gathered from the Spanish Ministry for the Ecological Transition and the Demographic Challenge [30]. This included accessibility to the beach, as well as the classification of the beach as "urban", "semi-urban" or "isolated". These two categories were combined into a single binomial variable, where 1 = accessible (classified as urban or semi-urban and / or easily accessible by car, and 0 = not accessible (classified as isolated and accessible only on foot or by boat). Semi-urban beaches not easily accessible on foot or by car were also classified as "not accessible". Further information from the same source included 16 variables related to recreational activities or facilities available on the beach. We assumed that these variables are related to a greater influx of public and, therefore, greater intensity in the use of the beach. These variables included 1) presence of a promenade, 2) signalling to get there, 3) available bus, 4) car parking, 5) footbath, rental of 6) sun umbrellas, 7) hammocks, or 8) scooters, 9) presence of a nearby tourist office, 10) restaurants or bars, 11) presence of playground for kids, 12) sports area, 13) sailing clubs, 14) available snorkelling tours, 15) scuba diving activities, or 16) available surfing areas. From these variables, a "local human use index" was calculated, where the presence of a service = 1, while its absence = 0. The local human use index was the percentage of the 16 services measured that were present on a beach. It should be noted that the presence of bins and cleaning services, the information of which was also available online and could contribute to a lower level of beach debris, were positively correlated to our local human use index ($\rho = 0.68$), and therefore was not further considered in our analyses. The local human use index, obtained from the 16 variables was strongly correlated to the accessibility of the beach (Mann-Whitney test: U = 37697; $P < 0.0001$), with accessible beaches showing much higher scores (mean = 43.4%) than non-accessible ones (mean = 16.7%). Since our "local human use index" has a more continuous distribution and better statistical properties, we did not consider beach accessibility further in our analyses.

We also obtained information for each beach regarding their degree of environmental protection, classifying it as protected if it was part of any European or Spanish environmental protection figure (including Natura 2000, national or natural parks, etc). Some of these environmental protection figures does not have, or have not developed yet, management plans to deal with residues or land uses. To account for these differences, we coded our "environmental protection" predictor as a three-level factor (0: no environmental protection, 1: environmental figure without management plan, and 2: environmental figure and associated management plan). There were also differences between the different environmental protection figures in the level of beach debris (Suppl. Material Fig. S1); however, we did not consider them together with the rest of predictors to prevent model over-parametrization and to keep the complexity manageable.

To quantify the anthropogenic pressure at the landscape scale, we measured (visually from Google Earth) the proportion of a 5-km circle around the beach covered by urban, industrial, cropland, greenhouse or natural land uses. To keep our list of predictors as simple as possible, we decided to consider only the proportion of natural use, as the inverse of the coverage of all other uses potentially contributing beach debris (urban, industrial, cropland, greenhouse). We complemented our measurements regarding anthropogenic pressure at the landscape scale by collecting information on the presence of nearby waste-water treatment plants [34], ports or marine farming facilities [35]. Ports and marine farming facilities may source different macro-litter to nearby beaches, including Styrofoam boxes and buoyes, ropes and fishing nets [10,36]. The presence of waste-water treatment plants may affect beach debris in two ways. First, the lack of treatment plants may cause waste water to be directly released into the sea, thus increasing the amount of macro-litter such as hygienic towels, cigarette butts or plastic wraps, that some people throw into the toilet [37]. In addition, waste-water treatment plants scan pill macro-litter after heavy rains if their capacity is overcome [e.g., 38]. We also obtained estimates [from ref 39] regarding the coastal population (number of inhabitants within a 25 km radius), coastal pollution (use of fertilizers and pesticides from agricultural activities, and urban inorganic pollutants) and shipping activity (number of ships sailing around the target beach). Coastal pollution was included as another measure of agricultural and urban pressure (together with the area covered by agricultural and urban use in the landscape nearby; see above), as agricultural activities may source macro-litter from the plastic containers used for fertilizer and pesticide application, and plastic debris from greenhouses and soil coverage [10,40]. Other anthropogenic impacts of interest available [39], such as fishing effort, were also considered initially, but discarded afterwards as they were highly correlated to some of other predictors used.

Overall, our anthropogenic predictors included, at the local level: our human-use index and the degree of environmental protection (3 level factor). At the landscape scale, we considered the proportion of nearby land (5 km diameter) covered by natural habitats, presence of waste-water treatment plants, ports or marine farming facilities nearby, and estimates of coastal population, coastal pollution and shipping activity.

2.2. Temporal variation in marine debris

From the 120 beaches from which we had data on multiple collections through time, we calculated the coefficient of variation in the number of items, and included time in between collections and number of visits (range 2–25) as additional predictors on top of the anthropogenic and environmental ones described above.

2.3. Statistical analysis

We used three complementary analyses to address our research objectives: i) linear models (assuming normal distribution of errors) to evaluate the relative importance and interactions between predictors as drivers of beach debris ́ amount and composition, ii) more in-depth multivariate analyses to better understand the drivers of beach debris ́ composition, and iii) linear models (assuming normal distribution of errors) to evaluate the temporal dynamics in beach debris ́ accumulation.

The level (number of items and kilograms collected) of beach debris was analysed using linear models. In these models, we included our geographical (latitude, longitude, demarcation), logistic (number of volunteers involved in each collection and beach width), environmental (island/mainland, substrate type, distance to the nearest river mouth, shore exposure index) factors, as well as local and landscape-scale anthropogenic pressures as predictors. The number of volunteers was included to control for differences in "sampling effort" between beach collections, assuming that more volunteers would be able to recover more debris. Local and landscape-scale anthropogenic pressures included our human local use index and environmental protection (local), and nearby natural land-use, presence of ports, fish farming or waste-water treatments, coastal population, coastal pollution and shipping activity (landscape). Interactions between environmental x local human pressure, environmental x landscape human pressure, and local x landscape human pressure were also considered. The models were later on simplified by removing non-significant predictors using AIC and F-ratio tests; first removing the non-significant interactions and later the main effects, until obtaining the most parsimonious model (based both on AIC and adjusted R^2). Once the most parsimonious model was obtained, we conducted a variance partitioning analyses, using the sum of squares of an ANOVA including the selected predictors [see ref 36 for a related approach]. These analyses were performed for the total number items (log-transformed to approach normality) and the number of kilos recovered, but also for the numbers (log-transformed too) of the four most common item types found (see Fig. 1), separately.

The composition of beach debris was analysed using the same approach as above, but using the three first nmds (non-metric multidimensional scaling) axes as the response variables. Non-metric multidimensional scaling is commonly used to ordinate samples according to the similarity on the species composition of biotic communities, but in our case it was conducted using the number of items per each of the 55 homogenized (across both classification schemes) categories of beach debris type as "species", with each beach collection as "sample". Data was first log-transformed to reduce excessive influence of the most abundant items. The 3D ordination had a stress level of 0.18, showing a good fit to our data. The first axis (hereafter nmds1) was related mainly to the number of bottles and caps found (Spearman's $\rho = -0.44$ and -0.49, respectively), metal cans ($\rho = -0.43$) and cardboard wrappers ($\rho = -0.41$). The second axis (hereafter nmds2) was related to the number of paper napkins ($\rho = -0.51$), macroplastic (>2.5 cm; $\rho = -0.43$) residues, rests of aluminium foil ($\rho = -0.39$), and cigarette butts ($\rho = -0.36$). The third axis (nmds3) was related to the abundance of macroplastics (>2.5 cm; $\rho = 0.62$) and metal can (-0.41) residues.

In addition to the linear models, we also analysed the effect of local and anthropogenic drivers on beach debris composition by using multivariate multiple regressions (DISTLM) for the continuous predictors and permutation-based multivariate ANOVAs (PERMANOVA) for the categorical predictors [details in Suppl. Material A; see ref 42 for a related approach]. Statistical models were performed separately for the number of items collected and their composition (using all databases), and for their weight (only data from Ambiente Europeo, since it was the only database with that information available).

To analyse beach debris' temporal variation we used the same linear models detailed above, but using the coefficient of variation (CV; [standard deviation/mean] × 100) calculated for all the collections for each beach ($N = 120$). In addition to the environmental and anthropogenic predictors, we also included the number of visits per beach and the average time in between consecutive collections, although these were not significant predictors and were removed during the model simplification procedure. Contrary to the analyses for level and composition of beach debris, were our large sample size allowed us to do so, we did not include logistic variables (number of volunteers, beach width) in the analysis of temporal variation. For the same reason, the CV was calculated for the number of items, but not for the kilograms collected, as the latter was only available from the database of Ambiente Europeo.

Multivariate analyses were performed using PERMANOVA+ for PRIMER v6 (Plymouth Marine Laboratory, UK), whereas the rest of statistical analyses were conducted using the MASS library in R [43].

3. Results and discussion

Citizen-science initiatives provide a unique source of large datasets of standardized information of paramount importance to evaluate global environmental issues [41,44,45], including coastal pollution [4,46–48]. Previous studies have built upon these citizen efforts to better understand the spatio-temporal variation in the amount and composition of beach debris [e.g., 45,48], and also to identify the commercial brands related to the items found [48]. Here, we integrated the volunteering work of thousands of individuals and a comprehensive gathering of satellite and online information. By doing so, we were able to evaluate the relative importance of environmental and anthropogenic factors –and their interactions- as drivers of the level, composition and temporal dynamics of beach debris in our coasts. This is a necessary step to generate key information that can support the design of novel strategies to mitigate this ever-growing environmental threat [e.g., 4,7].

An average of 58 ± 14 kg of garbage (mean±SE; range 2400–0.3 kg) and 803 ± 92 items (range 27429–4 items) per 100 m were collected on the 881 sampled beaches (Fig. 1). Beach debris was dominated by cigarette butts, small pieces of plastic (<2.5 cm), remains of cans and bottles, and plastic or cardboard wrappers (Fig. 1). These four types of garbage accounted for more than half of the items collected, and come mainly from single-use items from land (rather than sea) origin. These results match previous observations on other European beaches [25], or those of Australia [6], Chile [10], Colombia [36], Hawaii [49], or India [50], to name a few, and generally support a greater importance of land than sea origin as sources of this waste [4,51,52]. The proportion of land-sourced items in beach debris is often context-dependent and has been subjected to debate over the last decade [reviewed in ref 53]. However, current estimates are somewhere between 60–80% [14], in accordance to results reported here. Nevertheless, it is important to notice that sea activities –particularly shipping activities- also partly determined beach debris (significantly increasing the amount and altering its composition; Fig. 2, Table S4). Shipping constitutes a major input of marine debris, many of which strand on beaches [54]. Indeed, the interplay between sea- (shipping) and land-based (human use) human activities was, in general, the most important interaction between anthropogenic drivers, significantly influencing the number and composition of the items found (Fig. 2; Table S4). Regardless of the source, beach debris is dominated by a vast majority of everyday single-use items, illustrating a general problem well beyond the Spanish coasts [see refs. above], and a pressing need in the reduction and management of these single-use items.

Although the importance of many of the environmental and anthropogenic drivers of beach debris have been previously evaluated in isolation [6,10,14,18], the unprecedented comprehensiveness of our database allowed us to assess the relative importance of these different predictors collectively, and also consider the interactions between them. Both the level, number of items and composition of beach debris were co-determined by environmental and anthropogenic factors (Figs. 2 and 3; Fig. S5; Tables S4, S6). Both our multiple regression and multivariate analyses showed that the level of environmental protection and human use (local anthropogenic factors), the presence of aquaculture facilities and nearby land uses (landscape environmental factors) drove beach debris' amount and composition together with shore exposure to dominant winds, type of substrate, and the distance to the nearest river (environmental factors; Figs. 2 and 3; Tables SA.1-SA.3).

Importantly, the effects of anthropogenic and environmental drivers on beach debris' amount and composition were not independent from each other. Interactions between environmental and anthropogenic factors were ubiquitous (Fig. 3). Indeed, interactions between local anthropogenic and environmental factors, and between local and landscape anthropogenic drivers (the latter discussed above), were by far the strongest predictors. The latter illustrates the need to account for these multiple environmental and anthropogenic drivers of the spatio-temporal variation in beach debris collectively, as their effects depend upon each other and this could help to increase our ability to predict and mitigate this environmental issue. Environmental × human, and (local) human × (landscape) human interactions accounted for over 50% of the variance explained on the different attributes of beach debris (Fig. 3), and this proportion was even larger (~60% on average) when studying specific items individually (Fig. S5). Strong efforts have been devoted over the last few years to raise awareness amongst beach users regarding how to manage their waste [55], in which citizen science has a great potential [56]. These efforts could partly explain the decoupling –with the important exception of cigarrete butts (Table S6)- we observed between our local human-use index and the amount of beach debris. However, these efforts seem to have not worked fully (or not yet) as we still found a substantial proportion of significant human use effects, and previous reports show an increase in beach debris by over 40% between 2001 and 2021 [5]. Furthermore, the fact that cigarrete butts constitute the number one item of beach debris, highlights that there is still a large work to be done on environmental debris awareness, especially on beach

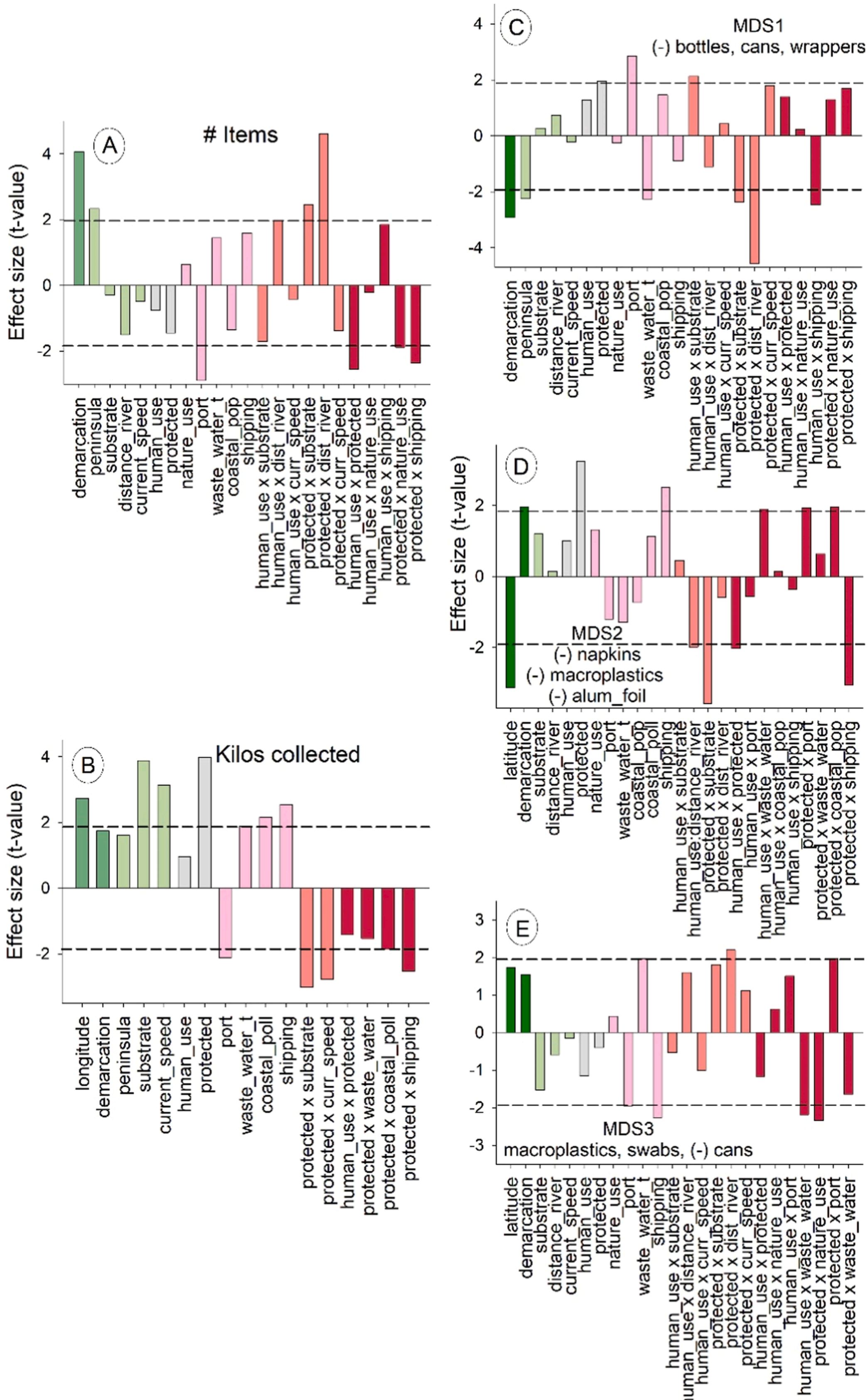

Fig. 2. Effect size of the different environmental (green colours) and anthropogenic (light grey and pink) factors, and their interactions (orange, red), on the number of items (A), kilograms collected (B) and composition of beach debris (C-E). Effect sizes (t-values) of the linear models, corrected by the number of volunteers and meters recovered are shown in all cases, with dashed lines indicating significant values (those above 1.96 or below −1.96).

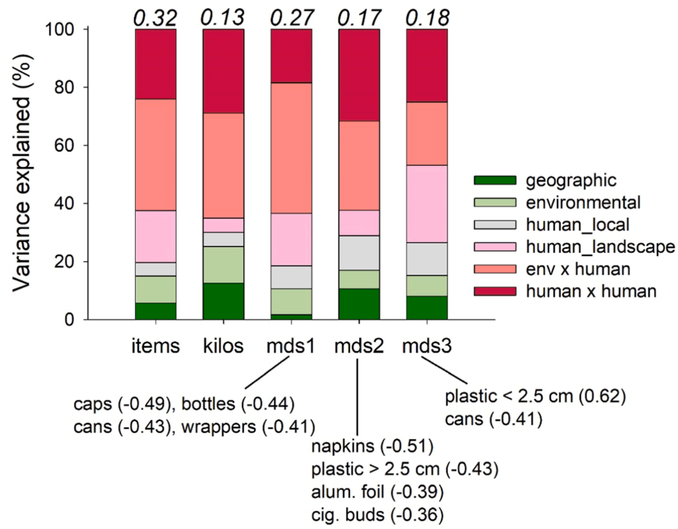

Fig. 3. Variance partitioning illustrating the relative importance of geographic (latitude, longitude, demarcation), environmental (substrate, distance to river, shore exposure index, mainland/island), anthropogenic pressure at the local ("human_local"; human use intensity, presence of an environmental protection figure) and landscape scales ("human_landscape"; land use nearby, presence of ports and waste water management plants, shipping activity, coastal population and pollution levels). Interactions between anthropogenic factors at the local and landscape scale ("human x human"), and between those and environmental factors ("env x human") are also shown. The adjusted R^2 of the most parsimonious models is shown for each response variable on the top of the graph. Variance partitioning was performed using the sum of squares from an ANOVA model performed with the set of predictors within the most parsimonious models; Table S3). The strongest Spearmans correlations between different types of items and each of the three nmds axis performed to analyse composition are also shown.

users.

Interactions with environmental factors were stronger for the level of protection than for the human use index (Table S4). Previously unexplored, environmental protection directly reduced macroplastic items or the number of cigarrete butts in populated areas (Table S6). The importance of the level of environmental protection can be partly explained because beaches are exposed to both marine and terrestrial disturbances. Thus, having protected areas that limit the number of users and restricts the uses in beaches may lower the level of exposure of these disturbances. In general, the highest number of items generally found in beaches close to a river mouth, exposed to dominant sea winds or with rocky (vs sandy) substrates [3,7] was partially reduced if these were under an environmental protection figure (protection x substrate [$F_{4,153} = 2.22$; $P = 0.06$], distance to river [$F_{2,153} = 7.80$; $P < 0.01$] and shore exposure index [$F_{2,153} = 4.66$; $P < 0.05$]). These strong effects of environmental protection, either individually or in interaction with other beach debris drivers, may reflect stronger efforts in beach cleaning in these spaces, limited shipping or other activities in the surroundings, or more environmental awareness in their visitors. Regardless of the mechanism behind, our results show that environmental protection could be a previously overlooked ally to control beach debris in our coasts. In addition, the interactions between the level of protection and other human activities we found, suggest that the former could reduce beach debris more efficiently in densely populated areas or on those with abundant shipping activity (Fig. 2, Table S4).

Despite considering most known anthropogenic, environmental, geographic and logistic drivers of beach debris, according to existing literature, a large fraction of its variation was unaccounted for in our models (maximum values of R^2 and adjusted R^2 of 0.44 and 0.32, respectively; see Fig. 3). This was also true for specific items (Fig. S5). These are figures similar to a previous study using standardized debris sampling and considering a large set of environmental and anthropogenic predictors in Australia [7], or a pan-European one including beach to beach variation with random effects [25]; ~50% of unexplained variance in both cases). A potential explanation for this result could be the strong and seemingly stochastic temporal variation found for different waste collections within a given beach across time. The average coefficient of variation amongst waste collections was 330% in the number of items collected, and this strong temporal variation remained even when collections dates differed just a week. This strong temporal variation has been previously acknowledged [14,27], yet its drivers are still poorly known. It is likely that storms or other extreme climatic events are of special importance when defining the levels of waste that reaches our coasts [e.g., 27,49,57], and may certainly have contributed to the large unexplained variation in our data. However, it is unlikely that such stochastic events would have biased our results in any particular direction, provided that our database covered nine years and the seasonal variation within (Table S2), and considering that our time-series analyses rendered qualitatively the same conclusions as our main analyses (e.g., Figs. 3 and 4B). Alternatively, atmospheric transport has been identified as a major source for microplastic pollution, even in remote regions [16,58]. Thus, it is a possibility that such atmospheric transport could also contribute larger debris to beaches, potentially explaining some of the remaining variance in our data.

Regardless of the influence of these unmeasured potential effects, we found that part of this temporal variation (over 50% of the very little variance explained) is driven by anthropogenic factors, particularly the interactions between those at the local and landscape scales (Fig. 4). The human use x shipping activity interaction (Fig. 4) could be reflecting the seasonal variation in recreational shipping activity, peaking in summer and buffered by local human intensity (more frequent throughout the year). Considering the very large temporal variability, and our very limited ability to predict it, these latter results clearly suggest that controlling the sources of beach debris, rather than intensifying cleaning campaigns, is the only effective way to reduce marine debris.

4. Conclusions and remaining research gaps

Our comprehensive assessment of the level, composition and temporal variation of beach debris across the Spanish coast revealed that such debris is dominated by single-use and land-sourced items, that should be regulated more strongly. Despite the large temporal variation found, our study reveals that environmental and anthropogenic pressures (both at the landscape and local scales) co-determine the level and composition of beach debris, and show the unexpected role of environmental protection as an ally to mitigate this issue.

Our results suggest that cleaning and monitoring efforts could be more effective if focusing mainly on rivers to prevent their spread to the marine environment, and on those beaches with rocky substrate, close to areas with large human populations or intense shipping activity, as these are more likely to accumulate debris. Our study shows that beach debris is heavily dominated by just a few the types of items: cigarrete butts, single-use plastic and metal items, and plastic wrappers, and similar findings are found elsewhere [7,14,25]. This helps focusing future research on the impacts of anthropogenic pollution, their sources, and their residence times [e.g., 60]. Especial care should be taken on the single-use items found to propose policies aiming at discouraging their use and identify the companies with larger responsibility to inform consumers about [e.g., 48, 53, 59]. Future research should aim at better understanding the role of time-dependent environmental predictors (e.g., extreme climatic events and atmospheric transport, both likely to vary under future climatic scenarios), as drivers of beach debris and its temporal dynamics. These overlooked predictors are expected to be key drivers of the distribution of beach debris and could gain even further importance under future climatic scenarios. In all these regards, extensive citizen science efforts can be a very powerful ally to gather this relevant information.

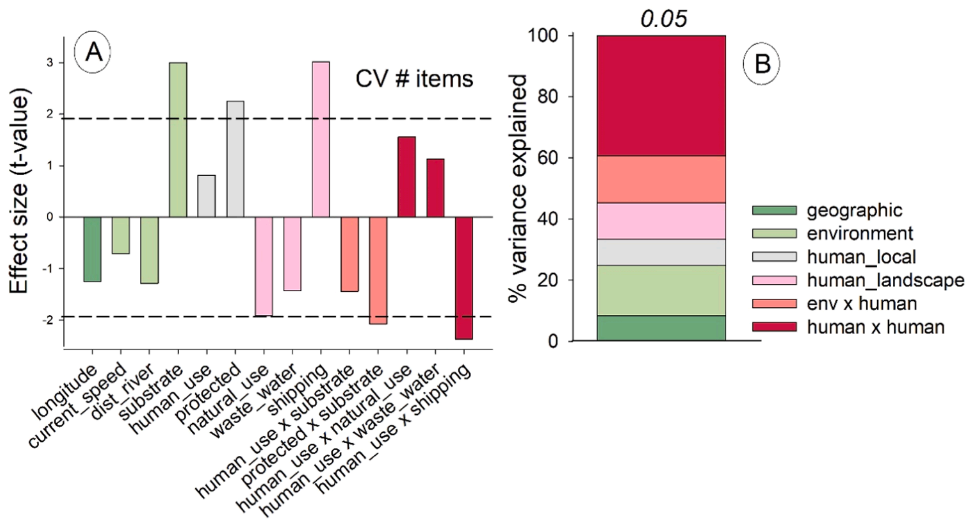

Fig. 4. Temporal variation analyses showing the effect size for the different predictors (A) and their corresponding variance partition analyses (B). Rest of legend as in Figs. 2 and 3.

Environmental implications

Plastic pollution is a global and growing environmental threat. Our study, based on a large citizen-science effort, considers the main environmental and anthropogenic drivers of beach debris accumulation acknowledged in current literature, to provide a sound and comprehensive assessment of the relative importance of these factors in determining the level, composition and temporal variation in beach debris accumulation. Beach debris is heavily dominated by single-use items and co-determined by the interaction between anthropogenic and environmental factors. Our findings may help environmental managers and policy makers to effectively reducing this threat based on informed decisions.

CRediT authorship contribution statement

Nuria Casado-Coy: Writing – review & editing, Methodology, Data curation. **Jose Emilio Martinez:** Writing – review & editing, Methodology. **Carlos Sanz-Lázaro:** Writing – review & editing, Project administration, Methodology, Formal analysis, Conceptualization. **Santiago Soliveres:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data is already available.

Acknowledgements

We really appreciate the altruistic efforts done by > 20000 volunteers who spent some of their time cleaning up our coasts. We also would like to thank Daniel Rolleri, Estíbaliz López-Samaniego and Xavier Curto from Ambiente Europeo, MARNOBA platform (Residuos Cero) and Surfrider, respectively, for their willingness and collaboration to share the data from their citizen science databases on the collection of marine litter on the beaches. Additionally, we would like to thank Marta Martínez-Gil Pardo de Vera from the of the Ministry for the Ecological Transition and Demographic Challenge for introducing us relevant contacts to obtain the citizen science databases. This study was supported by the Biodiversity Foundation of the Ministry for the Ecological Transition and Demographic Challenge from Spain [FBIOMARINA19–01]. SS and CSL acknowledge funding from the Spanish Research Agency (URBANCHANGE, TED2021–130908B-C44).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2024.133843.

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