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Coupling beach ecology and macroplastics litter studies: Current trends and the way ahead

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ABSTRACT

As sites of floating marine material deposition, sandy beaches accumulate marine litter. While research and assessment on beach litter is increasing and involves various actors (scientists, society and NGOs), there is the need to assess current and future dominant trends, directions and priorities in that research. As such, a textural co-occurrence analysis was applied to published scientific literature. Words were considered both singly and as part of compound terms related to concepts relevant to sandy beach ecology: morphodynamic state; Littoral Active Zone; indicator fauna. Litter as a compound term was also included. The main co-occurrences were found within compounds, with scarce interaction of "morphodynamic state" with the others, indicating the need for further integration of beach ecology paradigms into beached plastics studies. Three approaches are proposed to overcome the research limits highlighted: the unequivocation of terms, the consideration of adequate scales, and the attention to dynamics rather than just patterns.

1. Introduction

It is widely accepted that marine litter is a global phenomenon, recognized of concern at international levels therefore included in the UNEP initiatives such as the Sustainable Development Goals (SDG) or in G7 and G20 statements (Borja and Elliott, 2019). Indeed, SDG14 (Life below water) specifically has an extremely ambitious target to reduce or remove this source of pollution by 2025 (UN, 2015) although without further development that target has been criticized as being inaccurate and unattainable (Cormier and Elliott, 2017). Marine Litter has been defined by UNEP (UNEP, 2005) as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment". Macroplastics are a component of plastic litter, defined as plastic pieces above 25 mm size (Galgani et al., 2013), and further detailed as size-classes in the new guideline about macrolitter monitoring (Fleet et al., 2021). They include a broad range of materials and shapes, due to production, mechanical alterations or differential weathering and other degradation conditions of a complex of different polymers (Frigione et al., 2021). Macroplastics litter is often the source of secondary microplastic contamination (Andrady, 2011; Lambert et al., 2014; GESAMP, 2015). Although connected, research related to macroplastics litter differs greatly from that of microplastics in terms of study design, protocols, and analyses (Fleet et al., 2021). Addressing macroplastics contamination and pollution is likely to identify paths from source of littering to the access to food webs via breakdown.

1.1. Sandy beaches and beached plastics

Sandy beaches are an ecosystem exposed to and under threat from

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many global environmental problems, notable those termed the *triple whammy* of increased urbanization and industrialization, increased use of resources and decreased resistance and resilience to external threats such as climate change (Defeo and Elliott, 2021). The relatively young discipline (established in the 1980s, McLachlan, 1983) of sandy shore ecology began by identifying features shaping those physically-driven environments, and then proceeded by overlapping morphodynamic characterization with biotic data layers, finally superimposed on by human pressures (Defeo et al., in press). Current paradigms define the morphodynamic type of a beach as the interaction between sand particle size and exposure to tidal range and wave conditions: as such, dissipative beaches are characterized by gentle slopes, wide beach width and fine grain sizes as relevant features. By contrast, the reflective end of the scale occurs when the sediment is coarse and stored on the intertidal beach and backshore, and where there is no surf zone and waves surge directly up the beach face (McLachlan and Defeo, 2018). The macrofauna inhabiting beach environments reflects these variations: an increasing number of species is found toward dissipative beaches, which are more benign as less exposed to substrate tumbling. With a progression through the morphodynamic spectrum through intermediate beaches, most species become less successful, and few can colonize reflective beaches due to the harsher environment given by the saltation of coarse substratum particles subjected to the high energy of incoming waves. The morphodynamic state is hence relevant to beach functioning, with direct repercussion on the quality and quantity of ecosystem services (McLachlan et al., 2013; McLachlan and Defeo, 2018). Consequently, the occurrence of beached plastic could also be affected by the different exposure to and interaction with energy, matter and biota. The co-occurrence of environmental features and beached plastics data could reveal potential interactions occurring on matching spatial and/or temporal scales. It is hence timely to propose tools and standards quantifying beached plastic and beach ecological processes. For instance, the average specific gravity of plastics and polymers is 1.275 ± 0.303 g·cm^{-3} (calculated from AmesWeb, 2021) whereas that of substratum particles such as quartz grains is 2.65 g·cm^{-3} and that of marine mollusc shells 2.68–2.72 g·cm^{-3}. Therefore, plastic and polymer accumulate, are buried and re-suspended (Williams and Tudor, 2001). Density, shape and relative size of macroplastics and substratum particles are important when considering these dynamics, occurring along the land-sea axis (Lebreton and Andrady, 2019; Rangel-Buitrago et al., 2017; Moreira et al., 2016; Cresta and Battisti, 2021). Given the high relevance of the local level of beaches (Fanini et al., 2020), the variability in substratum and exposure will likely require tailored approaches depending on morphophysical and landscape features (Ryan and Perold, 2021) together with the application of standard protocols, essential to achieve data interoperability.

Macroplastics is also the most common subject of beach clean-up activities or citizen observation-based initiatives and monitoring actions. There is a common top-down approach to the topic, engaging society as citizen scientists and monitors (see the definition by ECSA, European Citizen Science Association http://ecsa.citizen-science.net/:). NGOs, private sectors and national agencies and departments are conducting surveys, campaigns and projects supporting data collections and evidence-based policies (Hidalgo-Ruz and Thiel, 2015; GESAMP, 2019; Syberg et al., 2020). Despite this, there are still challenges in the definition of the role of citizen science and data that it can provide (Haklay et al., 2021). However, it is through these activities that relevant evidence can be built, enabling macroscale patterns to be determined and finally be mainstreamed into policies. Indeed, it is through these campaigns that plastics were identified as the most common material composing human litter on the beach (Addamo et al., 2017). Also, bans on single use plastic items (SUP) were generally based on the top items found as beached macroplastics litter, on data collected by citizens and mediated by NGOs in their mainstream to policy making. Country implementation of international strategies such as the Programme of Measures for the European Marine Strategy Framework Directive (MSFD) - of which marine litter is Descriptor number 10 for determining Good Environmental Status - are also based on volunteer-led data collection. For example, the main marine litter monitoring in the UK has been the annual volunteer-led beach clean of the Marine Conservation Society (MCSUK) involving many thousand volunteers every September since 1994; this was recognized as part of the UK contribution to implementing the MSFD.

While these studies are powerful in depicting patterns and they strongly support governance via evidence-based information, studies tackling dynamics remain limited. Such studies would require the consideration of marine litter across temporal scales and disciplines, but also would need to be based on shared and quality-assured protocols, and shared data, which are a frequent constraint in large-scale studies (but see Morales-Caselles et al., 2021). The temporal dimension in particular reveals notable gaps, especially related to long-term designs and/or before-after impacts such as floods, typhoons, and bans of specific items e.g. single use plastic bags. Again, the relevance of the single beach unit in both social and ecological perspective would require attention since the very planning of actions.

1.2. Assessing plastics on beaches: protocols and state of the art

Reviews about methodologies for marine litter monitoring started in the 1990s (Rees and Pond, 1995) and standard methodologies are proposed by the Regional Seas Convention guidelines within their action plans such as Cheshire et al., 2009 (UNEP/IOC), Helsinki Convention (HELCOM, 2008), OSPAR Commission (2010) and Schulz et al. (2017). Furthermore, monitoring guidelines have been outlined for programmes such as the MSFD (Galgani et al., 2013), to support marine litter baselines (Hanke et al., 2019), threshold values (Van Loon et al., 2020) or providing harmonized list of items (Fleet et al., 2021). They mainly address: 1) Quantification (database – number, weight or volume); 2) characterization (composition - master lists); and 3) evidence-based policies for production consumption systems (e.g. brand auditing, target items campaigns, or littering sources).

Selection criteria for beaches to be monitored are also given, both in the framework of national programmes (Opfer et al., 2012), or international regulations such as MSFD (EC 2008 2008/56/EC), where marine litter represents an indicator of the environmental quality status of the ecosystem. As a general approach, a set of desirable characteristics is provided for identifying the sampling area to design monitoring and assessment programmes as well as for beach cleanup initiatives with volunteers (OSPAR, 2010; Galgani et al., 2013; GESAMP, 2019; WIOMSA manual -Western Indian Ocean Marine Science Association (Barnardo and Ribbink, 2020)), and UNEP/IOC manual (Cheshire et al., 2009).

In order to create robust and comparable quality-assured data, the monitoring methods have to be standardized, agreed and implemented consistently. When this relates to the areas that are monitored, the general indications about site selection include: accessibility of the site, and avoidance of steep slopes (15°-45°); areas not subjected to cleaning activities; avoid nesting sites for threatened species or presence of endangered or protected species; avoid streams, and natural or artificial elements likely to interfere with currents. In particular, the WIOMSA manual suggests a random selection of sites, and if this is not possible, a site selection guided by a pre-defined criterion, without previous investigation, in essence having a random sampling design. In all cases, the surveys for marine plastic macrolitter standing stock should be carried out along a predetermined length of 100 m running parallel to the shoreline (Barnardo and Ribbink, 2020).

There are a few protocols adapted to beach morphology, such as considering whether the area is macro or microtidal, and has reflective or dissipative conditions; fine sand or coarse sand or pebbles, presence/absence of organic litter (GESAMP, 2019). Turra et al. (2014) called for protocols relevant to sandy beach ecology (see also Moreira et al., 2016). However, to date, the integration of relevant sandy beach variables is left to single initiatives rather than embedded in protocols. However, beach structural features are intrinsically connected to functional processes occurring around sandy shores, from physical and biotic (faunal) conditions to socio-economic dimensions (see McLachlan and Defeo, 2018 for a recent comprehensive summary). For this reason, a greater connection of beach ecology with plastic studies would increase the relevance of research and enhance the support to policy and citizens. Given the high attention on the topic and the response by scientists which produce much literature about marine plastics litter, it was urgent to detect and communicate trends for future research. On this background, and with explicit focus on the macroplastics fraction, the aim here is to show the integration of ecological features of sandy beach systems into beached plastics litter studies. As such, the analysis of word co-occurrence in scientific publications was identified as suitable first step in this process.

2. Materials and methods

2.1. Keywords, compounds and co-occurrence in scientific literature

This analysis starts from the attention to concepts and related keywords, as this is the background for any further data organization and analysis. The textural approach of word co-occurrence analysis of published literature has proven to be insightful across scientific disciplines (Callon et al., 1983), including ecology (Neff and Corley, 2009). This approach was found relevant in identifying trends and gaps in research on different topics; here, it was applied to a range of keywords extracted from both beach ecology and plastic litter studies, as follows: 1) identification of keywords related to beach features relevant to geomorphology, ecology and biota, and of keywords related to beached plastic sizes (including macroplastics); 2) bibliometric analysis of how often, in published literature, these words co-occur; 3) recommendations on strategies and parameters to be applied within projects related to beached macroplastics litter.

We emphasise that this approach integrates beach ecology standard terms and concepts into marine macroplastics litter studies, and vice-versa (in a range of actions from research to opportunistic gap-filling visits, to citizen science campaigns and governance support). This has the added benefit of proactively and concurrently making data interoperable and beneficial to science and society.

In the synthesis here, given that globally relevant beach features extracted from the ecology of sandy shores are non-independent from each other, we therefore defined components as entities composed of a set of non-independent parts. This established a dimensionality in the exploration process, in a hierarchy defined by single keywords and compounds to which the keywords belong. Compounds and selected words were within the following categories:

Litter. The meaning of "litter" includes but is not limited to anthropogenic litter, which also is not exclusively related to plastics (Rangel-Buitrago et al., 2017). In the context of our analysis, litter was considered as a compound term, and given our intended focus on macroplastics litter, keywords were selected depending on the range of sizes most commonly used and standardized within plastics studies (Frias and Nash, 2019). Different plastic sizes are non-independent when considering weathering and breakdown, which are likely to occur on a beach, thereby creating secondary particles. Standing stock is a term originally related to biomass, but increasingly used to assess beached litter. It is specifically referred to a one-off count of beach plastics litter, and mentioned as such in international protocols and guidelines (JRC, 2013). It was therefore included in the compound.

The compound term "Litter" included the following keywords: "Plastic"; "Macroplastic"; "Microplastic"; "Nanoplastic"; "Macrolitter"; "Microlitter"; "Standing stock".

Morphodynamic state. The morphodynamic state is defined by sand, waves and tides and these two last are related to beach exposure; in turn, exposure relates to fetch distance and wind speed and direction. This state directly influences the human use of beaches, both individually and collectively through their determination of beach morphodynamic types (McLachlan et al., 2018). Morphodynamic variables are non-independent from each other, and a subtle combination of them categorizes each state, from dissipative to reflective. It can thus be hypothesized that on beaches, marine litter deposition, breakdown, resuspension and washing are also physically driven, likely by a set of physical variables largely overlapping to those characterizing morphodynamic states.

The compound term named "Morphodynamic" included the following keywords: "Beach exposure"; "Beach width"; "Beach slope"; "Grain size".

The Littoral Active Zone (LAZ). The LAZ concept was introduced as a budgetary approach to substratum dynamics (Tinley, 1985). A LAZ is composed by zones characterized by the dynamic exchange of mobile substratum, hence the LAZ is connecting the subtidal to the littoral and to the primary dune (Fig. 1). Recent extensions of the concept brought attention, from an initial energy and substratum consideration only, to the resident fauna behavior and to the social and ecological components of the system (Scapini et al., 2019; Fanini et al., 2021 respectively; Defeo et al., in press). The functionality of a beach is tied to the LAZ, and a functional LAZ is conferring resilience on the system.

The compound named "Littoral Zone" included the following keywords: "Sublittoral"; "Intertidal"; "Littoral"; "Beach"; "Dune".

Indicator fauna. To overlay a biotic data layer to the grid defined by morphodynamic state and LAZ, we considered a set of organisms recently highlighted as bioindicators of global relevance (Costa et al., 2020). These latter authors noted that the response to anthropogenic disturbances was related to the species (population, presence) organization level rather than higher (community or assemblage) ones. In this background, no organization level was considered, and single species were considered in the analysis as keywords. Finally, two flagship taxa with high conservation priority were added, such as nesting shorebirds (also mentioned in WIOMSA guidelines) and turtles (see McLachlan et al., 2013). Spawning fish, even though a relevant variable to both ecological and social template, was here not added as they are limited to specific (macrotidal and shallow sublittoral) waters, hence these are not universal.

The compound term "Fauna" included the following keywords: "Talitrid amphipods"; "Donacid clams"; "Ghost crabs"; "Spionid polychaetes"; "Beetles"; "Bird nest"; "Turtle nest".

2.2. Analysis

The keyword co-occurrence analysis was performed following established bibliometric steps of: information retrieval, pattern matching, data analysis, and data visualization (Cobo et al., 2011; Callon et al., 1983). A total of 32,304,541 unique abstracts were retrieved from PubMed -MEDLINE collection (accessed 03 April 2021). The abstracts were searched for the specific keywords, their synonyms and plural and hyphenated forms. The keyword occurrences in abstracts were then transformed to calculate their pairwise co-occurrences (Callon et al., 1983). These co-occurrences formed a network, which was analysed and visualized. The code is available here https://github.com/lab42open-team/pubmed_trend_analysis.

3. Results

There has been a large-scale increase of scientific publications targeting plastic (>80,000 abstracts) and litter (>20,000 abstracts) (Fig. 2). Even though these two keywords have been present in literature since the 1960s, the increase became exponential since the 1990s.

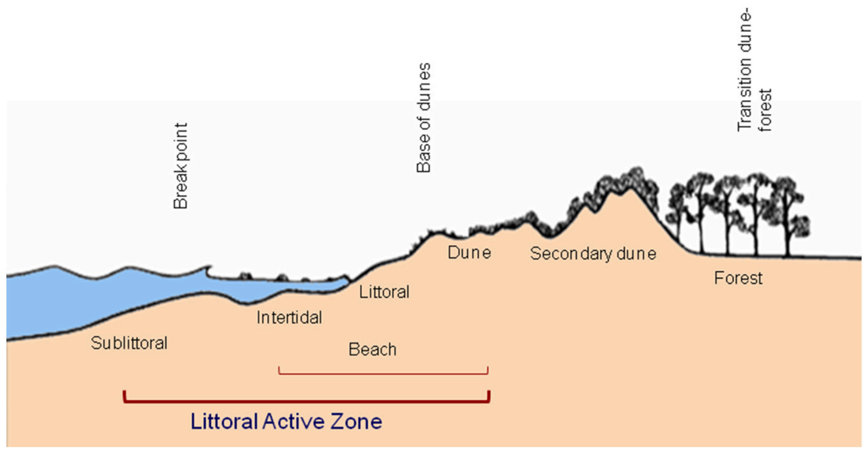

Fig. 1. Schematic representation of the Littoral Active Zone and keywords extracted for the analysis.

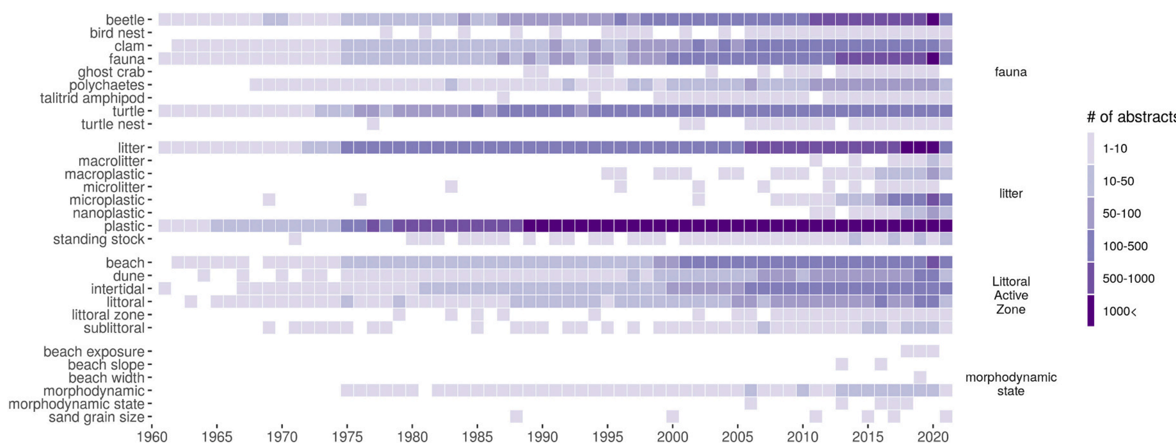

Fig. 2. Time heatmap of published literature. Keywords are on the Y-axis, grouped in compounds (visualized on the right).

Keywords related to plastic sizes, such as “microplastic” and “nanoplastic” appear to be on the same trend, although they started being mentioned in the last two decades. The heatmaps (Figs. 2 and 3) show an increase over time in literature as well as the co-dominance of faunal, litter and geomorphological terms.

The keyword “plastic” makes the strongest co-occurrences values: the highest co-occurrence is represented by words “plastic” and “microplastic” (991 abstracts including both words), followed by “plastic” and “litter” (583 abstracts including both words) (Fig. 3). These highest co-occurrence values were found within the “litter” compound. There were then 14 pairs of words co-occurring between 100 and 500 times; among them, eight pairs were across different compounds: “turtle” and “beach”; “turtle” and “plastic”; “plastic” and “beach”; “plastic” and “beetle”; “beach” and “litter”; “litter” and “beetle”; “litter” and “fauna”; “intertidal” and “fauna”. “Litter” is the compound being mentioned in six of them, in co-occurrence with keywords from the “fauna” and “LAZ” compounds.

The co-occurrence network (Fig. 4) highlights the way in which all keywords are generally used, similarly to a random network. The consideration of compounds, however, suggests a clustering, with “microplastic” being more connected to the network than words related to other plastic sizes, which remain at the edges of the network. Also keywords related to morphodynamic state remained at the margin, pointing at a scarce integration in beached plastics litter studies. It has to be noted however, that the lower number of publications (Fig. 2) could have played a role in defining this pattern. Finally, the two keywords related to beach-specific life stages of iconic species, i.e. turtle nest and

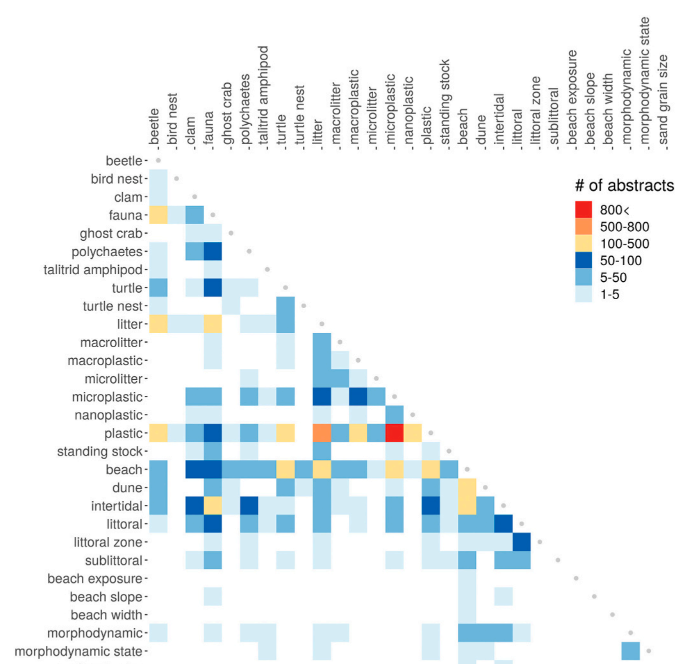

Fig. 3. Heatmap of co-occurrences of keywords (in alphabetical order).

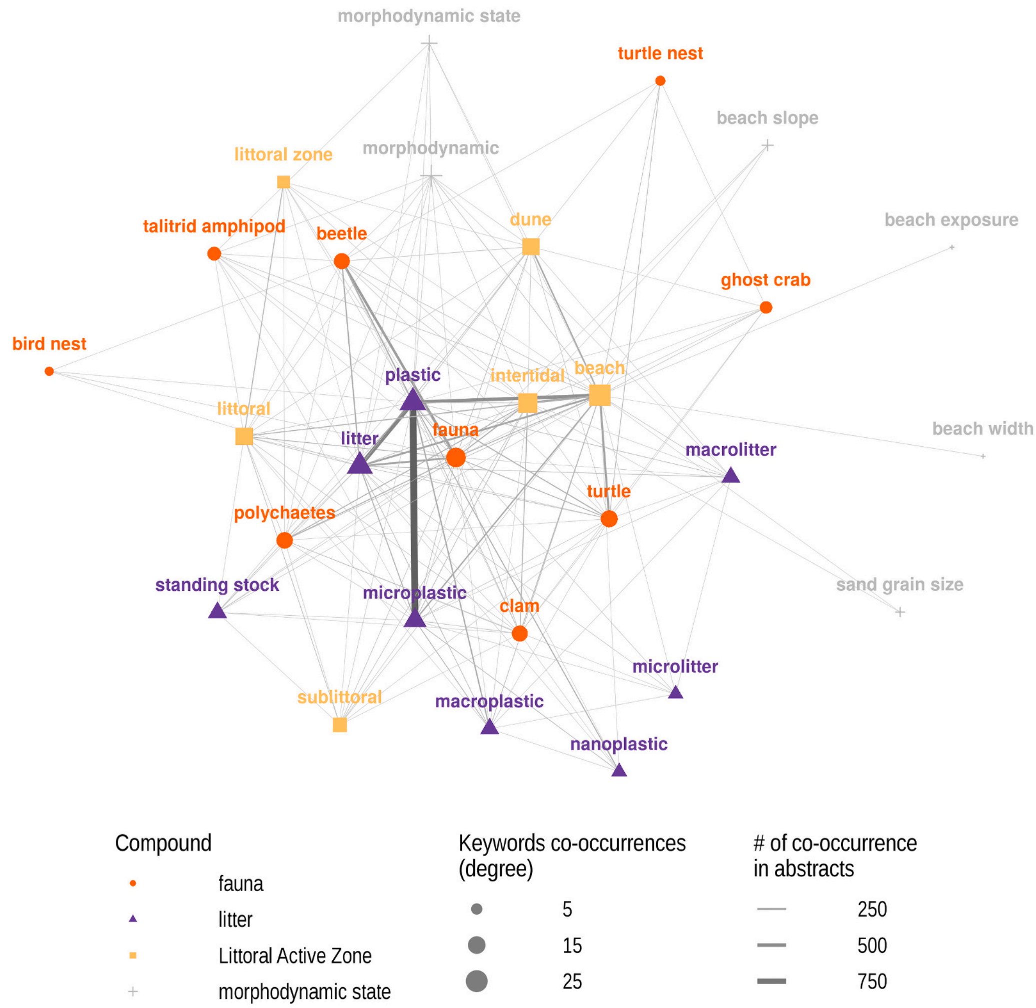

Fig. 4. Network visualization of co-occurrences. Compounds are marked in different colours and symbols. Sizes of symbols relate to the degree of co-occurrence of one word with all the others, while the thickness of the line indicates the number of co-occurrences between two single words. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bird nest, remain less connected. In contrast, the trend highlighted for the “LAZ” compound term is revealing that, in spite of the extremely scarce use of the concept (only recovered in the last few years after being neglected for decades), features included in the LAZ are being considered in research - especially “beach” but also “intertidal” and “littoral”- and the concept of the active zone could be directly fed with data proceeding from such studies, including those on plastics litter.

4. Discussion

The very large number of publications targeting plastics appears to include two trends related to macroplastics: 1) while still increasing, publications on macroplastics (unless “litter” and “macroplastic” are used as synonyms) are not increasing as much as those on microplastics, and 2) they remain less related to variables relevant to beach ecology. This latter point might hamper the consideration of a systems approach, where processes are regulated by key ecological variables, necessary to explain and predict the patterns observed. In a dynamic context such as the increasing number of publications on plastics, the detected use of keywords should serve as a warning to scientists, given that published literature – as analysed in this study - is the foundation of prospective research. Integration of newly produced data on plastics litter with known ecologically relevant features of beach ecology should proceed, especially in the view of the UN Decade of Ocean Science for Sustainability 2021–30, which has identified marine litter are a priority topic (Claudet et al., 2020; Elliott, 2021).

Research designed to obtain interoperable and comparable data would allow the ability to fully exploit information, toward advances in both sandy beach ecology and in studies related to beached macroplastics. Considering beaches as social ecological systems (Fanini et al., 2021; Defeo et al., in press) and the tight intertwining of the social and ecological parts of such a system, well-defined in space and easy to identify, such integrated information would promptly find multiple pathways for mainstreaming science evidence into society and governance.

From the analysis were derived potential constraints to integration, which were then grouped into three general topics: 1) unequivocation, 2) identifying a scale for the coupling ecology and plastics on beaches, and 3) targeting dynamics of beached plastics.

4.1. Unequivocation

With a rapidly increasing number of publications, and related datasets about plastics, meta-analyses will be required with a clear, unequivocal identification of items. In this respect, the use of terms which have been in use for long, but applied to other disciplines, should be used with caution. As examples, “litter”, and “standing stock” are adapted from ecology, although their meaning deeply differs when related to plastics or to natural material. Especially in the case of litter, the ambiguity also extends to a common perception among beach users and the public, i.e. whatever material is found stranded is litter, and is seen as damage to the aesthetics of landscape (see e.g. Williams et al., 2016). The distinction – starting from keywords - of natural vs. plastics substances should remain clear instead, due to their greatly different qualitative effects.

Also, terms such as macro-, meso- and micro- imply a range of sizes which differ between plastics and biology studies. The threshold of 5 mm as a discriminating size between macro and micro plastics (Frias and Nash, 2019, even though this is the most common, is not the only existing definition) does not apply to macro and microorganisms for instance, where the threshold is defined by the ability of resolution by the human eye. However, size categories are essential to unravel the interactions of plastics with beach substratum material and size, with unconsolidated material size spanning from sand classes (63 μm–1.5 mm), but also pebbles (2–64 mm) and cobbles (65–512 mm) (Blott and Pye, 2001), and a mixture of them. This is especially because of the importance of particle size in defining and interrogating the structure and functioning of beaches.

4.1.1. Recommendation

To avoid issues in current and future information management and analysis, it is recommended to add the word "plastic" whenever it refers to litter and/or standing stock, allowing recognition by improving discoverability in search engines and by text mining tools. The co-occurrence of these terms found in the analysis is a good sign, although such co-mention should become routine. The use of common synonyms (e.g. macroplastic OR macroplastics OR macro-plastic OR macro-plastics OR macro plastic OR macro plastics) should also become established for search engines.

Extending terminology standardization, terms such as macro-, meso-, micro- and nano- should consistently be accompanied by a dimension range, by the word "plastic" and used in one form (without a hyphen or space between them).

4.2. Identifying a scale for coupling ecology and plastics on beaches

A common ground for both beach ecology and beached macroplastics litter studies is the consideration of a single beach as biogeomorphological unit – a mesoscale in sandy beach ecology, where across- and along-shore physical and biotic patterns can be detected. Geomorphological characteristics shape biotic processes on sandy beaches with a well-defined across-shore gradient. It is therefore appropriate to assume that they also shape the interaction of plastics within the system. Broadly used protocols to study macroplastics litter do include some beach variables, although these are not framed in compound terms such as the geomorphological state and the LAZ. This prevents the identification of a beach as a system with boundaries and, as a consequence, the systemic effects of plastics as a stressor. Data on key variables for beach ecology (such as beach width, beach exposure, beach slope, dune presence) are indeed easy to gather, not least from aerial photographs or satellite images, and could frame the analysis of patterns within a systemic vision. In widespread protocols, it is recommended to use standard stretches or areas (e.g. 100 linear m transects as with OSPAR, or standard quadrats). While this allows consistency in the relative presence and abundance of plastics (see e.g. Clean Coast Index, Alkalay et al., 2007 and subsequent index modifications, which are still based on the number of items per area), it does not account for beach key features. Internationally-accepted protocols (Galgani et al., 2013; Hanke et al., 2019; GESAMP, 2019; Fleet et al., 2021) also consider freshwater inputs (Riverine Litter Observation Network) and urban areas as drivers in marine litter accumulation. However, the selection of units across a gradient of impact is often problematical.

4.2.1. Recommendation

By applying the ecological mesoscale (single beach) as the nominated unit, several dimensions for the interaction of beach ecology with beached plastics could be identified. The selection of sites could be less random and include the consideration of the morphodynamic state of beaches (from dissipative to reflective), as well as different substrata, and of the clear identification of the LAZ. In the case of extended beaches, the time/energy cost could be a limiting factor for researchers and/or citizen scientists. In these cases, indications from geomorphology (Nordstrom, 2005) and biodiversity studies (see specifically Battisti et al., 2017, for the application of biodiversity metrics to beached plastics) regarding the selection of subsites and replicates can be useful to optimize resources and create integrated datasets. Essential ecological variables defining the morphodynamic state could be cost-effectively integrated into protocols, given their simple measures: beach width, beach slope, exposure, grain size, and/or salinity. Furthermore, by considering single beaches as the unit for research across gradients, the concept of the gravity centre (Peng et al., 2017) could be developed to highlight spatial patterns such as those defined by cities and main freshwater discharges, and also to indicate temporal patterns (e.g. seasonal use of the beach). Finally, patterns related to a relevant ecological dimension could be connected to the social one, providing insights of a shift from reactive studies to proactive ones (Cinner et al., 2018).

4.3. Targeting dynamics of beached plastics

To address the problem of plastic pollution, it is of paramount importance to interrogate patterns observed with system drivers and dynamics, enabling the formulation of strategies and actions. Once the boundaries of the system are identified, the classification of internal and external drivers will follow logically, placing the information (which might be already largely available from existing datasets) as tiles in a mosaic. The LAZ was proposed as the unit relevant at the ecological and social-economic levels for the depiction of dynamics connecting these two states (Fanini et al., 2021) and could be considered as a unit also in the case of beached plastic studies. For example, hydrological or meteorological drivers, which may be important for budgeting or analysing dynamics of macroplastics on beaches, would act on the LAZ. Similarly, social drivers are also acting on the LAZ. In this respect, some good practices are already routinely established, such as the brand audits on beached items (for example using the bar-coding on labels), allowing the identification of dynamics of contamination and pollution (e.g. the age and source of the plastics). Many other actions at different scales might be explored to analyse the dynamics connecting producers/users/actors in charge of disposal, matching them with the patterns observed and reported in publications. Actions finely tuned to the specific context could be proposed, targeting, for example, the reduction of use and alternative choices to plastics (Riechers et al., 2021), as well as monitoring tools. Some of the LAZ components were found linked to beached plastics litter studies and so a data background is likely to be readily available following the conceptual up-take of the LAZ as part of a systems analysis. Temporal dynamics also deserve attention given that microplastics, as the degradation products of plastics and litter, have lately received a large amount of attention (Ivleva et al., 2017; Ryan, 2015;Rodrigues et al., 2021). Hence, it is timely to discriminate between primary and secondary particles, which is the dynamic connection between macro- and microplastic. Tools are increasingly available for the identification of plastic material found stranded, supporting essential information, such as toxicity, inertia, weathering (including biofilm creation) and break-down likelihood and follow up paths related to the occurrence of primary and secondary particles of plastics on a beach (Rodrigues et al., 2021). A focus on the weathering and breakdown of items on beaches might be a suitable inference method to link to studies on beach dynamics which started more than 50 years ago (see e.g. Frigione et al., 2021).

4.3.1. Recommendations

As with the budgetary approach to the dynamics of soft substratum – a concept on which the LAZ was originally based - budgetary approaches can also be established for plastics. Inputs and outputs into the LAZ could be estimated over different temporal scales, but also in terms of macro- and micro-plastic fractions (in terms of both weight and number of items, as already suggested in international protocols). This will shed further light on the eventual inter-dependency of sizes, especially if paired with the identification of social (e.g. tourism; fishery) and natural ecological/environmental (e.g. monsoons, beach exposure) drivers. Studies discriminating between primary and secondary microplastics should be encouraged, as they would greatly support the understanding of breakdown dynamics of plastics (GESAMP, 2015) while beached.

5. Conclusions

As remarked by Borja and Elliott (2019), it is no longer time to report occurrences of plastics without proposing solutions. It is also timely to tailor general solutions such as "increasing awareness; reducing littering; etc." to the specific context, i.e. defining system components, boundaries, and dynamics of interaction. Available data would then fit into such a systematic vision, allowing the elucidation of paths, on which calibrated solutions can be proposed and hold a higher likelihood of success. However, published literature showed that the coupling between plastic studies and the geomorphological beach system (the very background of its definition) is still limited. Therefore, the huge potential arising from integrated data collection still needs to be revealed. Integration could ultimately support governance, enhancing the return of research results as policy-informing and operational knowledge, especially in the case of beached plastics litter. This would counter the current trend in which beach managers and stakeholders are only exposed to a one-size-fits-all regulation with respect to beached plastics, whatever the exposure of the beach to waves and tides, and the size of the substratum particles. The consideration and inclusion of local characteristics would greatly sustain the small-scale management, often neglected by national and international guidelines. If intrinsic beach characteristics remain disconnected from monitoring programmes and we do not capitalize on the information available from beach ecology, there is the high risk of not increasing our understanding thereby disconnecting macroplastics litter studies from those beach features defining functional stability and ultimately, environmental sustainability.

CRediT authorship contribution statement

LF conceived the idea and led the writing;
SP performed the analysis and the data visualization; discussed the results;
OD; ME; VSS; MP participated to the writing from the beginning and through the revisions, bringing relevant contributions.

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.

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