frontiers | Frontiers in Sustainable Tourism

TYPE Original Research
PUBLISHED 22 August 2024
DOI 10.3389/frsut.2024.1371270

OPEN ACCESS

EDITED BY
Alix Varnajot,
University of Oulu, Finland

REVIEWED BY
Corry Yanti Manullang,
National Research and Innovation Agency (BRIN), Indonesia
Lucia Fanini,
University of Salento, Italy

*CORRESPONDENCE
Carol Maione
✉ cmaione@sdsu.edu

RECEIVED 16 January 2024
ACCEPTED 29 July 2024
PUBLISHED 22 August 2024

CITATION
Maione C, Fernandez G and Vito D (2024) Participatory mapping of transboundary pollution: the case of Imperial Beach, California. *Front. Sustain. Tour.* 3:1371270. doi: 10.3389/frsut.2024.1371270

Participatory mapping of transboundary pollution: the case of Imperial Beach, California

Carol Maione[1,2]*, Gabriela Fernandez[1] and Domenico Vito[1]

[1]Metabolism of Cities Living Lab, Center for Human Dynamics in the Mobile Age, Department of Geography, San Diego State University, San Diego, CA, United States, [2]Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy

Introduction: Transboundary pollution is a major global challenge and monitoring beach litter along international borders can reveal some of the pathways by which litter enters water bodies, and hence advance the implementation of measures to prevent pollution emissions into international waters.

Methods: In this paper, participatory mapping was used to detect beach litter in Imperial Beach, California, along the U.S.-Mexico international border. This study implemented a 3-step protocol including an introductory awareness workshop, a macro-debris survey to categorize and remove beach litter, and a qualitative assessment of pollution drivers.

Results: Results show that plastic litter is the most dominant across all transects (304 debris, 52.6% of all litter observations), with an average density of 76 pieces/transect, with plastic being the most common material. Participants identified some of the major causes of pollution with paucity of waste management facilities, tourism activities near/on the beach, and inflow of pollution across the border.

Discussion: The paper highlights the role of citizen science in monitoring pollution along large and border regions. Implications of this study include methodological and practical contributions to the study of marine pollution to supplement the current paucity of information on pollution movement and distribution.

KEYWORDS

beach litter, participatory mapping, citizen science, pollution monitoring, Imperial Beach

1 Introduction

Plastic debris has been documented in all aquatic environments across the world and is estimated to make up 80% of all floating particles (IUCN, 2021; UNEP, 2021). The impact of plastic pollution has become so significant (Andrady and Neal, 2009; Barnes et al., 2009; Thompson et al., 2009) that scientists suggest that we are currently living in a new geological era called "Plasticene" (Stager, 2011; Reed, 2015; Ross, 2018). Understanding the abundance and distribution of plastics across water bodies is fundamental to design and implement pollution mitigation strategies aimed at reducing pollution flows and their associated impacts (Nelms et al., 2022). Yet, identifying pollution types and spatial patterns necessitates great human effort and can be expensive and extremely time-consuming (Salgado-Hernanz et al., 2021). Additionally, data acquisition on transboundary pollution along border regions is especially problematic due to difficulty to trace flows across international waters, lack of unified and consistent monitoring and accounting systems (including measurement systems), and different policies and pollution mitigation strategies (Vito et al., 2022).

Several scholars advocate citizen science as a viable approach for collecting information on plastic pollution via engagement of volunteers in activities such as beach cleanups (Hidalgo-Ruz and Thiel, 2013; Battisti and Gippoliti, 2019; Rambonnet et al., 2019; Nelms et al., 2020, 2022; Fanini et al., 2022). Citizen science can bring several benefits to data collection, including overcoming logistics and financial constraints associated with the employment of trained scientists in the collection of large volumes of data (Nelms et al., 2017, 2022). Secondly, previous studies have demonstrated that citizen science is well-suited for studying large geographical areas (Rambonnet et al., 2019; Nelms et al., 2020; Syberg et al., 2020), and presents great potential for assessing transboundary pollution. Thirdly, the involvement of citizens in pollution monitoring and removal can serve the dual purpose of raising awareness of the scale and impacts of pollution and encouraging local communities to take an active role in pollution mitigation (Dickinson et al., 2012; Zettler et al., 2017; Nelms et al., 2019, 2022). Finally, the engagement of local communities allows to leverage indigenous and local knowledge about the territory to build capacity and empower stakeholders to find local-based solutions (Danielsen et al., 2018; Tengö et al., 2021; Albagli and Iwama, 2022).

Citizen science does not come without limitations. Concerns have raised regarding the quality and accuracy of the information collected by citizen scientists (Kosmala et al., 2016), which may be affected by the different skills of participants (e.g., participation in previous cleanups), their ability to understand and interpret the information (e.g., recognizing materials and types of litter items), as well as errors and biases (Bird et al., 2014). To overcome some of these constraints, a successful citizen science study requires the use of simple and standardized protocols for data collection, which can be easily understood and implemented by volunteer participants with different backgrounds and experience levels (Nelms et al., 2022). Furthermore, collected data require proper analysis (including elimination of errors and outliers) by trained scientists and cross-validation to increase the reliability of the information (Bonney et al., 2009; Zettler et al., 2017).

In this study, we explored the relevance of employing a citizen science approach to track beach litter along the US-Mexico international border, using Imperial Beach (California) as a main case study. Secondly, we characterized and quantified the amount of plastic debris to understand the proportion of plastic out of the collected beach litter. The context of analysis is particularly relevant for this study for two reasons. First, this region has the dual value of representing a complex tourist-commercial area where industrial activities (fisheries, tourist attractions, restoration and recreational services, and maritime transports) are both responsible for generating ocean plastic pollution and affected by its impact. Second, being a bordering region, it offers a unique opportunity to study the transboundary issues of plastic waste management, such as limited traceability of plastics, different policies and measures to allocate resources and keep material flows accountable, and uneven use and communication of data analytics to report about mismanaged plastic waste and pollution (Vito et al., 2022).

2 Materials and methods

2.1 Imperial Beach, California

The City of Imperial Beach is the southernmost beach town in California, located ∼5 miles north of Tijuana (Mexico). The investigation was carried out in the context of the Tijuana River (193 km), which originates in the Sierra de Juárez (Ensenada, Mexico) and flows across the international border into the U.S. to end in the Pacific Ocean. The area represents a vulnerable environment because the river is considered the most polluted waterway in San Diego County and one of the top-five most polluted rivers in California due to the influx of waste from Tijuana (Fairey et al., 1998; Van et al., 2012). Here, persistence of waste and pollution can result from (i) lack of debris removal and leakage containment targets; (ii) lack of consistent cleanups and removal efforts; (iii) inefficiency of the existing waste retainment infrastructure, especially due to waste overflowing during wet periods; and (iv) lack of consistent monitoring and waste assessment programs (URS, 2010, 2015; Weston Solutions, 2012; City of Imperial Beach, 2019; San Diego County Parks and Recreation, 2020).

2.2 Beach cleanup

For the analysis, we implemented a 3-step protocol, as prescribed by Hidalgo-Ruz and Thiel (2013), including (1) an introductory activity to raise awareness on marine litter and its impacts and provide the study's participants with basic information on how to collect and categorize litter; (2) a simple sampling protocol for large marine debris; and (3) a post-survey qualitative assessment to reflect on possible causes and impacts associated with beach litter (Figure 1).

2.2.1 Introduction and awareness

Introductory workshops were conducted during the month of April, 2022, at the Preuss School high school, under the University of California San Diego (UCSD), and at the Department of Geography's Metabolism of Cities Living Lab under the Center for Human Dynamics in the Mobile Age at San Diego State University (SDSU), San Diego (California). Workshop participants included high school and university students, teachers, researchers, and university staff. First, all participants were introduced to the topic of marine litter and plastic pollution, including their impacts on the marine environment, possible sources and pathways of marine pollution, and ways in which they could prevent pollution in their daily lives (e.g., reducing their plastic footprint, waste separation at home, etc.). Following, participants were presented with several case studies of participatory mapping and beach litter collection (e.g., Maione et al., 2022) to learn the role and importance of citizen science in data collection and beach litter removal. Thirdly, all participants received the sampling protocol to follow during the beach cleanup. Finally, they participated in a recycling concert. During this concluding activity, participants gave new life to domestic refuse and

FIGURE 1
(A) Introductory workshop. **(B)** Participants collecting beach litter. **(C)** Participants estimating the visual coverage within a quadrant. **(D)** Participant showing the most relevant SDGs associated with beach pollution. **(E)** Beach cleanup supervisors. **(F)** Post-survey sorting of collected litter items.

utilized plastic bottles, plastic cups, home goods containers, aluminum cans, disposable cutlery, and cardboard boxes to create musical instruments.

2.2.2 Sampling protocol

The beach cleanups took place on April 30th, 2022, in South Beach (32°58′ N, 117°13′ W), Imperial Beach (California). Prior to the sampling activities, the authors assessed the site conditions, including weather and tide, safety, and accessibility. Next, they identified the site's boundaries with physical barriers (e.g., separating walls and walking paths), as prescribed by NOAA (Lippiatt et al., 2013) and Intergovernmental Oceanographic Commission (2009), marked the boundaries with flag markers and ropes, recorded their GPS coordinates, and collected photographic evidence.

The sampling area was then divided into four consecutive transects sized 10 × 20 m perpendicular to the shoreline. The transects were selected based on their land uses and characteristics: transect 1 was located in proximity of the pier and closer to tourism and restoration activities; transect 2 was located in proximity of tourism and leisure facilities (e.g., volleyball courts, access to snorkeling tours, etc.); transect 3 was located further from tourism and restoration activities, and closer to the residential area; finally, transect 4 was located near the Tijuana River estuary along the U.S.-Mexico border (Figure 2).

Upon arrival, each participant received a sampling kit including a waste characterization table to classify litter items, one pen, one pair of gloves, one litter bag, one quadrant (1 × 1 m), and one strainer to sample within the quadrant. Participants were asked to:

- Record basic information including transect n., GPS coordinates of their assigned transects, photos of the sampling site, weather conditions, sampling date and time, and name of the surveyor.

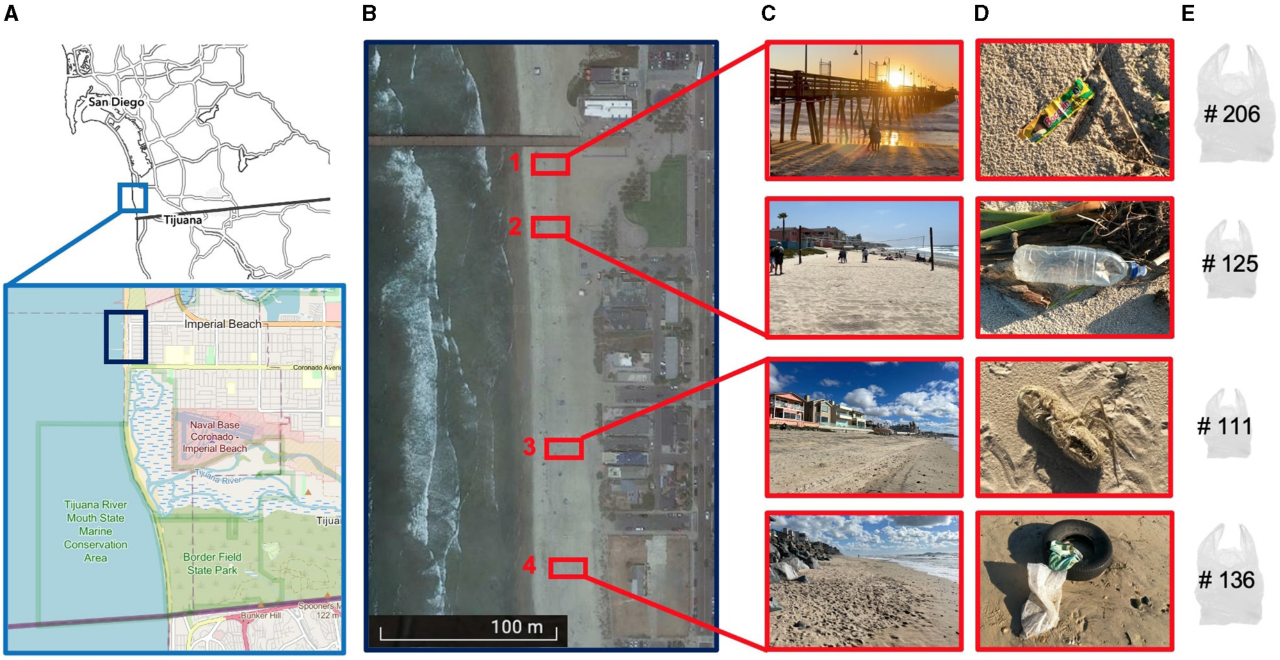


FIGURE 2
Map of the study site. **(A)** City of Imperial Beach, CA. **(B)** Transects along South Beach, Imperial Beach. **(C)** Photos showing the main characteristics of each transect. **(D)** Examples of litter items found on each transect. **(E)** Litter item count.

- Identify and characterize each litter item using the waste characterization table. Waste categories were defined based on MSFD classification and included: cloth/textile, food waste, wood, glass and ceramics, plastics, rubber, paper and cardboard, chemical and hazardous waste, and metal (Fleet et al., 2021). Only debris sized 2.5 cm or larger were surveyed, consistently with NOAA's operating guidelines (Lippiatt et al., 2013).
- Remove identified litter in the respect of personal safety (for example surveyors were asked not to remove hazardous materials, items with sharp edges, or contaminated waste).

2.2.3 Post-survey qualitative assessment

A concluding activity took place after the beach cleanup. During this activity, participants were asked to share their results and reflect on the following questions: (1) Where are the areas where litter is most prevalent? (2) How much litter occurs in the selected study site? (3) What is the litter composition? (4) What are the principal types of material? (5) What are the principal litter items? (6) Does the amount of litter vary across different transects?

Following, based on their personal experience and familiarity with the area, participants were asked to identify possible drivers of marine pollution, including principal waste generating sectors and activities located in the area, and environmental dangers with likely connections to marine pollution and in particular plastic pollution. Finally, they were asked to translate these problems into one or more of the United Nations' Sustainable Development Goal (SDG; UN, 2015).

2.3 Beach litter characterization and quantification

Post-survey, all collected beach litter was brought back to the lab, where the authors analyzed and validated the litter composition analysis. Each litter bag was processed following four steps. Firstly, the authors emptied each bag and re-classified the collected items to confirm (or not) the information recorded by the cleanup participants. Concerning chemical and hazardous wastes, surveyors were instructed to record the item's information but were specially asked not to collect them; hence, these materials were not included in the lab analysis. Secondly, the authors sun-dried all collected waste for a period of 3 h at 27°C. The third step was only performed for plastic waste, consistently with the study's objectives of analyzing the proportion of plastic out of the total collected beach litter. To this end, the authors recorded the amount (kg) of plastic by application. Detailed information on collected plastic items were used to determine density of plastic litter (kg/m^2) and transect coverage (n/m^2). This information was then used to determine the Clean Coast Index (CCI), defined by Alkalay et al. (2007) as the measure of appearance of plastic litter on the coast. The index identifies five cleanliness categories ranging from very clean (when no plastic litter is seen) to extremely dirty (when most of the beach is covered with plastic litter). Finally, all collected items were stored into separate litter bags for disposal.

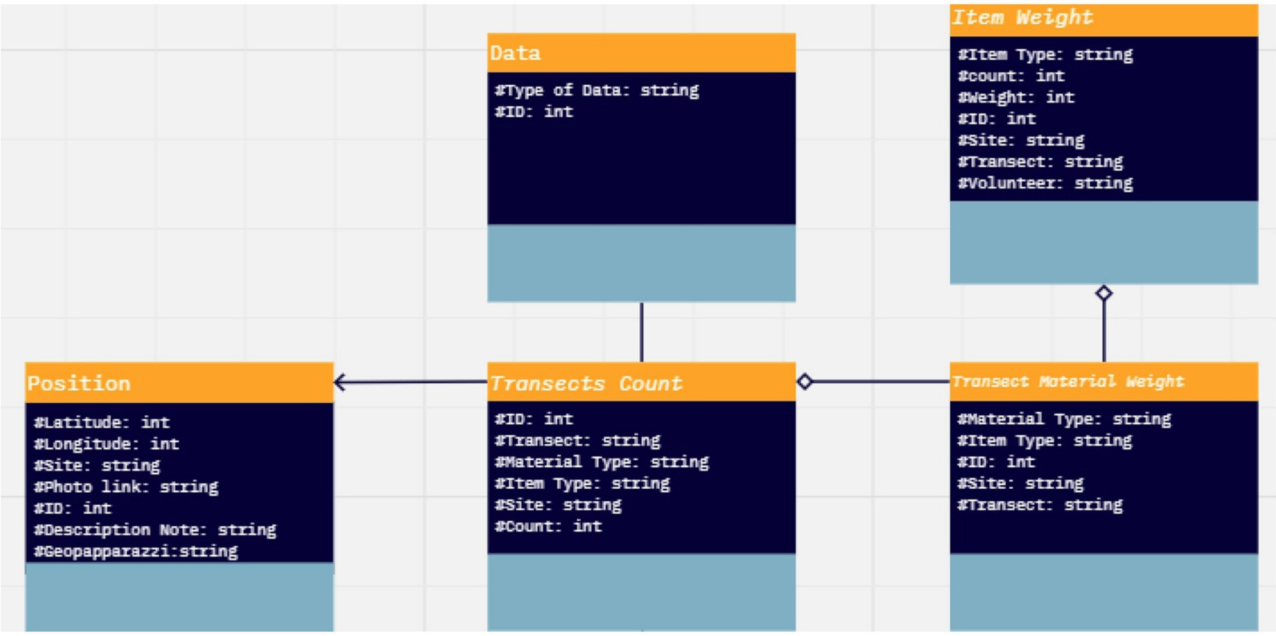
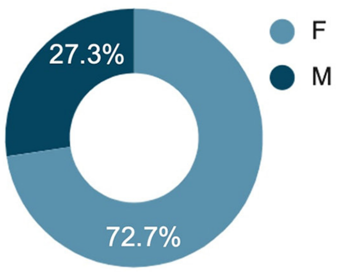


FIGURE 3
Entity-Relation structure of the database for collection of citizen science data.

A Respondents' gender



B Respondents' age groups

ID	Age range	Frequency
1	< 18	2 (9.1%)
2	18-24	10 (45.5%)
3	25-36	7 (31.8%)
4	50-59	2 (9.1%)
5	60-69	1 (4.5%)

FIGURE 4
Demographics of the cleanup participants. **(A)** Respondents' gender. **(B)** Respondents' age groups.

2.4 Citizen science data repository

The data collected are stored into a relational database (repository) that record all the different experiences of beach litters. Figure 3 shows the structure of the database for the overall collection of data.

3 Results

3.1 Volunteer participation

The beach cleanup involved 22 participants, including eight high school students aged 18 years old, eight college and graduate students aged 21–36, two teachers aged 50 and 65, respectively, two university staff aged 34 and 51, respectively, and two children aged 10 and 11 with accompanied guardian (Figure 4).

3.2 Beach litter composition

The participants returned 18 bags of litter (some participants worked in small groups; Table 1, Figure 5). A total of 578 litter items were collected across the four transects and, out of these, more than half (304 debris, 52.6%) were plastics. Plastic shopping bags, drink bottles, plastic caps and rings from bottle caps, wrappers, straws, and styrofoam containers were among the most found plastic items. Paper and cardboard was the second most common beach litter material (88 items, 15.2%), with paper fragments, paper packaging, paper plates and trays being the most found litter items; followed by metal (48 items, 8.3%), including beverage cans, bottle caps, and aluminum foil, and food waste (33 items, 5.7%). All other waste materials constituted <5% of the total observations, respectively. For transect 1, the surveyors collected 4 bags of litter, for a total of 206 litter items, including 92 (44.7%) plastic items, 34 (16.5%) paper

10.3389/frsut.2024.1371270

and cardboard, 24 (11.7%) metal pieces, and 20 (9.7%) chemical and hazardous waste (not collected). Concerning transect 2, the surveyors collected five bags of litter filled with 125 L items. Of these, 83 (66.4%) were plastics and 10 (8.0%) were rubber. The surveyors collected 4 L bags on transect 3, for a total of 111 L items, including 49 (44.1%) plastics, 17 (15.3%) paper and cardboard, and 15 (13.5%) food wastes. Finally, 5 L bags were collected on transect 4, filled with 136 L items. Of these, 80 (58.8%) were plastics, 29 (21.3%) were paper and cardboard, and 11 (8.1%) were food wastes.

3.3 Occurrence and abundance of plastic debris

As shown in Table 1 above, plastic was the most prevalent litter type on all transects, with an average density of 76 pieces/transect. Table 2 presents an overview of the plastic coverage for the four selected transects. Plastic litter was recorded by all surveyors, with an average of 12.3–23 plastic items per surveyor/group. For transect 1, we recorded the highest frequency of plastic pollution, with 92 items weighing ∼2.5 kg, but the lowest plastic density (0.01 kg/m^2). The most common plastic items collected by our surveyors were chips/sweets wrappers and other wrappers, straws, plastics caps/lids, plastic tags, plastic shopping bags, and COVID-19 masks. For transect 2, we recorded 83 plastic debris weighing 4.9 kg, with a density of 0.02 kg/m^2. Common plastic items included plastic cutlery, wrappers, styrofoam containers, and COVID-19 masks. Transect 3 reported the lowest frequency of plastic pollution, for a total of 49 plastic debris weighing 3.0 kg, with a density of 0.02 kg/m^2. Examples of common items found in transect 3 include wrappers, cigarette butts, and polystyrene pieces. Finally, transect 4 reported the highest density of plastics, with 80 pieces weighing ∼8.2 kg, for an average density of 0.04 kg/m^2. Examples of common items found in transect 4 include polystyrene pieces, wrappers, and straws. For all transects, the CCI was moderate (CCI = 5–10), with transect 1 presenting the highest value (CCI = 9.2) and transect 3 presenting the lowest value (CCI = 5).

3.4 Qualitative assessment

Post-survey, we asked all participants to share their findings and comment on similarities and differences among the four transects through a community perception survey (Table 3). The citizen engagement was influenced by the Delphi method to collect citizen perception and attitudes during the intervention (Cunha et al., 2022). Participants were interviewed and guided through a series of discussions on key issues related to coastal pollution in the 4 transects. The connection with the UN SDGs was introduced by aligning the discussions with specific SDG references within the local context, ensuring that the outcomes were practical and relevant to Imperial Beach. Before the interviews, participants were given an overview of the SDGs to enhance their knowledge and provide context for the discussion. Participants shared their knowledge, concerns, and recommendations on similarities and differences among the four transects. This qualitative research method involves collecting and analyzing the perspectives and

TABLE 1 Imperial Beach litter composition analysis by transect (N = 578).

Transect information			Litter composition by type								
Transect n.	Litter bag ID	N. of surveyors	Plastic	Rubber	Paper and cardboard	Glass and ceramics	Metal	Cloth/textile	Food waste	Wood	Chemicals and hazardous waste
1	4	6	92	1	34	15	24	-	6	14	20
2	5	5	83	10	8	6	4	8	1	5	-
3	4	6	49	7	17	5	11	2	15	5	-
4	5	5	80	1	29	2	9	-	11	2	2
Tot.	18	22	304 (52.6%)	19 (3.3%)	88 (15.2%)	28 (4.8%)	48 (8.3%)	10 (1.7%)	33 (5.7%)	26 (4.5%)	22 (3.8%)

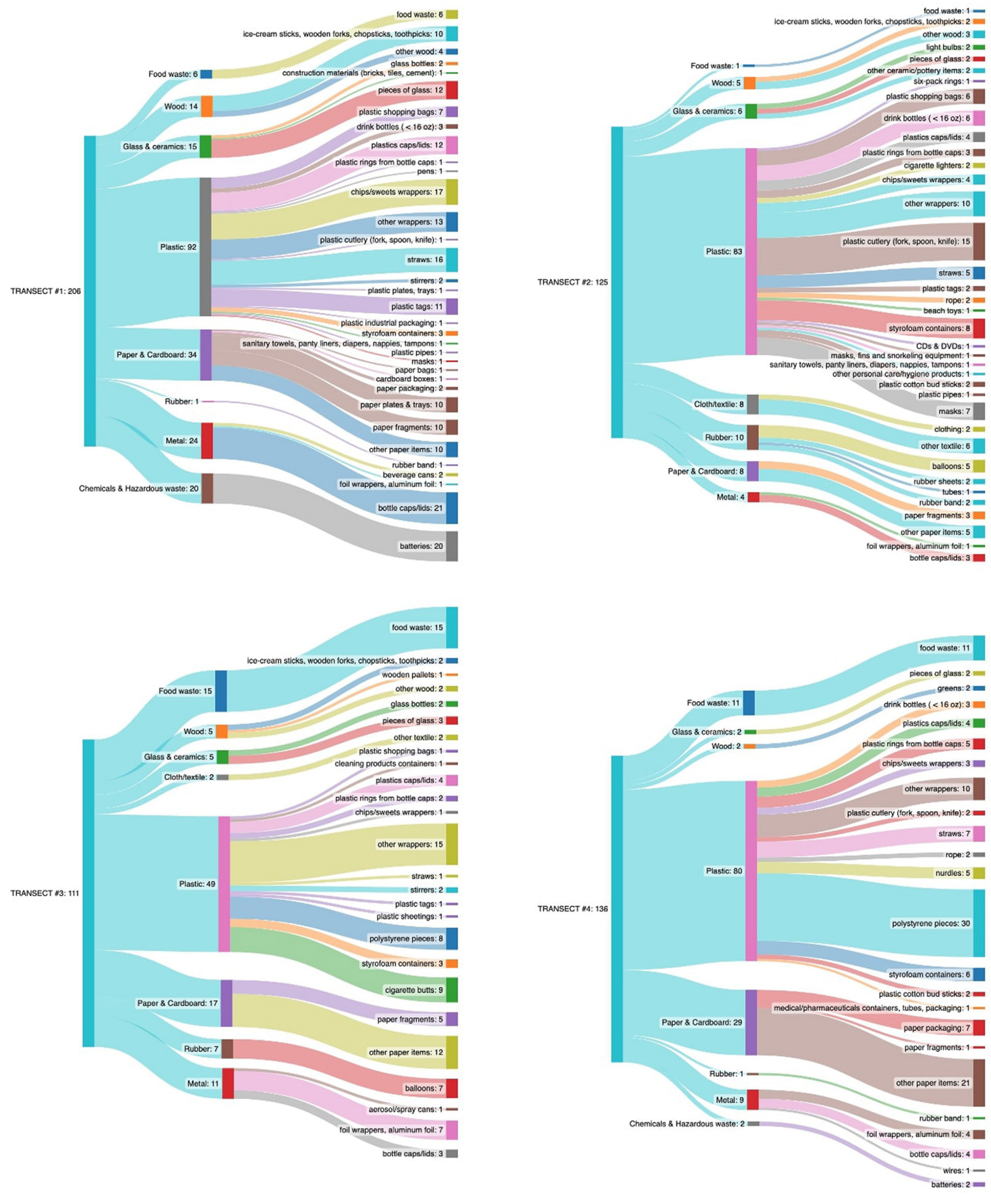


FIGURE 5
Beach litter composition analysis by material and litter type and transect ($N = 578$).

experiences of community members to gain insights into their views on environmental issues and the outcomes of specific interventions. Moreover, participants acknowledged that plastic accumulations varied among the transects and identified possible causes in different land uses and beach activities occurring in proximity of each transect. For example, participants from transect

TABLE 2 Amounts and types of collected plastics.

Transect n.	Plastics (n)	Amount (kg)	Density (kg/m^2)	Likelihood of collection (n/surveyor)	Transect coverage (n/m^2)	Clean Coast Index
1	92	2.5	0.01	23	0.46	9.2
2	83	4.9	0.02	16.6	0.42	8.4
3	49	3.0	0.02	12.3	0.25	5
4	80	8.2	0.04	16	0.40	8

1—the transect with the highest plastic frequency—observed that the insufficient presence of trash cans, especially near commercial and food activities, or the lack of information about the location and use of existing trash cans were major drivers of littering. According to their experience, commercial and food packaging were the main sources of plastic on transect 1, which was also reflected by the higher presence of plastic tableware, food and other wrappers. Based on their observations, participants raised the need to mitigate beach pollution by improving local infrastructure (SDG9) and implementing sustainability initiatives involving local and tourist communities (SDG11).

Concerning transect 2, participants noticed that the presence of tourism and leisure activities contributed to a widespread presence of plastic debris across the entire transect. In particular, they observed a majority of plastic tableware and bottles, as well as personal equipment (e.g., masks). Participants suggested the need to implement sustainability measures (SDG11) to foster and incentivize sustainable consumption of plastic, responsible behaviors, and pro-environmental practices during leisure activities (SDG12).

With regard to transect 3, surveyors noted that the transect presented the lowest frequency of plastic debris. According to their experience, a possible explanation is that the transect was located in a residential area further away from tourism uses, and therefore is less exposed to dwellings and beach users. However, participants found a fair amount of cigarette butts and house goods which, in their opinion, were linked to the houses' direct access to the beach. Hence, they suggested the necessity to implement sustainability measures (SDG11) and responsible consumption behaviors (SDG12) across the households with direct access to the beach.

Finally, all participants agreed that transect 4 presented the higher density of plastic debris. Unsurprisingly, participants noted that the proximity of the international border was a major contributor to pollution, and in particular plastic pollution, on transect 4, including littering activities, transboundary pollution flowing across rivers and outflows, and waste being washed ashore. Notably, participants reported a higher presence of microplastics, such as nurdles. For what concerns possible solutions to mitigate pollution in the area, they suggested the urgency to protect land and sea wildlife, with particular attention to the wildlife refuge located along the border (SDG14). Second, they raised the need to implement sustainability measures on both sides of the border (SDG11). Third, it was suggested that information and awareness campaigns on plastic pollution and its impacts on the local ecosystems are needed, especially to sensitize communities on the effects and risks associated with transboundary pollution (SDG4). Finally, some participants mentioned that water and sanitation was a major issue in the area, especially due to the lack of wastewater treatment and the frequent runoff of chemicals and sewage, which impair beach activities and can cause severe damage to human and environmental health (SDG6).

4 Discussion

Our study presents the results of a beach cleanup conducted in Imperial Beach, California, along the U.S.-Mexico border. The findings of our analysis records the quantity, entity, and magnitude of marine pollution, and specifically plastic pollution, through a detailed comparative analysis of four transects. The implications of this study provide useful information on the nature and distribution of plastic wastes on the coastal line. This information is useful to orient policies and capillary intervention both to interventive and preventive action.

Citizen science initiatives such as beach cleanups are globally spreading thanks to their power to include communities, activate and spread awareness on environmental topics. From a practical point of view, a combination of citizen science approaches represents an effective understanding to reduce the amount of pollution in the environment (Nelms et al., 2022). From a scientific point of view, it offers an opportunity to gather insightful, real-time, and consistent data on abundance, distribution, and composition of plastic accumulations across larger areas, such as international borders. Additionally, as researchers, learning from residents exposed to environmental injustices and polluted beaches can enhance our understanding of local challenges.

This study uses the UN SDGs as a framework to guide our efforts, influenced by the Marine Strategy Framework Directive where marine litter is established as a descriptor and quantified accordingly. This approach is beneficial to localize the UN SDGs by pinpointing specific goals and references to devise practical solutions tailored to local governments. The proposed approach aims in fact to identify actionable goals and strategies inspired by the SDGs to address specific local challenges related to coastal pollution (Campbell et al., 2019; Fritz et al., 2019; Fraisl et al., 2020). Furthermore, engaging in a multifaceted approach to citizen science involving beach cleanup protocols, waste categorization, and community surveys offers a robust and comprehensive strategy for creating awareness about waste in coastal tourism areas.

In particular, the data presented in this study have the dual value of providing insights on perception and behaviors related to

TABLE 3 Imperial Beach's community perceptions on beach pollution and its drivers by transect.

Transect	Observations on litter	Most found plastic debris	Possible drivers of pollution	Future areas of intervention
1	Plastic was the most surveyed material, especially near commercial and food activities	Straws; chips/sweets wrappers; other wrappers; plastic tags; plastic caps/lids	Proximity of commercial and food activities; paucity of trash cans; lacking/poor information on trash cans location and instructions	SDG9: Industry, innovation and infrastructure; SDG11: Sustainable cities and communities
2	Plastic was abundant across the entire transect	Plastic cutlery; other wrappers; styrofoam containers; masks; drink bottles; plastic shopping bags	Proximity of sport and leisure activities; mixed land uses	SDG11: Sustainable cities and communities; SDG12: Responsible production and consumption
3	Plastic was <½ of the total litter observations; presence of food waste and other waste associated with residential uses	Other wrappers; cigarette butts; polystyrene pieces	Housing with direct access the beach	SDG11: Sustainable cities and communities; SDG12: Responsible production and consumption
4	Higher density of plastic and microplastics	Polystyrene pieces; other wrappers; straws; styrofoam containers; nurdles	Border area; cross-border rivers and water outflows contributing to pollution; transboundary pollution washed ashore	SDG14: Life below water; SDG11: Sustainable cities and communities; SDG4: Quality education; SDG6: Clean water and sanitation

plastic pollution on beaches, hence expanding our understanding of the impacts of beach users on the provision of ecosystem services (e.g., cultural services including societal goods and benefits), which integrity is jeopardized by the growing threat of mismanaged waste and pollution in the coastal environment, which can eventually lead to alteration of the original functions (Defeo et al., 2021).

Secondly, the findings of this study provide consumers with evidence-based quantitative data on waste mismanagement, which could be used to support guidelines for the proper waste disposal at the household level and promote responsible behavior during beach visits to prevent pollution. When considering connecting households' role in change and transnational issues, it is essential to consider how individual actions at the household level can influence broader, transnational environmental issues. By fostering responsible waste disposal practices and promoting environmental stewardship within households, we can create a cumulative effect that contributes to global sustainability efforts. Household level changes can reduce local pollution, which in turn can lessen the burden on transnational waterways and coastal areas. This connection underscores the importance of grassroots efforts in tackling global environmental challenges.

Our findings resonate with those of previous studies employing citizen scientists in data collection: implementing a structured beach cleanup protocol, as outlined and conducted by scholars (Nelms et al., 2017, 2022), not only educates participants in environmentally friendly practices, but also enables the collection of valuable data on the extent and nature of beach pollution. Secondly, waste categorization, as demonstrated by Rochman et al. (2015), deepens the analysis by providing insights into the sources of pollution and the potential impact of nearby land uses. Thirdly, scholars such as Ottinger (2017) and Ottinger and Cavalier (2016), add a crucial human dimension, revealing community perceptions, behaviors, and experiences related to beach pollution.

Finally, participatory mapping is a well-known practice that can contribute to building community cohesion, help to engage participants to be involved in resource and land-related decision-making, raise awareness about pressing land-related issues and ultimately contribute to empowering local communities and their members (Mwandundu, 2009; Vito, 2018). Participatory approaches in spatial analysis are rooted in the implementation of Participatory Rural Appraisal (PRA) methods during the 1980's. Their success shows the fast growth of people's participation (Oakley, 1991). As a result, from the very birth of the concept of participatory mapping (Denwood et al., 2022), citizen science data have been used extensively in studies on biodiversity and pollution, and crowdsourced data are increasingly used by UN operational agencies (de Sherbinin et al., 2021).

While this study proposed a hybrid beneficial approach, future research should address certain limitations. For instance, the subjective nature of community surveys may introduce bias, and researchers should explore ways to mitigate this (Conrad and Hilchey, 2011). For example, collecting data in a biased way inevitably leads to the production of low quality data (i) bad data processing, mainly caused by the fact that when amateurs collect data through cheap, unverified, uncalibrated sensors, the immediate fear is to have "junk data"; and (ii) the observer effect, related to the fact that observation generally specifically alters human behavior and thus the process of measure (Cuff et al., 2008).

Additionally, long term studies could enhance our understanding and behavioral change. Moreover, incorporating emerging technologies, such as machine learning and remote sensing, could provide a more accurate analysis of pollution patterns and aid in developing targeted interventions for pollution mitigation in coastal areas. Despite these considerations, the integration of diverse citizen science methods remains a promising avenue for advancing both knowledge and awareness of beach pollution.

To address these issues, the protocol proposed in this study included the preliminary training of participants on both general and specific goals of data acquisition, and a follow-up activity to qualitatively map the interconnections between the observed issues and the SDGs. The development of such citizen-centric protocol has the dual value of fostering awareness on the overall global goal of plastic pollution in the sea and related SDGs (Maione et al., 2022), and bridging existing gaps in citizen science databases via standardization of sampling procedures in a simple, clear, and understandable manner. The standardized acquisition protocol is indeed pivotal to validating the accuracy of citizen science data, while it also provides practical and policy implications.

In this way, not only does citizen science contribute to create awareness among participants and finally community but also allows to have data on debris density over controlled areas that can estimate material flows related to activities on the performed area: by classifying the type of litters collected and georeference the point of collection is indeed possible to reconduct to the possible types of anthropogenic activities at the source of the waste and thus plan localized strategies to address plastic pollution problem.

5 Conclusion

This is the first study of its kind to use citizen science to map transboundary pollution along the U.S.-Mexico border. The current study proposes an easy and replicable methodology to detect and monitor beach litter via participatory mapping, beach cleanup protocols, and community perception surveys. The study can be applied in other ways to enable inquiry of other border areas and larger coastal regions. Our findings revealed that plastic was the most dominant material on all surveyed sites, and possible sources of plastic pollution were identified with commercial and leisure activities, households, and pollution inflows across the U.S.-Mexico international border. However, some limitations of the proposed approach are associated with the involvement of citizen volunteers. Our analysis can supplement the current paucity of data on transboundary pollution in general, and on plastic pollution in the Southern California and the Baja California region in particular, hence informing decisions on beach and coastal management. Transboundary pollution is a significant issue that needs to be addressed, particularly in beaches with high concentrations of pollution (sewage, bacteria, viruses, parasites, fertilizers, pesticides, radioactive substances etc.) along the US-Mexico border, indicating increased awareness and a willingness to contribute to achieving the UN SDGs for surfers, fishermen, citizens, tourist, and all types of people. Finally, future research could investigate the extent and distribution of beach pollution on both sides of the border to compare material information and draw cross-national implications.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/participants or patients'/participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

Author contributions

CM: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. GF: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. DV: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

We would like to thank the Preuss School, Tri-M Music Honor Society at the University of California of San Diego Nai-Ching Hwong and Carla Petraglia (Ecology Club), the City of Imperial Beach, the Metabolism of Cities Living Lab, Center for Human Dynamics in the Mobile Age, and Department of Geography volunteers and researchers that contributed to this work and sponsored the event including Ming-Hsiang Tsou, Thomas Derig, Karenina Zaballa, and others. All participants were informed about the use and dissemination of the study's results, including the use of photographs from the events.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Albagli, S., and Iwama, A. Y. (2022). Citizen science and the right to research: building local knowledge of climate change impacts. *Human. Soc. Sci. Commun*. 9:. doi: 10.1057/s41599-022-01040-8

Alkalay, R., Pasternak, G., and Zask, A. (2007). Clean-coast index-a new approach for beach cleanliness assessment. *Ocean Coast. Manag.* 50, 352–362. doi: 10.1016/j.ocecoaman.2006.10.002

Andrady, A. L., and Neal, M. A. (2009). Applications and societal benefits of plastics. *Philos. Trans. Royal Soc. B Biol. Sci*. 364, 1977–1984. doi: 10.1098/rstb.2008.0304

Barnes, D. K., Galgani, F., Thompson, R. C., and Barlaz, M. (2009). Accumulation and fragmentation of plastic debris in global environments. *Philos. Trans. Royal Soc. B Biol. Sci*. 364, 1985–1998. doi: 10.1098/rstb.2008.0205

Battisti, C., and Gippoliti, S. (2019). Not just trash! Anthropogenic marine litter as a "charismatic threat" driving citizen-based conservation management actions. *Anim. Conserv*. 22, 311–313. doi: 10.1111/acv.12473

Bird, T. J., Bates, A. E., Lefcheck, J. S., Hill, N. A., Thomson, R. J., Edgar, G. J., et al. (2014). Statistical solutions for error and bias in global citizen science datasets. *Biol. Conserv*. 173, 144–154. doi: 10.1016/j.biocon.2013.07.037

Bonney, R., Cooper, C. B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., et al. (2009). Citizen science: a developing tool for expanding science knowledge and scientific literacy. *BioScience* 59, 977–984. doi: 10.1525/bio.2009.59.11.9

Campbell, J., Sahou, J. J., Sebukeera, C., Giada, S., Gilman, J., Hur, Y. R., et al. (2019). *Measuring Progress: Towards Achieving the Environmental Dimension of the SDGs*. Available at: https://stg-wedocs.unep.org/handle/20.500.11822/27627 (accessed August 26, 2023).

City of Imperial Beach (2019). *General Plan and Local Coastal Program Land Use Plan*. Available at: https://files.ceqanet.opr.ca.gov/250078-2/attachment/doJr0ADe3N3RN964rmBpN1FqyLOCIcIG2w-SDoWu0V2zvOEGFW4dFGkRANMurvWkdpMEGYfoJ1TAZPXx0 (accessed August 26, 2023).

Conrad, C. C., and Hilchey, K. G. (2011). A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environ. Monitor. Assess*. 176, 273–291. doi: 10.1007/s10661-010-1582-5

Cuff, D., Hansen, M., and Kang, J. (2008). Urban sensing: out of the woods. *Commun. ACM* 51, 24–33. doi: 10.1145/1325555.1325562

Cunha, M. C., Marques, J., Dias, L. C., Cotera, I. R., and Triantaphyllidis, G. (2022). A Delphi based approach to the assessment of new marine litter reduction and processing technologies. *Front. Mar. Sci*. 9:886581. doi: 10.3389/fmars.2022.886581

Danielsen, F., Burgess, N. D., Coronado, I., Enghoff, M., Holt, S., Jensen, P. M., et al. (2018). *The Value of Indigenous and Local Knowledge as Citizen Science*. UCL Press. Available at: https://www.jstor.org/stable/pdf/j.ctv550cf2.15.pdf (accessed August 30, 2023).

de Sherbinin, A., Bowser, A., Chuang, T. R., Cooper, C., Danielsen, F., Edmunds, R., et al. (2021). The critical importance of citizen science data. *Front. Clim*. 20:650760. doi: 10.3389/fclim.2021.650760

Defeo, O., McLachlan, A., Armitage, D., Elliott, M., and Pittman, J. (2021). Sandy beach social-ecological systems at risk: regime shifts, collapses, and governance challenges. *Front. Ecol. Environ*. 19, 564–573. doi: 10.1002/fee.2406

Denwood, T., Huck, J. J., and Lindley, S. (2022). Participatory mapping: a systematic review and open science framework for future research. *Ann. Am. Assoc. Geogr*. 112, 2324–2343. doi: 10.1080/24694452.2022.2065964

Dickinson, J. L., Shirk, J., Bonter, D., Bonney, R., Crain, R. L., Martin, J., et al. (2012). The current state of citizen science as a tool for ecological research and public engagement. *Front. Ecol. Environ*. 10, 291–297. doi: 10.1890/110236

Fairey, R., Roberts, C., Jacobi, M., Lamerdin, S., Clark, R., Downing, J., et al. (1998). Assessment of sediment toxicity and chemical concentrations in the San Diego Bay region, California, USA. *Environ. Toxicol. Chem*. 17, 1570–1581. doi: 10.1002/etc.5620170819

Fanini, L., Bozzeda, F., Salvo, V. S., and Pinna, M. (2022). Information gain and loss between masterlists and intermediary-level protocols for the sampling of beached macrolitter. *Estuar. Coast. Shelf Sci*. 276:108012. doi: 10.1016/j.ecss.2022.108012

Fleet, D., Vlachogianni, T., and Hanke, G. (2021). *A Joint List of Litter Categories for Marine Macrolitter Monitoring. EUR 30348 EN*. Luxembourg: Publications Office of the European Union.

Fraisl, D., Campbell, J., See, L., Wehn, U., Wardlaw, J., Gold, M., et al. (2020). Mapping citizen science contributions to the UN sustainable development goals. *Sustainabil. Sci*. 15, 1735–1751. doi: 10.1007/s11625-020-00833-7

Fritz, S., See, L., Carlson, T., Haklay, M. M., Oliver, J. L., Fraisl, D., et al. (2019). Citizen science and the United Nations sustainable development goals. *Nat. Sustainabil*. 2, 922–930. doi: 10.1038/s41893-019-0390-3

Hidalgo-Ruz, V., and Thiel, M. (2013). Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. *Mar. Environ. Res*. 87, 12–18. doi: 10.1016/j.marenvres.2013.02.015

Intergovernmental Oceanographic Commission (2009). *UNEP/IOC Guidelines on Survey and Monitoring of Marine Litter*. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/13604/rsrs186.pdf?sequence=1andisAllowed=y (accessed September 3, 2023).

IUCN (2021). *Marine Plastic Pollution*. International Union for Conservation of Nature. Available at: https://www.iucn.org/sites/default/files/2022-04/marine_plastic_pollution_issues_brief_nov21.pdf (accessed September 3, 2023).

Kosmala, M., Wiggins, A., Swanson, A., and Simmons, B. (2016). Assessing data quality in citizen science. *Front. Ecol. Environ*. 14, 551–560. doi: 10.1002/fee.1436

Lippiatt, S., Opfer, S., and Arthur, C. (2013). *Marine Debris Monitoring and Assessment: Recommendations for Monitoring Debris Trends in the Marine Environment*. Available at: https://repository.library.noaa.gov/view/noaa/2681 (accessed May 25, 2023).

Maione, C., Fernandez, G., Vito, D., Marsaglia, L., Cortez, M., and Buurstee, C. (2022). "Protecting our oceans with citizen science: El Astillero, Nicaragua," in *SDGs in the Americas and Caribbean Region. Implementing the UN Sustainable Development Goals—Regional Perspectives*, eds. W. Leal Filho, N. Aguilar-Rivera, B. Borsari, R.B. de Brito, and P. B. Andrade Guerra (Cham: Springer), 1.

Mwandundu, S. (2009). *Good Practices in Participatory Mapping*. Rome: The international Fund for Agricultural Development.

Nelms, S. E., Coombes, C., Foster, L. C., Galloway, T. S., Godley, B. J., Lindeque, P. K., et al. (2017). Marine anthropogenic litter on British beaches: a 10-year nationwide assessment using citizen science data. *Sci. Tot. Environ*. 579, 1399–1409. doi: 10.1016/j.scitotenv.2016.11.137

Nelms, S. E., Duncan, E. M., Broderick, A. C., Galloway, T. S., Godfrey, M. H., Hamann, M., et al. (2019). Plastic and marine turtles: a review and call for research. *ICES J. Mar. Sci*. 76, 143–153.

Nelms, S. E., Easman, E., Anderson, N., Berg, M., Coates, S., Crosby, A., et al. (2022). The role of citizen science in addressing plastic pollution: challenges and opportunities. *Environ. Sci. Pol*. 128, 14–23. doi: 10.1016/j.envsci.2021.11.002

Nelms, S. E., Eyles, L., Godley, B. J., Richardson, P. B., Selley, H., Solandt, J. L., et al. (2020). Investigating the distribution and regional occurrence of anthropogenic litter in English marine protected areas using 25 years of citizen-science beach clean data. *Environ. Pollut*. 263:114365. doi: 10.1016/j.envpol.2020.114365

Oakley, P. (1991). *Projects With People: The Practice of Participation in Rural Development*. Geneva: International Labour Organization.

Ottinger, G., 2017. Making sense of citizen science: Stories as a hermeneutic resource. *Energy Res. Soc. Sci*. 31, 41–49. doi: 10.1016/j.erss.2017.06.014

Ottinger, G., and Cavalier, D. (2016). "Social movement-based citizen science," in *The Rightful Place of Science: Citizen Science*, pp. 89–103. Available at: http://www.researchgate.net/profile/Darlene-Cavalier/publication/305489010_The_Rightful_Place_of_Science_Citizen_Science/links/5790fc1e08ae4e917d0468c7/The-Rightful-Place-of-Science-Citizen-Science.pdf

Rambonnet, L., Vink, S. C., Land-Zandstra, A. M., and Bosker, T. (2019). Making citizen science count: best practices and challenges of citizen science projects on plastics in aquatic environments. *Mar. Pollut. Bullet*. 145, 271–277. doi: 10.1016/j.marpolbul.2019.05.056

Reed, C. (2015). Dawn of the plasticene age. *New Scientist*. 225, 28–32. doi: 10.1016/S0262-4079(15)60215-9

Rochman, C. M., Tahir, A., Williams, S. L., Baxa, D. V., Lam, R., Miller, J. T., et al. (2015). Anthropogenic debris in seafood: plastic debris and fibers from textiles in fish and bivalves sold for human consumption. *Sci. Rep*. 5:14340. doi: 10.1038/srep14340

Ross, N. L. (2018). The "plasticene" epoch. *Elements* 14:291. doi: 10.2138/gselements.14.5.291

Salgado-Hernanz, P. M., Bauzà, J., Alomar, C., Compa, M., Romero, L., and Deudero, S. (2021). Assessment of marine litter through remote sensing: recent approaches and future goals. *Mar. Pollut. Bullet*. 168:112347. doi: 10.1016/j.marpolbul.2021.112347

San Diego County Parks and Recreation (2020). *Tijuana River Valley—Needs and Opportunities Assessment—Sediment Technical Memorandum*. San Diego, CA. Available at: https://www.sdparks.org/content/dam/sdparks/en/pdf/Resource-Management/Appendix%20E%20-%20Sediment%20Technical%20Memorandum.pdf (accessed October 10, 2023).

Stager, C. (2011). *Deep Future: The Next 100,000 Years of Life on Earth*. New York, NY: Macmillan.

Syberg, K., Palmqvist, A., Khan, F. R., Strand, J., Vollertsen, J., Clausen, L. P. W., et al. (2020). A nationwide assessment of plastic pollution in the Danish realm using citizen science. *Sci. Rep*. 10, 1–11. doi: 10.1038/s41598-020-74768-5

Tengö, M., Austin, B. J., Danielsen, F., and Fernández-Llamazares, Á. (2021). Creating synergies between citizen science and Indigenous and local knowledge. *BioScience* 71, 503–518. doi: 10.1093/biosci/biab023

Thompson, R. C., Swan, S. H., Moore, C. J., and Vom Saal, F. S. (2009). Our plastic age. *Philos. Trans. Royal Soc. B Biol. Sci*. 364, 1973–1976. doi: 10.1098/rstb.2009.0054

UN (2015). *The 17 Goals*. Available at: https://sdgs.un.org/goals (accessed October 10, 2023).

UNEP (2021). *Policy Options to Eliminate Additional Marine Plastic Litter: By 2050 Under the G20 Osaka Blue Ocean Vision. Report of the International Resource Panel*. Nairobi: United Nations Environment Programme. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/36440/POEAMPL.pdf (accessed October 10, 2023).

URS (2010). *Report of Trash, Waste Tire and Sediment Characterization*. Tijuana River Valley, San Diego, CA: URS Corporation.

URS (2015). *Tijuana River Watershed Management Area Water Quality Improvement Plan*. URS Corporation. Available at: https://www.sandiego.gov/sites/default/files/legacy/stormwater/pdf/TJR_WaterQualityImprovementPlan_021715.pdf (accessed November 15, 2023).

Van, A., Rochman, C. M., Flores, E. M., Hill, K. L., Vargas, E., Vargas, S. A., et al. (2012). Persistent organic pollutants in plastic marine debris found on beaches in San Diego, California. *Chemosphere* 86, 258–263. doi: 10.1016/j.chemosphere.2011.09.039

Vito, D. (2018). Enhancing participation through ICTs: how modern information technologies can improve participatory approaches fostering sustainable development. *Sustain. Urb. Dev. Global.* 10, 131–145. doi: 10.1007/978-3-319-61988-0_10

Vito, D., Fernandez, G., and Maione, C. (2022). A toolkit to monitor marine litter and plastic pollution on coastal tourism sites. *Environ. Eng. Manag. J*. 21, 1721–1731. doi: 10.30638/eemj.2022.153

Weston Solutions (2012). *Tijuana River Bacterial Source Identification Study*. *Final Report*. Available at: www.waterboards.ca.gov/sandiego/water_issues/programs/tijuana_river_valley_strategy/docs/previous_meetings/2012_Tijuana_River_Bacterial_Source_Identification_Study-Final_Report.pdf (accessed November 15, 2023)

Zettler, E. R., Takada, H., Monteleone, B., Mallos, N., Eriksen, M., and Amaral-Zettler, L. A. (2017). Incorporating citizen science to study plastics in the environment. *Analyt. Methods* 9, 1392–1403. doi: 10.1039/C6AY02716D