Marine Pollution Bulletin 151 (2020) 110794

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Measuring plastic pellet (nurdle) abundance on shorelines throughout the Gulf of Mexico using citizen scientists: Establishing a platform for policy-relevant research

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ARTICLE INFO

Keywords:
Nurdles
Marine debris
Microplastic
Citizen science
Gulf of Mexico

ABSTRACT

There is an increasing awareness of microplastics within the global problem of marine plastic pollution. In 2018, small plastic pellets or “nurdles” were observed on the beaches of Corpus Christi, Texas. A citizen science project, “Nurdle Patrol,” was established by the Mission-Aransas National Estuarine Research Reserve to monitor the presence of nurdles, with volunteer interest enabling this project to expand across the Gulf of Mexico region. This case study describes the sampling methodology, the policy framework, and initial quantitative data from the citizen science project on nurdle distribution along the Gulf coast. A total of 2042 Nurdle Patrol surveys have been conducted by 744 citizen scientists covering shorelines from Mahahual, Mexico to Fort Jefferson, Florida. All 20 of the highest standardized nurdle counts were recorded at sites in Texas. Results can inform decision-maker response across regulatory scales and further research on nurdle pollution.

1. Introduction

Plastic pollution in the marine environment is a growing problem globally, including microplastics such as nurdles (Avio et al., 2017). Almost all plastic products originate from small plastic pellets known as nurdles. Nurdles are manufactured and shipped around the world to factories where they are melted down and molded into plastic products such as bottles, grocery bags, cups, sunglasses, etc. Nurdles can be made of polyethylene, polypropylene, polystyrene, polyvinyl chloride, or other plastic types; plus a variety of additives are mixed into the plastics to create pellets of different densities. Due to their small size and buoyancy, nurdles are hard to contain and have been recorded washing up on beaches all over the world (Eriksen et al., 2013; Fernandino et al., 2015). Nurdles have likely been entering waterways since the 1940s when plastic started being mass produced (Jambeck et al., 2015). The first scientific reports of nurdles washing up on beaches were published in the 1970s (Carpenter and Smith, 1972; Carpenter et al., 1972). Current estimates for the quantity of pellets entering the environment is 230,000 tons per year globally (Sherrington, 2016), with > 167,000 per year annually from Europe (Hann et al., 2018). Scientists in the U.K. have estimated that there are 5–53 billion pellets released annually in that region alone (Cole and Sherrington, 2016). Plastic pellets can be lost to the environment at all stages of the plastics supply chain where pellets are handled, including at the manufacturing site, during transportation, loading, storage, and at the fabrication facility (Karlsson et al., 2018).

Several studies have identified multiple turtle, fish, and bird species that ingest nurdles (Carpenter et al., 1972; Kartar et al., 1973; Baltz and Morejohn, 1977; Plotkin and Amos, 1988; Plotkin and Amos, 1990; USEPA, 1992b). The list of species known to ingest plastic pellets numbers in the hundreds (Kühn et al., 2015), although effects on animals are difficult to quantify. Though there has not been a direct link between nurdles and impacts on animals, several studies have shown that microplastics in general can have physiological effects on behavior (Mattsson et al., 2014), metabolism (Lu et al., 2016), and reproduction changes (Sussarellu et al., 2016). To date, the impacts of nurdles passing through the food chain remain uncertain.

In September 2018, a high number of nurdles were observed on

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https://doi.org/10.1016/j.marpolbul.2019.110794
Received 27 September 2019; Received in revised form 27 November 2019; Accepted 29 November 2019
Available online 29 January 2020

Mustang and North Padre Islands near Corpus Christi, Texas.[1] Researchers at the University of Texas Marine Science Institute (UTMSI) estimated that between 300,000 to 1 million nurdles per mile were present for at least 24 miles of Mustang and North Padre Islands. State agencies believed this to be a unique event, likely to be caused by an offshore spill during transportation, and there would be no cleanup measures taken to remove the nurdles from impacted beaches. Due to the known impacts of microplastics on wildlife as well as significant uncertainties about ecosystem impacts, a Gulf of Mexico-wide citizen science project, *Nurdle Patrol*, was established in November 2018 by the Mission-Aransas National Estuarine Research Reserve (Reserve) located at UTMSI to sample concentrations of nurdles at beaches across the Gulf of Mexico in an effort to better understand regional presence on beaches, potential sources, and appropriate policy response. Nurdle data from this project can be used by agencies for planning policy responses, and by researchers to identify sampling locations for future studies on impacts of plastic pellets on fish and wildlife, ecology, and chemical absorption.

This study describes the design, methodology, and evolution of the Nurdle Patrol monitoring project, summarizes the data collected to date, and reviews the utility of the project as it relates to policy decisions and agency action. This case serves a policy-relevant study for other countries and jurisdictions managing for micro-plastic pollution, especially in coastal regions where heavy industry (such as petro-chemical manufacturing) dominate the economic landscape.

1.1. Citizen science

A citizen science project can be a useful tool for gathering great amounts of data across large spatial scales (Conrad and Hilchey, 2011; Galgani et al., 2015; Hidalgo-Ruz and Thiel, 2015; Forrest et al., 2019). A citizen scientist is, “a volunteer who collects and/or processes data as part of a scientific enquiry,” with the origins of citizen science tracing back to the 1700s, and the rise of paid “professional” sciences being a relatively modern phenomenon (Silvertown, 2009; Bonney et al., 2014). The most well-known examples of citizen science come from the field of ornithology where the Audubon Society's Christmas Bird Count has occurred since 1900 and where the Cornell Lab of Ornithology has been inviting the public to participate in bird surveys for decades (Droege, 2007; Bonney et al., 2009). Citizen science crosses disciplines however, with projects ranging from studies on bees to galaxies (Bonney et al., 2014). These projects have been remarkably successful in advancing scientific knowledge including how bird populations change in distribution over large scales of time and space (Wells et al., 1998); the impacts of environmental change on breeding success (Rosenberg et al., 1999); ecological impacts of climate change (Hickling et al., 2006); invasive species (Roy et al., 2012); habitat loss (Warren et al., 2001); how disease spreads through populations (Hochachka and Dhondt, 2000); and how models can predict ecological patterns from citizen science data (Kelling et al., 2009), ibid.

An exponential rise in the amount of citizen science research projects in the field of natural and social sciences is a phenomenon of the past ten years with reasons that include: the easy availability of tools to share information (i.e. smart phones and social media), the increasing realization among scientific experts that the public is a source of free labor, skills, and finance; and the rise of the outreach component in the scientific grant-making process (Silvertown, 2009). Despite its rise in popularity, citizen science papers are still underrepresented in peer reviewed literature for two reasons: the newness of the term, and the difficulty that occurs when trying to fit citizen sciences into a traditional disciplinary approach because citizen science spans the natural and human sciences (Silvertown, 2009).

The Reserve's Nurdle Patrol citizen science project adopts key components of the guidelines for good practice of the Cornell Laboratory for Ornithology, including standardized methods of data collection, explicit assumptions, having a hypothesis in mind, and non-financial awards for participants (i.e. recognition on social media) (The Cornell Ornithology Lab, 2010). The Reserve's project shares key design components with the best known case of marine litter-focused citizen science: the OSPAR Beach Litter Project. The OSPAR project is focused on the North Atlantic and implemented in European countries adjacent to the North Sea, Celtic Seas, Bay of Biscay, and Iberian Coast. This project studies how much marine litter is present in the environment and how this changes over time. Its design includes site selection criteria, sampling protocols, photographic guides for interpreters, and information on training (OSPAR Commission, 2010).

Classification systems for typologies of citizen science projects exist, and include hypothesis-driven research (i.e. Evolution Mega Lab); Volunteer Mapping and Monitoring (i.e. The Audubon Society's Christmas Bird Count); and tools such as identification of species or online collaborative tools (i.e. iSpot). The Nurdle Patrol citizen science project is of the monitoring and mapping typology, arguing that because there is uncertainty over distribution, abundance, and impacts, numbers should be mapped and monitored.

1.2. Citizen scientific data and policy response

This case study will describe the citizen science project methodology developed for creating a platform for potential future policy decisions and nurdle research. To date, much of the research on how citizen science can lead to policy change remains theoretical. Bonney et al., 2014 outline ways that citizen science research organizers may better organize to make such an impact through associations and digital tools. Citizen science data, also known as “opportunistic data” is a convenient way to fill regulatory gaps that require information be collected at spatio-temporal scales that may be unrealistic given agency budgets (Isaac et al., 2014). Weaknesses of opportunistic data that may present challenges for decision-maker use include: a lack of standardized protocols; the “noise” generated by the lack of standardized protocols resulting in the loss of “signal” or real detected change in targeted monitoring variables; variation in recording intensity between collectors; uneven spatial coverage; uneven sampling effort per visit; and uneven detectability (Isaac et al., 2014). For these reasons, the uptake of evidence generated by citizens among policy-makers is limited, and policy-relevant citizen science research remains rare (Hyder et al., 2015). However, the value of citizen science is becoming more widely recognized by governments, with the United Nations Environment Program (UNEP) stating that it is an essential means of achieving environmental sustainability, or the ability of linked human-natural systems to absorb disturbances and retain essential features (Hyder et al., 2015).

There are a range of agencies, jurisdictions, and scales of policy in place to respond to marine debris. Therefore, policy response is inherently complex and involves many agencies with divergent missions and regulatory authority (NOAA Marine Debris Program, 2018). The policy context for marine litter begins with several early international policies meant to reduce marine litter including the 1972 London Dumping Convention. The “London Convention” was one of the first global conventions to protect the marine environment from marine

[1] A rapid assessment was completed by researchers at the University of Texas Marine Science Institute (UTMSI) to get a rough estimate of nurdles washed up on the shoreline. Estimates were calculated to be between 300,000 to 1 million nurdles per mile on Mustang and North Padre Islands. Surveys were conducted in October 2018 by using a half meter quadrat placed randomly at the high tide line where nurdles were present at each mile for 24 miles. The number of nurdles found at the surface within the quadrat were counted and multiplied in a linear length to one mile. Due to the nature of tides, winds, beach maintenance practices, and driving on the beach, limited surveys were performed. Hurricane Michael made landfall in Florida on October 10, 2018 that created a storm surge along the nurdle spill area in Texas that went to the sand dunes and scattered nurdles across the beach profile.

pollution, and to prevent dumping of waste into the sea. It was amended in 1996 to modernize the convention and outline acceptable waste, and implemented only in 2006 (International Maritime Organization (IMO) 1996). The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) of 1973 and 1978 (enacted in 1988) was adopted in response to a large number of tanker accidents is intended to prevent pollution from ships (IMO, 2014a, 2014b). This policy prevents ships from dumping plastic at sea.

After MARPOL, subsequent policy to reduce marine litter has been primarily voluntary (Borrelle et al., 2017). The National Oceanic and Atmospheric Administration (NOAA) along with UNEP created the Honolulu Strategy, a global framework for the prevention and management of marine litter or debris (UNEP and NOAA, 2011). Within this strategy, target setting for local, regional, and national actors for reductions in marine debris or for specific actions to reduce marine debris are not required by law. Instead, the Honolulu Strategy aims to further voluntary strategies for preventing and reducing marine debris that include: reducing the amount and impact of land-based sources of marine debris into the sea; reducing the amount of sea-based sources of marine debris including lost cargo; and reducing accumulated marine debris on shorelines, benthic, and pelagic habitats (UNEP and NOAA, 2011).

Much of the regional, Gulf of Mexico policy context for marine debris is voluntary and collaborative as well, with the regional organization the Gulf of Mexico Alliance (GOMA) working with NOAA to create a Regional Action Plan with an initiative on Marine Debris (GOMA, 2016). The goal of this initiative is to "assess, reduce, prevent, and eliminate marine debris" (GOMA, 2016, pg. 38). Much like the Honolulu strategy, a major priority of this initiative is education and outreach to governments and industry, and enhanced research.

At the Federal Level, relevant laws for mitigating hazards and spills include the Comprehensive Environmental Response, Compensation, and Liability Act (CERLA) commonly known as the Superfund, whereby a federal "Superfund" is used to clean hazardous spills and emergency releases of pollutants. The U.S. Environmental Protection Agency (EPA) has authority to find those responsible and assure their cooperation in the cleanup. The Clean Water Act, as it is commonly known, is the result of several amendments including the Federal Water Pollution Control Act Amendments of 1972 (FWPCA), subsequent amendments in 1977, and Oil Pollution Act of 1990 (OPA 90). The U.S. Coast Guard (USCG) responds to pollution and hazardous spills in navigable waters of the U.S. and adjoining waters. The USCG in the coastal zone and the EPA in the inland zone work collaboratively to ensure immediate removal of discharges of oil or hazardous substances. OPA 90 also requires the USCG to prevent the discharge of hazardous substances into navigable waters, shorelines, into waters of the U.S. Exclusive Economic Zone (EEZ) that may negatively impact natural resources. U.S. Fish and wildlife through its Environmental Contaminants section of Ecological Services is responsible for hazards removal and spills.

At the state level, in Texas there are several key regulatory agencies that respond to marine debris hazards collaboratively with federal counterpart agencies. Within Texas state law, hazards are defined as the chance that injury or harm will occur to persons, plants, animals, or property. The Texas Commission on Environmental Quality (TCEQ) is the state agency that leads the statewide Hazardous Material and Oil Spill Response program. Much like the EPA, its federal counterpart, its statutory authority is over inland hazardous spills, with coastal spills managed by the Texas General Land Office (GLO). The GLO is a supporting state agency for Hazardous Material and Oil Spill Response. It is responsible for marine debris removal on tidally influenced state-owned lands and Gulf-facing beaches, and maintains an agency-level Debris Management Plan approved by FEMA. The TCEQ and GLO efforts at Hazardous Material and Oil Spill Response are collaborative, with assistance from petroleum and commercial fishing industries, as well as the USCG. The USCG is responsible for hazards when they occur beyond state waters and in navigable waterways, and thus works closely with the GLO. The Railroad Commission of Texas and Texas Parks and Wildlife Department (TPWD) also serve as support agencies for Hazardous Material and Oil Spill Response and with each responsible for cleanup within industrial areas and state parks and wildlife management areas respectively.

Local governments have authority to develop local hazard management plans or initiatives, and have a great responsibility to do so as they are often the first to witness a spill. Counties, cities, and towns may have hazard response plans in place for spills. Such plans include incident classification dividing spills into incidents, emergencies, and disasters; initial reporting protocols for citizens who discover spills; response activities of city and county personnel; cleanup procedures; recovery processes that may extend after a cleanup occurs overseen by the local executive authority i.e. county judge in the Texas context. As part of local response, cost data is preserved, and the responsibility for financing cleanup is that of the group responsible for the spill. Preparing a local government plan is not required by state law, and therefore, it does not exist in all cities, towns, and municipalities. In addition to local governments, navigation districts (commonly known as port authorities) of which there are 24 statewide in Texas, are considered political subdivisions of the state of Texas, and have authority for removing marine debris within their jurisdiction.

1.3. Study region

The Gulf of Mexico is located in North America and is surrounded by the United States on the northern half, Mexico on the southern half, and Cuba along the southeastern side (Fig. 1). The Gulf basin is approximately 1.6 million km^2 in size, and is considered one of the most important offshore petroleum production regions in the world (US Energy Info. Admin., 2019). Wind and currents can play an important role on the distribution of marine debris in the Gulf of Mexico (Wessel et al., 2019). The Gulf Stream Current is a warm Atlantic Ocean current that loops from the Caribbean to the tip of Florida, and creates a strong loop current that sheds off westward before dissipating. The current is known for bringing marine debris from other parts of the world into the Gulf that washes up on beaches in high numbers, particularly in Texas (Wessel et al., 2019). The Gulf of Mexico also has several major rivers that flow into it, including the Mississippi and the Rio Grande rivers in the U.S., and the Grijalva and Usumacinta rivers in Mexico. The Gulf coast is comprised of narrow barrier island systems, low lying marsh, and sandy beaches.

2. Methods

In November 2018, the Mission-Aransas National Estuarine Research Reserve created a citizen science project called "Nurdle Patrol," which has volunteers record concentrations of nurdles along

Fig. 1. Map of the Gulf of Mexico.

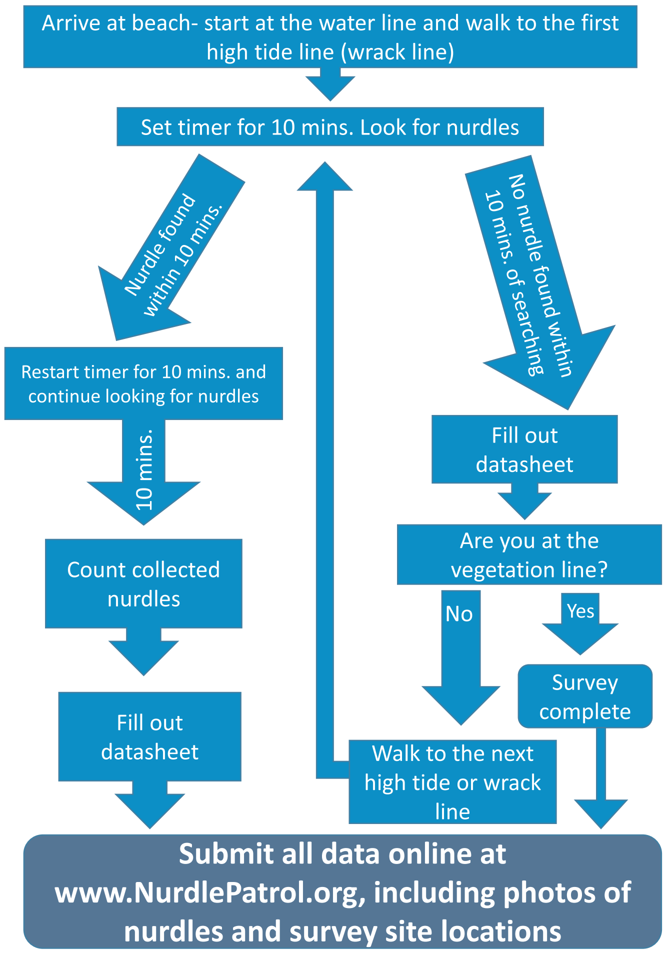

Fig. 2. Nurdle Patrol survey decision making flow chart.

shorelines using the approved methodology described here. Nurdle Patrol adopted and modified an existing monitoring method developed by Fidra (2013), a Scottish environmental nonprofit in the United Kingdom that created The Great Nurdle Hunt in 2013 (https://www.nurdlehunt.org.uk/).

2.1. Data collection

The survey methodology (Fig. 2) consists of hand picking nurdles for a 10 minute period that starts once the first nurdle has been collected. Citizen scientists watch a four minute training video on how, when, and where to collect, as well as where to submit the data (Tunnell, 2019). Citizen scientists able to conduct regular sampling are encouraged to choose a beach, or multiple beaches, to survey once a month.

All surveys start at the water line and move up to the nearest/first high tide line (wrack line; Fig. 3). Once the surveyor has located the beginning point, a ten minute timer is started, and they begin searching for nurdles. If no nurdles are found at the first high tide line after 10 min, the volunteer then moves to the second high tide line, and so on until the highest wrack line or vegetation line is searched. Each tide or wrack line is searched for ten minutes before moving to the next. Volunteers should only move to the next line, if no nurdles were found at the previously searched line. Once a nurdle is found, the timer is restarted for 10 min and nurdle collection begins. If nurdles are found at the first high tide line, then that is the only wrack line that will be surveyed at this site. During the survey, all nurdles are placed directly into a baggie or jar to reduce the likelihood of losing the pellets.

After the 10 minute nurdle collection period, the surveyor stops and counts the number of nurdles collected. The surveyor takes a photo of nurdles collected and of the area surveyed, and records the time, date, and GPS location of the survey. The volunteers are also asked to record any notes, such as whether the nurdles were found at the newest high tide or whether there were other natural or manmade debris on the beach. If no nurdles were found at any of the wrack lines up to the highest inland wrack line, which is often a sand dune, vegetation line, road, or seawall, then a zero is recorded as the number of nurdles collected.

All data are submitted online into the www.NurdlePatrol.org web portal, including photos of nurdles and survey site locations. After data are uploaded to the website, nurdles are disposed of properly or retained for education purposes.

2.2. Data formatting and statistics

For this project, each continuous time period that a single volunteer spends searching for nurdles is considered one survey. Each reported total number of nurdles found is considered a count. Multiple surveys can therefore result in a single count if a group of people surveying together report a single total number of nurdles collected.

Since surveys are often conducted by groups that report a single count and are sometimes shorter or longer than the standard 10-minute collection time, each nurdle count is standardized to the number of nurdles collected by one individual in 10 min. For example, if two individuals survey for a 30 minute period and the surveyors combined collected 100 nurdles, the standardization process would divide the total number of nurdles collected by two (100 nurdles ÷ 2 surveyors = 50 nurdles per surveyor), then divide that number into 10 minute increments (50 nurdles per surveyor ÷ 30/10 min = 16.6 nurdles per surveyor per 10 min).

There is a risk of artificially inflating nurdle abundance values if this standardization is applied to counts associated with survey times shorter than the standard 10 min. However, volunteers will sometimes shorten the survey period if very large numbers of nurdles are present and counting the collected nurdles will be extremely time-consuming and labor-intensive. A disproportionate number of high abundance counts would therefore be removed if short survey counts are discarded (17% of all nurdle counts > 1000 are from surveys < 10 min long vs. 1% of all nurdle counts < 1000). In addition, volunteers may be discouraged from sampling high-abundance areas if the labor associated with a strict 10-minute minimum collection period is perceived to be unreasonable.

The risk of substantially inflating nurdle abundance by standardizing counts from short surveys increases as collection times and count values decrease. This risk was quantified as the probability of the reported count being double the actual average number of nurdles present, multiplied by the factor the count would be multiplied by for standardization (10 min ÷ the number of survey minutes completed). This value was > 0.01 for the 4 short survey counts of 10 or fewer nurdles. These 4 counts were therefore not included in the results here due to the greater chance of the standardized values being high relative to what might have been collected during a 10-minute time frame.

Volunteer information in the data reported to the Nurdle Patrol coordinator includes the total number of volunteers participating in a count and the name of the collector lead. This information was used to calculate the total number of unique volunteers that have participated in the project. Each collector lead was counted as a volunteer once, and each unique number of people sampling with each collector lead was counted as a set of unique volunteers. This means that if one survey lead always sampled with one other person, the survey lead and that one person would be counted once for a total of 2 unique volunteers. If the same lead also conducted a count with two other people, those two people would count as unique volunteers in addition to the lead and the single person from the other counts, for a total of 4 unique volunteers.

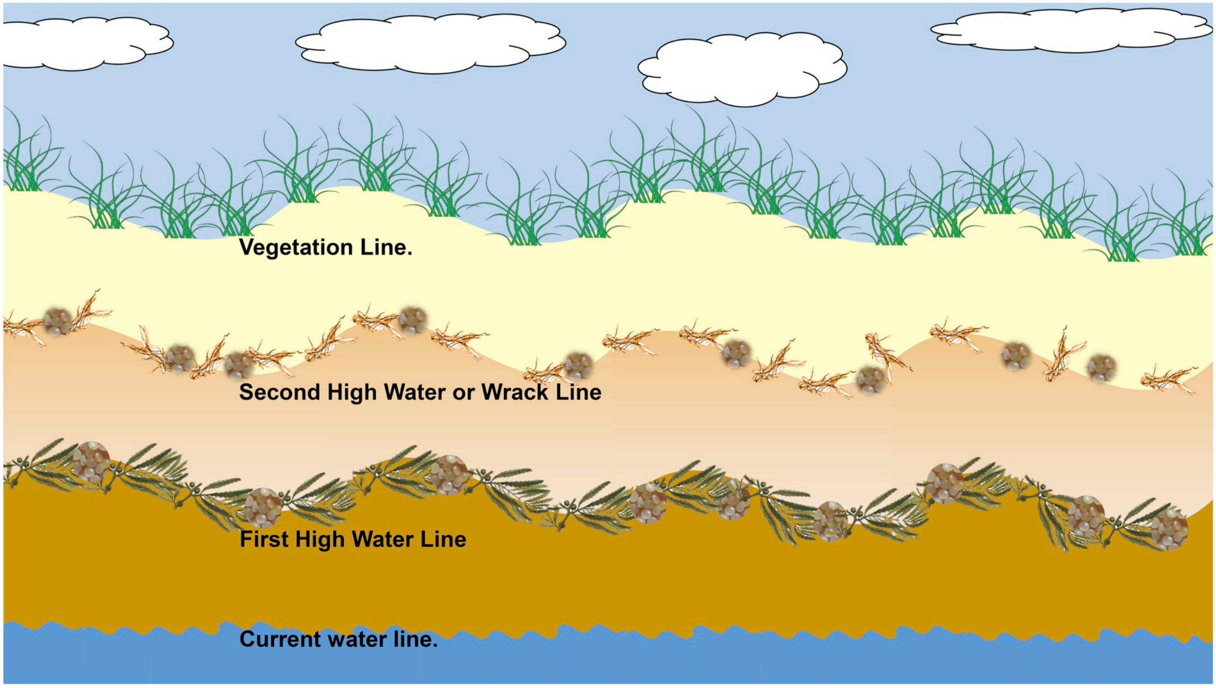

Fig. 3. Figure of wrack lines along a beach from water line to vegetation line.

Long-term temporal patterns in nurdle abundance, such as seasonal variations or correlations with Gulf of Mexico current patterns, were not examined in the present study due to the relatively short temporal coverage (< 1 year) of the dataset at the time of this publication. As the Nurdle Patrol monitoring program continues, the dataset is expected to expand to include multiple years of data and repeated samples at specific locations. These attributes will allow for a wider range of analyses to be performed.

3. Results

A total of 2042 Nurdle Patrol surveys (resulting in 1144 counts) were conducted by 744 citizen scientists covering shorelines from Mahahual, Mexico to Fort Jefferson in the Dry Tortugas of Florida from November 2018 to August 2019 (Fig. 4). Sampling sites for this project were located in Texas (73%), Florida (12%), Mississippi (2%), Alabama (4%), Louisiana (2%), and Mexico (7%). Most surveys have been conducted in Texas (Table 1; Fig. 5), where the highest mean number of nurdles collected per survey has also been observed (Table 1). All 20 of the highest standardized nurdle counts were recorded at sites in Texas (Table 2), with the highest count of 30,846 nurdles collected in 10 min occurring in Galveston Bay on the northeast portion of the Texas coastline (Fig. 4B). There were 148 counts that recorded zero nurdles, with 76 (51%) of those being from Florida (Fig. 5). Florida was the only state in which counts of zero nurdles made up the highest proportion of values, with all other states having the highest proportion of counts falling in the 1–30 nurdle/10 min range (Fig. 5).

New high tide nurdle events were categorized as counts that recorded nurdles at the first high tide line closest to the water where water levels had been within the past 24 h, possibly indicating new nurdles coming on shore. There were 326 new high tide events documented with 283 of those events occurring in Texas (87%).

4. Discussion

The original intent of the Nurdle Patrol effort was to monitor nurdle concentrations along Mustang and North Padre Islands in Texas; however, the interest from other institutions, nonprofits, and the public was widespread throughout the Gulf of Mexico and beyond, providing an opportunity to greatly expand the area of observation, covering from Mahahual, Mexico to the Dry Tortugas of Florida. There are now 744 citizen scientists that together have contributed > 400 h to conducting nurdle surveys. Working with citizen scientists greatly improved the spatial scope of this project, and allows for a bigger picture of nurdle concentrations to be seen across the Gulf.

However, the use of citizen scientists to collect small plastic pellets on the beach creates some challenges. First, nurdles are hard to find if the surveyor has never seen a nurdle before. Second, the number of nurdles collected can be dependent on how motivated the surveyor is. The areas with the highest concentrations (Galveston Bay and Cox Creek in Texas) were examined closely to ensure the concerns mentioned above were not a factor in abnormal data collection. Areas with zero counts along the west coast of Florida were also visited by the Nurdle Patrol coordinator to ensure data validity. Close examination of images submitted, talking to surveyors, and independent site visits to areas with high and low concentrations validated that the data being submitted are accurate.

Out of the 2042 surveys conducted, very few nurdles have been found in the state of Florida, with increasing numbers of nurdles being collected as you move west across the Gulf of Mexico (Fig. 4). The highest number of nurdles being documented is on the upper Texas coast in Galveston Bay (Table 2), which also is the location of the majority of plastic pellet manufacturers in the United States (US EPA, 1992a). In September 2018, when the nurdle event was first recorded along Mustang and North Padre Islands in Texas, the conclusion was that the nurdles originated from a container ship or during shipping transportation. Between the initial event in September 2018 and August 2019, 283 high tide events have washed additional nurdles onto Texas beaches. Although possible sources of nurdles washing up on Gulf beaches could be Gulf Stream currents, major rivers from the U.S. and Mexico, or the shipping industry used to transport nurdles, the highest concentrations being observed by this project are in bay systems that coincide with the locations of plastic pellet manufacturers. This association suggests that these bays are sources of nurdles and not sinks. These findings are similar to a U.S. EPA study called the Harbor Studies Program (US EPA, 1992a) that sampled floating debris, including

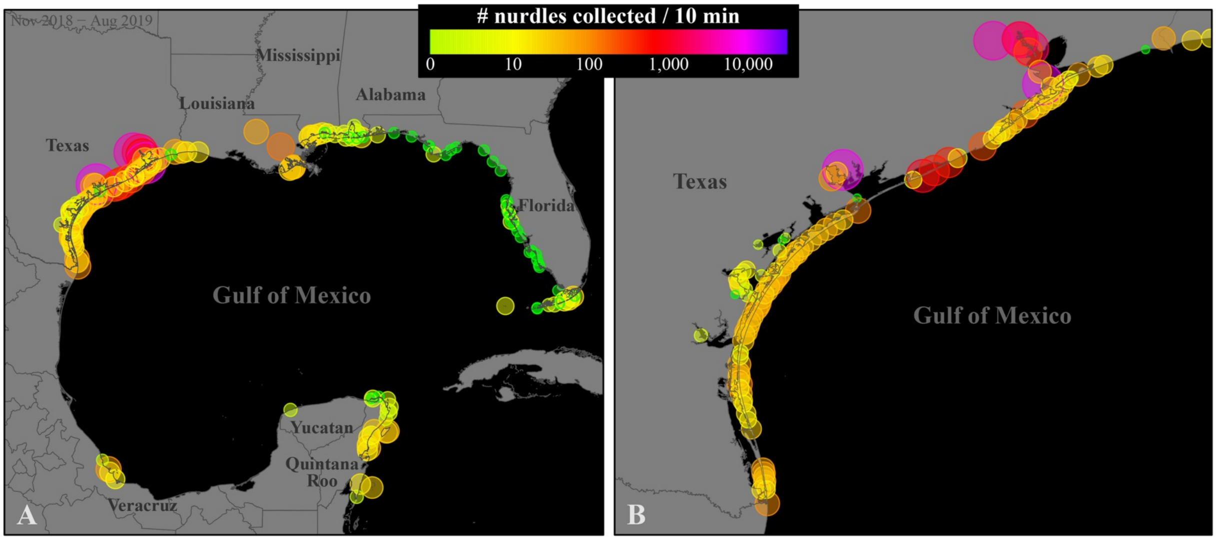

Fig. 4. Map of A) the Gulf of Mexico and B) Texas showing number of nurdles collected per 10 min along shorelines from November 2018 to August 2019. Points represent means of counts taken within each square of a 0.1° (A) or 0.05° (B) grid and are colored and scaled according to the log value of the mean (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 1
Numbers and proportions of surveys conducted and nurdles collected by country and state.

Country	State	Surveys conducted		Nurdles collected		Mean number of nurdles per survey
		Number	% total	number	% total	
United States		1979	97	194,281	99	98
	Texas	1164	57	181,216	93	156
	Mississippi	634	31	11,991	6	19
	Florida	102	5	195	< 1	2
	Alabama	59	3	156	< 1	3
	Louisiana	20	1	723	< 1	36
Mexico		63	3	1191	1	19
	Veracruz	34	2	849	< 1	25
	Quintana Roo	28	1	341	< 1	12
	Yucatan	1	< 1	1	< 1	1
Total		2042	100	195,472	100	96

plastic pellets, at 14 harbors around the coastal United States. Using a fine-mesh net towed behind a boat to collect water surface samples of small plastic debris, the study found plastic pellets in 13 of the 14 harbors surveyed. The Houston Ship Channel had the highest concentrations of plastic pellets recorded in the United States at 700,344 pellets. New York City had the second highest concentration of plastic pellets in the EPA study at 8766.

The findings of this research relate to specific goals within the UNEP and NOAA Honolulu protocol and are therefore policy-relevant. First, Strategies A1 and B1 of the Honolulu Protocol ask stakeholders to conduct education and outreach on the need for improved waste management on land and at sea (2011). Nurdle survey data is featured on Reserve social media accounts, mainstream media platforms such as television, and other outreach material reaching hundreds of people per day. Results have also been shared with state- and local- level policy makers in relevant agencies (county officials, TCEQ, GLO, TPWD) that ensure compliance with policy and law (UNEP and NOAA, 2011). One-on-one outreach in the form of data-sharing to producers and manufacturers has also occurred. This is related to Strategy A6 of the Honolulu Protocol which asks stakeholders to build capacity to enforce compliance with regulations and permits involving litter. The longer term policy aim of this research is to implement industry best

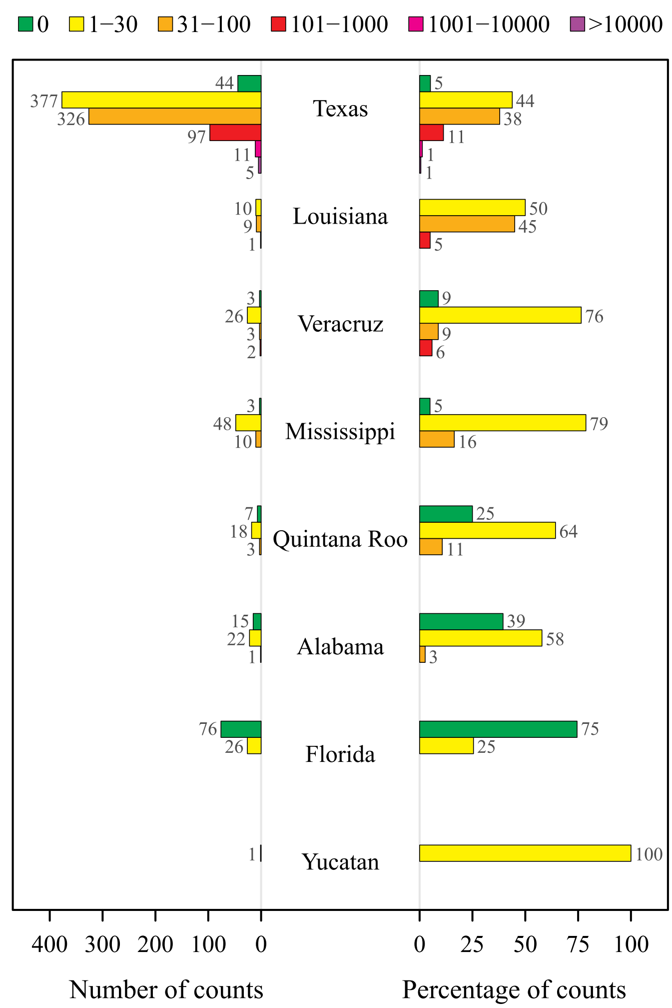

Fig. 5. Number of counts in each state and percentage of counts in each state falling within specified ranges of nurdles/10 min.

management practices designed to minimize accidental cargo loss at sea, or accidental pollution by land (Strategies A3 and B3 of the Honolulu Protocol). Outreach and awareness building on distribution and

Table 2
List of 20 highest nurdle counts standardized to nurdles collected in 10 min. All sites listed are located in Texas.

Site	Latitude	Longitude	Date	Nurdles/10 min
Galveston Bay - Texas City Dike	29.39	−94.89	2019-07-16	30,846
Galveston Bay - Texas City Dike	29.39	−94.89	2019-06-28	19,239
Lavaca Bay - Cox Creek and HWY 35	28.69	−96.53	2019-06-29	16,500
Lavaca Bay - Cox Creek and HWY 35	28.69	−96.53	2019-07-22	16,233
Galveston Bay - Texas City Dike	29.39	−94.89	2019-08-06	16,135
Galveston Bay - La Porte – Morgan's Point	29.68	−94.98	2019-06-14	7290
Galveston Bay - Texas City Dike	29.39	−94.88	2019-04-26	5300
Buffalo Bayou Hidalgo Park	29.75	−95.29	2019-08-24	4950
Lavaca Bay - Cox Creek at HWY 35	28.69	−96.53	2019-05-19	4000
Lavaca Bay - Cox Creek at HWY 35	28.69	−96.53	2019-04-24	3540
Galveston Bay - Texas City Dike	29.39	−94.89	2018-12-12	2720
Galveston Bay - La Porte - Sylvan Beach	29.65	−95.01	2018-12-20	2232
Galveston Bay - San Jacinto Battleground State Park	29.75	−95.07	2019-02-14	2216
Galveston Bay Lynchburg Ferry	29.76	−95.08	2019-07-27	1970
Galveston Bay Lynchburg Ferry	29.76	−95.08	2019-07-27	1275
Galveston Bay Ship Channel - Monument Inn	29.76	−95.08	2019-01-26	1199
Lavaca Bay - Cox Creek at HWY 35	28.69	−96.53	2019-04-17	1000
East Matagorda Peninsula - shell banks	28.64	−95.87	2019-01-27	948
Galveston Bay Sylvan Beach Park	29.65	−95.01	2019-07-28	529
Matagorda Island - 15 miles north of access road	28.68	−95.78	2019-01-29	471

numerical estimates of nurdles is the first step.

Nurdle Patrol data has resulted in action from some but not all of the federal, state, and local agencies. Examples of responsive agencies include The Texas Water Development Board, which is examining the possibility of using its hindcasting models to determine where the nurdles might have originated. TPWD has expressed interest in developing methodology to calculate how many nurdles are present per mile when a spill occurs. TCEQ is discussing their role in stormwater permitting for the manufacturing facilities, a possible source for nurdles based on evidence of high concentrations in manufacturer facilities near Galveston. There is still significant uncertainty at the decision-maker level about how to incorporate citizen science data into official action, and local and federal action based on this data remains to be seen. That said, initial responses from state agencies shows promise for the use of citizen science at this scale. Future research can determine why decision-makers across scales may face challenges in implementing official responses using citizen science data.

Other groups may utilize this data in addition to decision-makers. The high concentration areas shown on the nurdle maps provide researchers with sampling site locations that could be used for target studies on microplastics' impact to the environment and substantiate the cause for concern. Studies on chemical absorption, fish and bird ingestion, microbial transport, plastic degradation, soil contamination, food web transfer, bioaccumulation, water quality influences, and economic impacts, are some examples of future research.

5. Conclusions

Ten minute nurdle surveys along beaches of the Gulf of Mexico show high concentrations of plastic pellets on the upper Texas coast in Galveston Bay, sites where nurdles are manufactured. The Nurdle Patrol citizen science project data could provide a starting point for investigations by regulatory agencies to find possible sources of nurdles, justification for new research on environmental impact of plastics, and creating public awareness that engages communities about the concerns associated with plastic in the environment. This data has enabled some state agencies to plan further research on sources, permitting procedures, and official counts. Federal and local scale agency response have not been as immediate as state response. This suggests that further research into how and why decision-makers use citizen science data is needed at these scales. Regionally, the states surrounding the Gulf of Mexico may use this research to identify a stressor, and to develop new policies to handle the problem of pellet loss to the environment. Nurdles washing up on beaches of the Gulf of Mexico bays and estuaries has likely been happening for decades based on reports from the EPA, but appears to be a new concern that the states along the Gulf of Mexico have not had to deal with before. Any new regulations on plastic pellet handling should consider all points of pellet loss to increase the success of new rules. Ultimately, the authors of this study recommend implementation of best management practices at all sites handling pellets, including manufacturing sites and the distributors transporting nurdles to and from these sites.

Author credit statement

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Jace W. Tunnell: Conceptualization, Methodology, Validation, Data Curation, Investigation, Project Administration. Kathleen M. Swanson: Conceptualization, Methodology, Investigation. Kelly H. Dunning: Conceptualization, Investigation. Lindsay P. Scheef: Software, Formal Analysis, Data Curation, Visualization. All authors: Writing – Original Draft, Writing – Review & Editing.

Funding

This work is supported by 11th Hour Racing: Grant No. G-1906-58461.

Declaration of competing interest

None.

Acknowledgements

We thank all the citizen science volunteers that are collecting data on a monthly basis. There are many partners that have taken the lead to organize their own volunteers for collecting data under this program which include: The National Park Service, 11th Hour Racing and Elizabeth Kratzig, Flyaway Paper Straws, Surfrider Foundation, Friends of Padre, Tampa Bay Estuary Program, Parley for the Oceans, Rookery Bay Research Reserve, Texas Master Naturalist, Weeks Bay National Estuarine Research Reserve, the Universidad Veracruzana in Veracruz, Mexico, Nicholls State University, Old Lady Academy, Saint Stanislaus, Conrad Blucher Institute, Choctawhatchee Basin Alliance, Texans for Clean Water, Galveston Bay Foundation, and the University of Texas

Rio Grande Valley. Special thanks to Letha Boudreaux from Saint Stanislaus for her contribution of photos to create the graphical abstract, and for her continuous education to her students about nurdles. Finally, thanks to Horacio Pérez-España from Universidad Veracruzana and to Jasper Hamlet of Fidra for their thorough review and guidance on this paper.

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