Marine Pollution Bulletin 140 (2019) 1–8

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

Baseline

Quantifying marine debris associated with coastal golf courses

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ARTICLE INFO

Keywords:
Plastic pollution
Golf balls
Point-source pollution
Marine debris
Microplastic

ABSTRACT

Identifying terrestrial sources of debris is essential to suppress the flow of plastic to the ocean. Here, we report a novel source of debris to the marine environment. From May 2016 to June 2018, we collected golf balls from coastal environments associated with five courses in Carmel, California. Our 75 collections recovered 39,602 balls from intertidal and nearshore environments adjacent to, or downriver from, the golf courses. Combining our collections with concurrent efforts of the Monterey Bay National Marine Sanctuary and the Pebble Beach Corporation, we report the retrieval of 50,681 balls, totaling approximately 2.5 tons of debris. We also examined decomposition patterns in the collected balls, which illustrate that degradation and loss of microplastic from golf balls to the marine environment may be of concern. Our findings will help to develop and direct mitigation procedures for this region and others with coastal golf courses.

Plastic pollution is a pervasive anthropogenic modification of coastal and marine ecosystems. At present there are over five trillion pieces of plastic at sea, together weighing more than a quarter million tons (Eriksen et al., 2014). The vast majority of plastic debris originates from continental landmasses and rivers and enters the ocean at a rate of 8–12 million metric tons per year (Jambeck et al., 2015; Lebreton et al., 2017). Identifying point sources of plastic pollution is critically important, but often challenging; as a result, there is a need to document debris sources to stem the flow of plastic to the marine environment.

Golf courses can have positive or negative impacts on adjacent aquatic systems. A meta-analysis on the ecological impacts of golf courses concluded that while golf courses constructed in urban or agricultural habitats have a net positive impact on local ecosystems and biodiversity, the opposite is true for courses within or adjacent to natural areas (Colding and Folke, 2009). A study of sediment associated with fresh- and saltwater adjacent golf courses have found high concentrations of chromium, zinc, mercury, and organochlorine pesticides (Lewis et al., 2001). Waterway-adjacent golf courses have also been responsible for algal blooms and eutrophication leading to fish kills (Lewitus et al., 2003, 2008). Golf balls originating from courses near the coast are a previously unaccounted source of marine pollution. On coastal courses, even skilled golfers routinely hit balls into the ocean, and high numbers can accumulate in nearshore environments. However, the extent of golf balls in the marine environment has not been quantified.

To our knowledge, there have yet been no studies of golf balls in coastal or intertidal environments, or of the degradation of golf balls in underwater ecosystems. Contemporary golf balls generally consist of a polyurethane elastomer shell filled with cis-1,4-polybutadiene or synthetic rubber (Tzivanis et al., 2003). Zinc oxide, zinc acrylate, and benzoyl peroxide added to the solid core allow flexibility and enhance durability. Zinc acrylate and zinc oxide are acutely toxic in aqueous environments and zinc oxide has been demonstrated to induce proteomic stress responses in algae, crustaceans, and fish (Wong et al., 2010). The degradation of golf balls may have long-term adverse effects in the form of leached chemical pollutants and unrecoverable microplastics released to the marine environment.

In this study, golf balls were collected from the ocean and beaches along the central coast of California adjacent to two coastal golf courses and at a river mouth with three riverside golf courses. The main objectives of our study were 1) to describe the quantity and distribution of golf balls in the intertidal and nearshore marine environment, 2) to characterize where golf balls enter the ocean and aggregate in our study area, and 3) to estimate the amount of plastic material lost from golf balls to the marine environment. Our results could be used to create more effective and efficient cleanup protocols for regulation and recovery of golf ball emissions from coastal and riverside golf courses.

1. Study sites

We observed three sites along 11.2 km of the central coast of California. Our three sites north to south were Cypress Point (CP),

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https://doi.org/10.1016/j.marpolbul.2019.01.013
Received 22 July 2018; Received in revised form 6 January 2019; Accepted 7 January 2019

Fig. 1. Location of the three main study sites along central California coast near the town of Carmel, California. A) Cypress Point site B) Pebble Beach site C) Carmel River Mouth site.

Table 1
Totals from the 75 collections conducted at our nine subsites. Balls per collection column was calculated by dividing the total number of balls at each subsite by the number of collections done at that subsite. From May 2016 to June 2018 we recovered a total of 39,602 balls.

Site	Subsite	Number of collections	Number of balls collected	Balls per collection
Cypress Point	15	1	562	562
Cypress Point	16	3	920	307
Pebble Beach	6	5	146	29
Pebble Beach	8-1	19	11,605	611
Pebble Beach	8-2	13	2776	214
Pebble Beach	18-1	16	16,338	1021
Pebble Beach	18-2	10	4445	445
Carmel River Mouth	CRM 1	6	2431	405
Carmel River Mouth	CRM 2	2	379	190

Pebble Beach (PB), and the Carmel River Mouth (CRM) (Fig. 1). These sites were chosen due to their proximity to nearby golf courses. While both PB and CP border the western edges of their corresponding golf courses, the Carmel River Mouth is 3 km downstream from the recently closed Rancho Canada golf course, 6.3 km downstream from Quail Lodge Golf Club, and 13.5 km downstream from Carmel Valley Ranch Golf Course. Each site was surveyed at both high and low tides no fewer than four times total (Table 1).

The most northern site, Cypress Point (36°34′53.15″N 121°58′28.76″W), is a series of rocky coves bordered by granite cliff sides, adjacent to the Cypress Point Golf Club. Two subsites were observed within CP (15 and 16) in a 1.9 km range of shoreline (Fig. 2A). The subsite names refer to the corresponding hole number nearest the collection location. Cypress Point Golf Course has three holes that require golfers to clear a stretch of ocean to reach the green. These holes are internationally renowned for their difficulty, and allow for errant shots to deposit golf balls in the nearshore environment. This golf course is the on the tip of an unprotected peninsula where large swells often impact the shoreline making it dangerous to dive this site; therefore, it is only accessible by boat or kayak.

The northernmost subsite of CP is 15 (Fig. 2A). Subsite 15 is a narrow slot of ocean directly under the fifteenth hole of the golf course. This cove ranges from 0 to 8 m wide and 92 m from the cliffside to the mouth of the cove. It has a seasonal beach with a gradual sloping sand and cobble substrate, facing northwest and unprotected from swells. The beach is bordered by a steep 7 m tall granite hillside with the 15th green of the golf course adjacent to the cliff edge. This cove divides the 15th fairway in half, forcing the golfers to hit across the water to the green. The water depth within the cove ranges from 0 to 4 m. From June–September, a thick kelp mat forms on the floor.

Subsite 16 is used as a direct water hazard of the 16th hole of the golf course; golfers must hit the ball approximately 193 m over the cove to reach the green (Fig. 2A). In the cove the water depth varies from 0 to 4 m with a variety of sand, cobble, boulder, and kelp substrate. This subsite has only minor seasonal changes. The cove faces directly north, protected from only south swells. In the summer months drift kelp and growth cover the sea floor. This area was chosen because it is a high loss area with golf balls often lost due to overshot to the northwest.

Fig. 2. Detailed aerial view of sites and subsites, including the routes golf balls travel along holes adjacent to the coast. A) Cypress Point site B) Pebble Beach site C) Carmel River Mouth site.

The second study site is the coast adjacent to the Pebble Beach Golf Links (36°34′0.34″N 121°56′34.37″W; Fig. 2B). The course has seven seaside holes that use the ocean as a hazard. The northern boundary of this site begins 20 m north of the green of the 18th hole and includes subsites along the coast for 2.5 km to the south. There are five subsites within this site, identified as 18–1, 18–2, 6, 8–1, and 8–2 (Fig. 2B). All subsites with the exception of 8–2 do not have beach access and must be reached either by kayak or boat. The accessibility of each of the five subsites varies by season. In the summer (June–October), kelp and sea grasses blanket the seafloor and reduce visibility thus making it difficult to find and collect balls safely. In addition, winter swells tend to remove sand and uncover balls. As a result, surveys took place November through May at the PB site.

The most northern of the PB subsites is 18–1 (Fig. 2B), which includes the 300 m shoreline adjacent to the 18th green of the golf course. The surveyed area spans 10 m offshore, and reaches a maximum depth of approximately 3.5 m. The substrate is sandstone, with deep fissures along the bottom. Adjacent to the shore is a vertical 5 m concrete hillside with the 18th green of the golf course bordering to the cliffs edge. The second PB subsite is 18-2 (Fig. 2B). This subsite is the 427 m length of shoreline adjacent to the 18th fairway of the golf course. Neighboring the shore is a 5 m vertical hillside, which abuts the golf course. The west facing shore is long, straight, and protected from the northwest swells. Water was surveyed up to 10 m offshore. The substrate is sandstone with deep fissures, cobble, and boulder patches. Subsite 6 is a small rocky cove, 0–4 m wide and 31 m long, on the northern side of Arrowhead Point (Fig. 2B). The west-facing cove is a 15 m hillside adjacent to the 6th fairway. This cove is relatively protected from the swells due to its location. This subsite was chosen because it is used as a hazard, and therefore may accumulate high concentrations of golf balls. Subsite 8-1 is a southern facing cove 237 m of Arrowhead Point (Fig. 2B). The cove is a sandy beach approximately 1–4 m wide and 12 m long bordered by a vertical 15 m hillside. Subsite 8-1 faces south and is often protected by a rocky structure that protrudes from the western side of the cove out 95 m from the hillside and into the ocean. This location was chosen as a subsite because it is used as a water hazard for 8th hole of the golf course. Subsite 8-2 is the southernmost PB subsite (Fig. 2B). It is a long and narrow cobble beach, 156 m long and 1–10 m wide. The southwest-facing cove and Arrowhead Point protects it from most swells. There is poor visibility in this subsite in all seasons with the exception of winter. The cove acts as a water hazard for the 8th hole of the golf course, where golfers must hit the ball 230 m across the body of water.

The southernmost study site is the Carmel River mouth, on Carmel River State Beach (36°32′19.59″N 121°55′40.17″W; Fig. 2C). This sandy beach is 520–530 m long by 60–150 m wide (Fig. 2C). The beach faces southwest and consists of thick-grained sand and often small river-transported stones. Due to changes in river flow, this site is highly variable. Throughout our study, the flow of the Carmel River was highly variable and ranged from 0 to 309 $m^3 sec^{-1}$. In the years of our study, the river was breached from November to May, between 100 and 500 m from the northern boundary of the beach. Though the Rancho Canada golf course closed in December of 2017, golf balls from 47 years of operation may still be available for recovery. Both of Rancho Canada's 18-hole golf courses used the Carmel River on multiple holes. Further upstream are Quail Lodge and Carmel Valley Ranch Golf Club, located 6.3 km and 13.5 km upriver from the ocean, respectively. These courses, both currently in operation, use the Carmel River as a border and a hazard. The Carmel River site had two subsites: subsite 1 is the beach north of the river and ocean junction, and the subsite 2 is the river and lagoon (Fig. 2C). Because the winter months bring heavy rains, swells, and increased turbidity, this site is not diveable during the winter, but it is possible to walk transects on the beach in winter to recover balls.

2. Collection methods

All collection efforts aimed to remove golf balls and other marine debris, but only golf balls were recorded. At each site the number of collections varied due to weather and swell restraints. Collections were completed independent of the tide and time of day, although most occurred just after a large swell came through in order to improve the likelihood of finding increased numbers of balls. For underwater surveys, collectors would walk, swim, or kayak (dependent on swell and site conditions) to the subsite. Collections were done using a two-step approach, with an initial sweep parallel to and a perpendicular return to shore. Beginning at the beach, divers slowly swam back and forth parallel to the shore, visually scanning the sea floor and collecting all encountered balls. Upon encountering a large aggregation of balls we suspended the sweeping protocol to retrieve the aggregation before resuming sweeping. When a ball was trapped or wedged between rocks or organic material, the diver removed the ball with minimal environmental impact. Divers used floats (e.g., abalone float, Bank's Board, kayak, etc.) to hold the recovered balls and debris. Distance from shore surveyed depended on conditions of the subsite. After reaching maximum distance from shore, divers slowly returned to the beach, scanning while swimming. Golf balls were also collected from the shore at each subsite. All balls were recorded as originating in the corresponding ocean subsite. Once the collection had been completed, the balls were secured in bags and packed out.

3. Sorting and statistical methods

After collection, a majority of the balls (n = 35,985) were segregated into stages to examine spatial patterns in ball decomposition and to approximate plastic loss to the environment. Because golf balls are negatively buoyant their degradation process deviates from the course of degradation of synthetic material observed in other studies (Corcoran

Stage	Surface description	Feeling	Condition	Suitable for play	Examples
1	Intact polyurethane coating, potentially weathered surface, new to worn lettering, minor scuff marks	Waxy, Smooth	Pristine to Good	Yes	
2	No polyurethane coating, external white paint beginning to wear away, leaving paint in the dimple	Chalky, textured	Poor	No	
3	Chalky surface, dimples still visible but all paint and polyurethane gloss has worn off	Chalky, slight texture	Poor	No	
4	Smooth surface, no dimples or paint or polyurethane	Smooth, gritty	Poor	No	
5	Core is exposed in any way; ball may still have gloss as long as there is an exterior laceration	Varies	Poor	No	

Fig. 3. Criteria used to stage the balls collected in the study. Stage 1 balls are in playable condition and can be re-sold. Stage 5 balls have exposed core but are otherwise highly variable in appearance; some are largely intact but with a missing portion of outer shell while others have only small parts of the initial ball remaining.

et al., 2009; Cooper and Corcoran, 2010). However, the erosion of golf balls in our study followed a predictable pattern from the persistent mechanical action of the dynamic intertidal environment. We categorized golf balls based on the erosion of each layer of the golf ball, as follows: Stage one balls exhibit a polyurethane gloss and have no abrasions to the surface of the ball. These balls are in playable condition. Stage two balls lack the polyurethane gloss but still have paint within the dimples of the ball. Stage three golf balls lack all paint but still have a dimpled texture. Stage four balls no longer have dimples, and stage five balls include any golf ball damaged to expose its inner core (Fig. 3).

By categorizing the golf balls removed from each collection site, sources and sinks were identified based on the percentage of low (intact) and high (degraded) stage balls per population. Moreover, by determining the amount of mass lost per ball at each stage, the amount of microplastic lost to the environment was calculated for all balls collected. Statistical comparisons between total number of balls between years and sites and balls of specific degradation stages were conducted using chi-squared tests in R (ver. 3.4). Significance was determined at $\alpha = 0.05$. Where applicable, results are reported as averages ± standard error.

4. Findings and discussion

From May 2016 to June 2018, 75 collections from three study sites yielded 39,602 golf balls. Four collections from CP yielded 1482 balls, 62 collections at PB yielded 35,310 balls, and eight collections from the CRM yielded 2810 balls (Table 1). Pebble Beach subsite 18-1 had the highest average ball yield: 1021 balls retrieved per collection. Locating dense aggregations of hundreds or even thousands of balls here was not uncommon (Fig. 4). Concurrent with our study, teams from the Monterey Bay National Marine Sanctuary (MBNMS) and The Pebble Beach Corporation were conducting golf ball collections. The focus of the MBNMS efforts was to survey and collect data on the location of golf ball aggregations; as a result, their dive team did not perform complete clean ups, recovering only a portion of the balls found. While the focus of the efforts of the Pebble Beach Corporation was to retrieve as many balls as possible, their collections took place solely on beaches and cliff sides, whereas our results show that high densities of golf balls accumulate in the ocean and surf zone as well. Because their retrieval procedures differed, we simply summarize their totals here. The MBNMS team conducted 17 collections and retrieved 1429 balls, while the Pebble Beach Corporation led 42 beach-based collections and recovered 9650 balls. Including their efforts, 50,681 golf balls were recovered from our three field sites from May 2016 to June 2018.

Of the nearly 36,000 golf balls we segregated into stages, stage 2 balls showing light wear were most common (34.14% of total), while severely degraded stage 5 balls were least common (2.91% of total); however, there were distinct inter-annual differences. For example, there were significantly more stage 1 balls (playable condition) retrieved in the first season (2016–2017) than in the second season of collection (2017–2018; $\chi2 = 245.84$; $P < 0.0001$). There were also significantly more stage 5 balls retrieved in the first season than in the second season of collection ($\chi2 = 77.52$; $P < 0.0001$) (Fig. 5). This suggests that the refill of golf balls is not due to new balls entering the ocean, but rather by the replacement of new golf balls with older golf balls.

To further understand golf ball entry points and aggregation sites, during the second season of collection all balls retrieved within subsites were sorted by degradation stage. By collecting data unique to each subsite, patterns in ball degradation began to emerge. First, considering the two subsites associated with the 18th hole at the PB site, there were a significantly fewer stage 1 balls at subsite 18-1 than at 18-2 ($\chi2 = 11.37$; $P = 0.0007$); correspondingly there was also a significantly greater number of severely degraded balls (stages 4 and 5) at 18-1 than at 18-2 ($\chi2 = 64.67$; $P < 0.0001$). There was also a higher proportion of stage 1 balls at subsites 6, 8-1, and 8-2 than at either of the subsites associated with the 18th hole. These patterns helped to

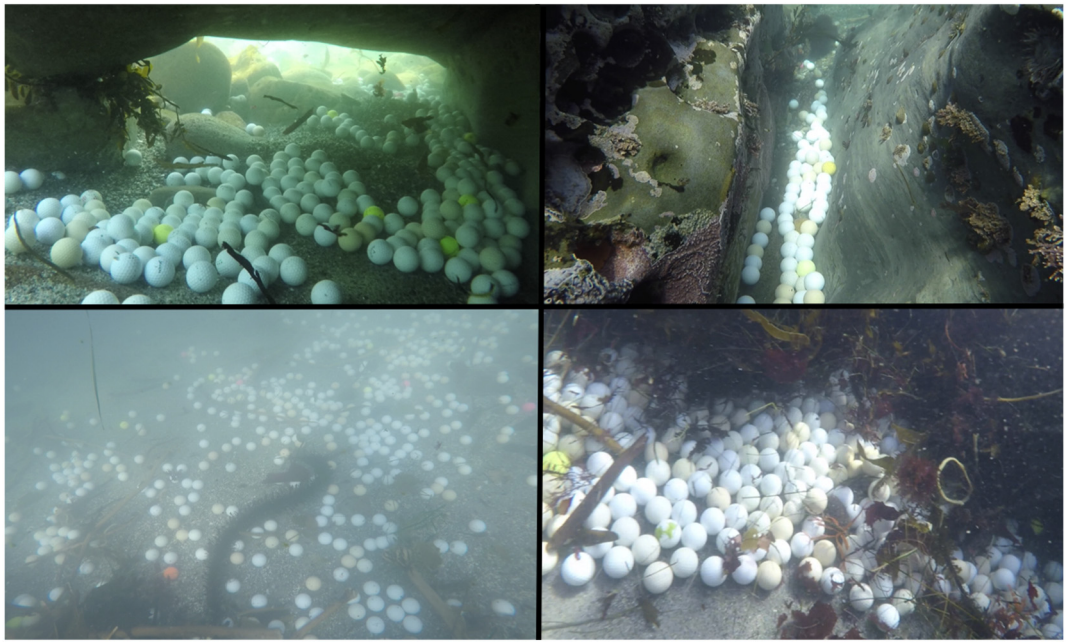

Fig. 4. Several examples of dense aggregations of hundreds of golf balls encountered in the nearshore environment at the Pebble Beach study site.

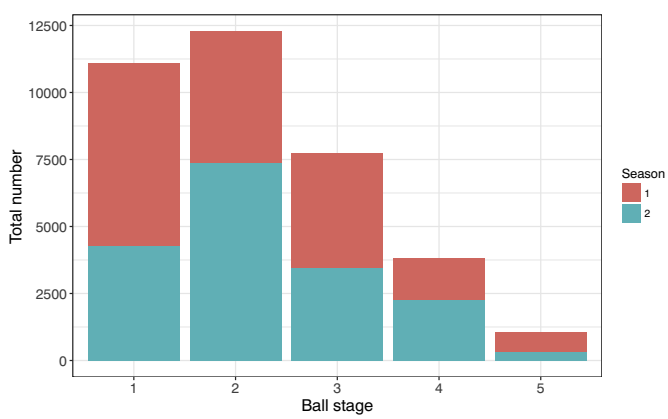

Fig. 5. Number of balls recovered by stage and season. In the first season we encountered and recovered many more pristine (stage 1) and highly worn (stage 5) balls than in the second season.

identify areas that at act as golf ball sources and golf ball sinks in the location of our study.

Understanding the quantity and erosion of golf balls in the nearshore marine environment was a primary objective of this study. Golf balls are only slightly negatively buoyant and thus even light currents can move and potentially redistribute balls. Over the course of the study, we noted that golf ball movement is seasonally and geographically distinct. From repeated observations we classified areas along at the PB site as golf ball sources – major entry points of golf balls to the marine environment – and golf balls sinks – locations where golf balls tend to remain and aggregate. Sources are near areas where the golf course uses the ocean as a natural hazard. Balls recovered from these sources exhibit less wear on average with the majority categorized as stage 1. Subsite 18-2 is an example of a golf ball source with the majority (80.71%) of balls recovered there classified as stage 1 or 2 (Fig. 7). The highest-yielding sink was PB subsite 18-1. Here, the percentage of stage 1 balls was the lowest of any PB subsite (17.07%); congruently, this subsite also had the highest proportion of stage 3–5 balls recovered (42.79% of total; Fig. 7). The movement of balls north along the 18th fairway could explain why exceptionally dense aggregations of worn balls (stages 3–5) were found at subsite PB 18-1, and newer balls (stages 1 and 2) were found more commonly at PB 18-2 (Fig. 7).

Repeated accumulations of golf balls found at sites we designated as golf ball sinks may have resulted from burying and unburying of balls with changes in weather or water movement. On multiple occasions, balls were entirely cleared from a location and yet the next collection less than a week later yielded a number of balls similar to, or greater than, the initial collection. For example, at subsite PB 18-1, between 1/28/18 and 2/17/18, a refill of 4146 golf balls occurred. Interestingly, 95% of those balls exhibited some degree of wear (stages 2–5), indicating that a large number of golf balls may have been buried under sand and cobble and became exposed after our initial collection on 1/28/18. In our experience, large numbers of balls were found buried underwater in the sand at subsites CP 15, PB 18-1, and 8-1. We suggest that balls quickly refilling sites we term 'golf ball sinks' at our study sites are not new golf balls, but old golf balls that had been buried under the sand. These sinks are hotspots for collection efforts, contain predominantly stage 2–5 balls, and may hold decades of golf ball pollution under sand and cobble.

The underwater movement of balls observed in each subsite is likely responsible for the physical degradation of the golf balls. Once the outer shell is completely worn away, only a wound rubber or solid interior core remains, and each wound core unravels into nearly 300 m of buoyant rubber thread. Furthermore, the small synthetic material eroded off golf balls will be nearly impossible to recover. The mass required by the United States Golf Association (USGA) for a conforming ball is 45.93 g. In order to quantify the amount of synthetic material permanently lost to the environment, 100 balls from each degradation stage were randomly selected and weighed. By subtracting the measured mass from the initial mass (45.93 g), we calculated the approximate weight of plastic lost to the ocean. Using this approach, we found that the average mass of plastic lost to the environment was 0.18 g ± 0.02 g for stage 1 balls, 0.35 g ± 0.03 g for stage 2 balls, 0.49 g ± 0.04 g for stage 3 balls, 1.45 g ± 0.06 g for stage 4 balls, and 10.16 g ± 1.39 g for stage 5 balls (Fig. 6). By extrapolating the average amount of synthetic material lost for a ball at each stage, multiplied by the number of balls we found in each stage, we estimate 27.93 kg of synthetic material has been released into the environment from the balls we collected in the form of irrecoverable micro- and nanoplastic.

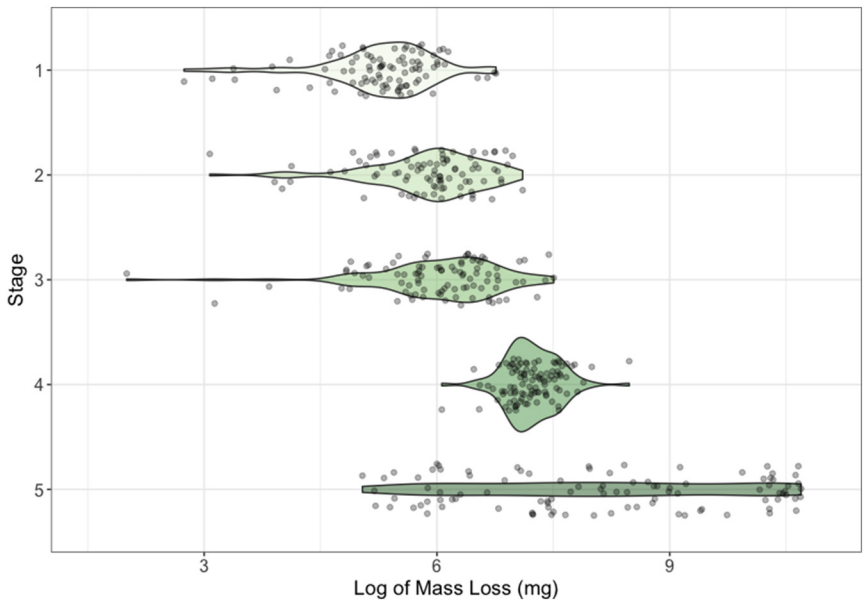

Fig. 6. Violin plots showing the amount of mass lost for 100 randomly selected golf balls in each stage of decomposition as calculated by weighed mass subtracted from original mass of a golf ball (45.93 g). Scale is in log-transformed milligrams lost from the original mass. Stage 4 and 5 balls lose substantially more mass than less worn (stages 1, 2, and 3) balls.

Fig. 7. Spatial distribution of golf balls by stage recovered at the PB site.

While these results do not indicate that golf balls contribute considerably to the overall quantity of microplastic in the ocean, they do identify a novel source of this contamination to the coastal marine environment. Further work is needed to determine the rate at which golf balls are degrading to optimize retrieval of balls before they become significantly worn – stages 4 and 5 – at which point they have already released several grams of microplastic.

Golf courses adjacent to rivers also contribute to marine golf ball pollution. The number of golf balls washed out to sea from the Carmel River is influenced by local precipitation and corresponding river flows. For example in January 2017, subsite CRM 1 experienced high golf ball yields. During this period, the Carmel River had an exceptionally high average flow rate of 341.68 $m^3 s^{-1}$(USGS, 2018). In February 2017 the river continued to flow at an above average rate, though aggregations of balls did not continue to appear on the beach. Whether the river no longer carried balls or if the strong flow sent the balls into deeper water is unknown. During our second season of collections, the Carmel River watershed received far less precipitation (USGS, 2018), and similar golf ball aggregations were not observed, indicating river flow may play a causal role in aggregations at this site. Similar results were found studying sediment-bound microplastics in coastal watersheds; a significant portion of this debris washed out to sea following marked increases in river flow (Hurley et al., 2018). Future efforts at the CRM site should follow periods of heavy rainfall and river flow to maximize cleanup efficiency.

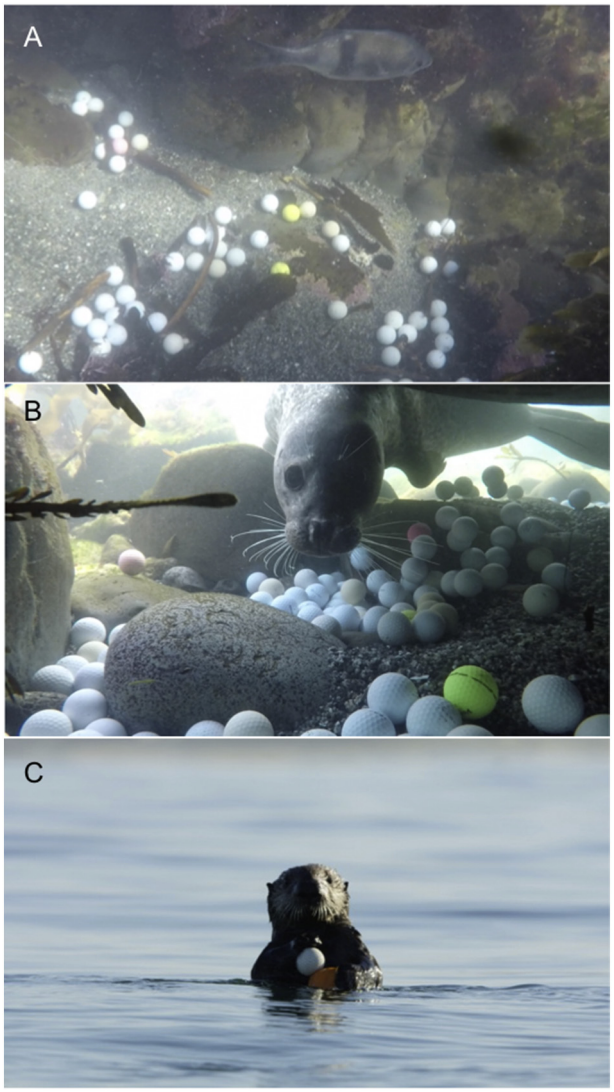

Fig. 8. Several examples of wildlife observed in close proximity to, or interacting with, golf balls at our study sites. A) Pile perch (*Rhacochilus vacca*) swims near an aggregation of balls B) Harbor seal (*Phoca vitulina*) investigates a member of our recovery team near a dense aggregation of golf balls C) Threatened southern sea otter (*Enhydra lutris nereis*) handles a golf ball.

5. Conclusions

In central California, the Pebble Beach Golf Links host 62,000 rounds of golf per year and has been in operation since 1919 (Dunbar, 2018). The average golfer loses 1–3 balls per round (Hansson and Persson, 2012), which implies that between 62,000 and 186,000 golf balls are lost to the environment each year at the Pebble Beach Golf Links. This translates to 3.14–9.42 tons of debris annually. While a portion of these balls is lost to non-oceanic regions adjacent to the course, the coast and intertidal environments still have a high likelihood of accumulating mishit balls. Using a conservative estimate of 10,000–50,000 balls lost to sea annually gives a range of 1–5 million golf balls lost to the coastal environment during the century that this course has been in operation. These projected numbers indicate that this issue has been overlooked for decades.

On a global scale, the number of coastal and riverside golf courses is unknown; however, there are a total of 34,011 eighteen-hole golf courses worldwide (National Golf Foundation, 2015). Some of these courses – like CP and PB – include ocean hazards, while other courses use river hazards, which create the potential for debris to accumulate and drain into the ocean. With a global population of 60 million regular golfers (defined as playing at least one round per year), and a likely average of nearly 400 million rounds played per year (National Golf Foundation, 2015), the scale of this issue quickly magnifies.

The present study documented the presence, quantity, and erosion of golf balls in the nearshore marine environment and did not focus on the potential harm to wildlife. However, we also frequently observed wildlife in close proximity to, or in some cases, interacting with the golf balls (Fig. 8). It is possible that once this debris ages, fragments, and biofouls it could be mistaken for prey and accidentally consumed by marine organisms (Savoca et al., 2017; Vroom et al., 2017; Procter et al., 2019). While no impacts on the local flora and fauna have been observed, the density of debris in these regions indicates that wildlife of the MBNMS should be monitored.

Golf ball pollution is likely an underreported problem associated with coastal courses worldwide. Nearshore marine environments in close proximity to golf courses may similarly accumulate debris and should be surveyed to develop context-dependent mitigation strategies. Marine plastic pollution is a diffuse and seemingly intractable global problem, but the identification and remediation of known point sources of pollution is a tangible step in reducing the deleterious impacts of anthropogenic activity on marine systems.

Acknowledgments

We are indebted to Jack Johnston for conducting dozens of our initial collections resulting in thousands of recovered golf balls. We also wish to thank Captain Phil Sammet of Siren Charters for assisting with collection efforts and providing transportation services; Professor Doug Smith of California State University, Monterey Bay for assistance with river flow metrics; Scott Kathey, Dive Safety Officer at the National Oceanic and Atmospheric Administration for his encouragement and data sharing. We also appreciate the help of Rachel Anderson for editorial assistance and local diver Peter Matthews for his collection efforts in support of this work. Finally, we thank an anonymous reviewer whose feedback greatly improved the manuscript.

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