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Anthropogenic Litter Abundance and Accumulation Rates Point to Seasonal Litter Sources on a Great Lakes Beach

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Abstract: The ecology of anthropogenic litter (AL) (i.e., trash) in marine ecosystems is a growing field of research. Freshwater and marine ecosystems have similar AL densities, but research on the assemblage and accumulation rates of AL in freshwater environments is less common. We studied AL accumulation at Pratt beach, located on Lake Michigan in Chicago, IL, USA. The beach has a concrete pier at the south end, with two areas of grass bisected by a walking path. Pratt beach receives many daily visitors, but unlike other urban beaches, it has no daily municipal beach grooming. We established five 60 m transects parallel to the shoreline, with increasing distance to the shoreline. Each transect was divided into four habitat zones (i.e., pier, south vegetation, path, and north vegetation). All AL within 1 m of each transect was collected biweekly from March-November 2015. AL density (No. m^{-2}) and input rate (No. m^{-2} day^{-1}) were highest at the pier, regardless of distance from the shoreline. Fall had the highest AL density relative to spring or summer. We concluded AL inputs at the pier were dominated by direct littering and the retention of wind- and wave-blown AL at the pier's wall. The study beach had much higher AL than adjacent beaches which received municipal AL cleaning, suggesting cleaning is effective at reducing AL density. This study suggests that, given the mobile nature of AL by natural processes, infrequent sampling may underestimate total AL abundance. Management efforts for AL should be directed towards the greatest AL accumulation sites within a beach, and at prevention of direct littering from visitors.

Keywords: *marine debris, urban, Lake Michigan, trash, glass, pollution, beach maintenance*

Abundance of anthropogenic litter (AL) and the ecological and economic consequences of AL are well documented in marine environments (Abu-Hilal and Al-Najjar 2009; Cózar et al. 2014; Kühn et al. 2015). Recent studies in lakes and rivers confirm that AL is abundant in freshwaters and its density is comparable to marine ecosystems (Hoellein et al. 2014; Driedger et al. 2015; Rech et al. 2015; McCormick and Hoellein 2016). However, more research is needed to examine the ecological dimensions of AL, such as rates of input, output, and breakdown, as well as biological interactions. For example, repeated measurements of AL density over time are needed to document AL movement and to quantify the anthropogenic and natural factors driving its redistribution (Ryan et al. 2009; Carson et al. 2013; McCormick and Hoellein 2016).

Anthropogenic litter represents a complex assemblage of material types, some of which are highly mobile. For example, McCormick and Hoellein (2016) tracked individual AL items to show that the most common AL types in the riparian zone of an urban river (e.g., cans, bottles, plastic bags) had a turnover time of about one year. Export of AL was driven by flooding, seasonality, and capacity for materials to become entrained in debris dams and vegetation (McCormick and Hoellein 2016). Similarly, Bowman et al. (1998) recorded AL abundance and material (e.g., plastic, metal, glass, paper, wood, cloth) to track AL mobility on Mediterranean beaches. The short AL turnover rate at those sites, less than six months, indicated that beaches are not the final resting place for AL, but rather a brief interruption in the constant movement of AL in aquatic environments. These studies conclude that AL density on a single date is not descriptive of total AL inputs over time. While it may appear that the same amount of AL is present over repeated visits, it is apparent from these studies that some portion of the AL standing stock has arrived and departed, so gross input may not be represented.

The Laurentian Great Lakes are the largest contiguous body of freshwater in the world, a critical resource for communities and industries in the region, and an emerging site of focus for AL ecology in surface waters, sediment, and beaches (Zbyszewski and Corcoran 2011; Zbyszewski et al. 2014; Driedger et al. 2015; Hoellein et al. 2015). Assessments of AL density and composition on Great Lakes beaches have used a diversity of approaches to assess spatial variation, and thereby infer its sources and movement. For example, citizen-science datasets have been used to address AL density on Lake Michigan beaches to show positive correlations between beach-goer activity, proximity to urban centers, and AL abundance (Hoellein et al. 2015). Other studies followed a transect-based study design to examine spatial patterns of AL abundance on Great Lakes beaches, with a focus on the plastic component of AL (Zbyszewski and Corcoran 2011; Zbyszewski et al. 2014). Those results suggested proximity to AL sources including urban environments and industrial manufacturing, combined with lake currents, drive distribution of plastic AL on beaches. Finally, Hoellein et al. (2014) used transects to study AL abundance on a Lake Michigan beach, and compared those values to the benthic and riparian zones of an urban river. Overall, research on Great Lakes AL density and composition is in its early stages, and to our knowledge, no studies have returned to permanent transects to measure temporal patterns in AL abundance and quantify net input rates on Great Lakes beaches.

The purpose of this study was to examine AL composition over time using permanent transects. Our objectives were to 1) measure spatial and temporal patterns in AL density, distribution, and accumulation rates; 2) examine temporal changes in AL to infer primary sources; 3) scale up net input rates to determine annual load of AL; and 4) directly compare AL density on Lake Michigan beaches with data collected via different methods (i.e., transect-based and citizen-science-based) and at sites which experience different municipal management (i.e., beach grooming or no beach grooming). With respect to spatial patterns, we hypothesized that AL would be highest next to a pier which delineated the south end of the beach, and closest to the water's edge. We also hypothesized that AL density would be highest in summer and lowest in fall and spring, as beach visitors were likely the dominant AL source. We expected that AL density would be higher when measured using a transect-based study design, as opposed to using citizen-science data, as volunteer scientists may be more likely to underestimate total AL density. Finally, we hypothesized that AL density would be higher on the study beach, which receives no municipal cleaning, relative to beaches that receive regularly scheduled maintenance.

Methods

Study Site

Data collection was completed at Pratt beach, a public beach and dunes restoration area in a densely populated urban neighborhood in Chicago, IL that covers an area of 11,366 m^2 (Figure 1). The dunes restoration area is surrounded by public beaches, and was established in 2003 to serve as a sanctuary for native plants and migratory birds. There are no stormwater outlets, combined sewer outflows, or streams near the restoration area. Public beaches are maintained by the Chicago Park District from Memorial Day (last Monday of May) to Labor Day (first Monday of September; Hoellein et al. 2015). However, the dunes restoration area at Pratt beach is not actively cleaned by the city of Chicago or by volunteers. We established five 60 m long permanent transects parallel to the shoreline. The transects were spaced 11-47 meters apart and divided into four habitat zones: pier, south vegetation, path, and north vegetation. The pier at Pratt beach is a solid concrete structure spanning the entire south edge of the restoration area. The south and north vegetation areas consist of re-emergent native dune grasses, and the beachgoers

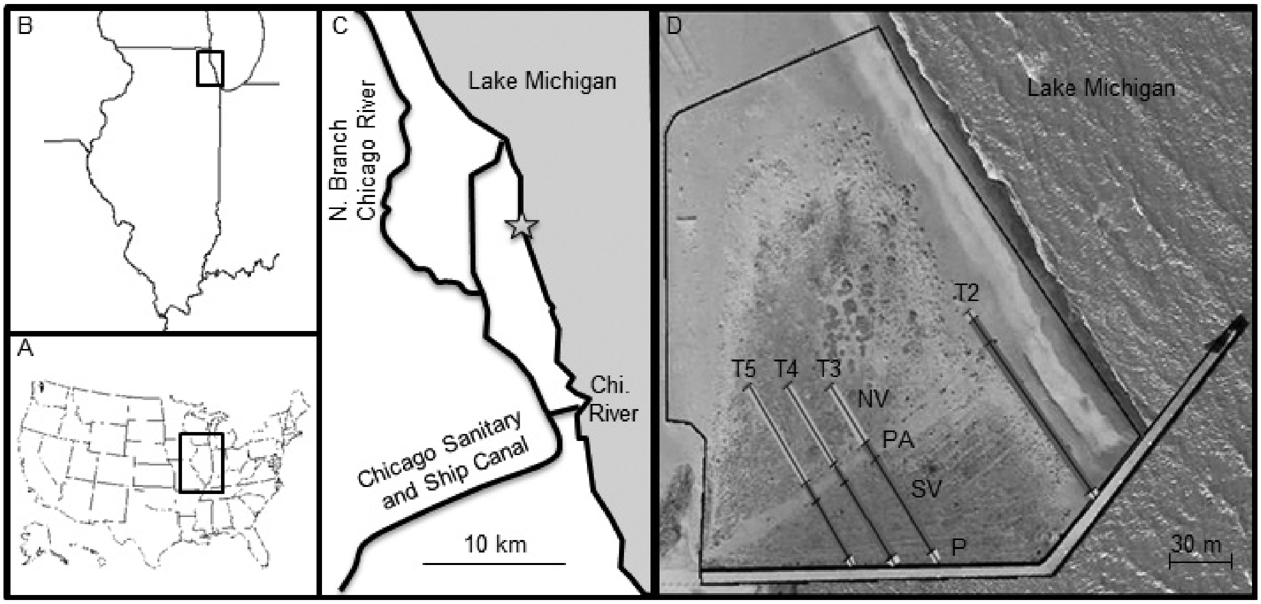

Figure 1. Lake Michigan study site located at Pratt beach in northeastern Illinois. (D) Location of transects (T2-T5) in pier (P), south vegetation (SV), path (PA), and north vegetation (NV) habitat zones.

path consists of sand and bisects the vegetation zones. Transect 1 was eliminated from the analysis after it was inundated by lake level rise soon after the start of the project.

Data Collection and Categorization

All AL visible to the naked eye located within 1 m of each transect line was collected biweekly from March 19, 2015 until November 18, 2015. Collection dates were classified by season, where spring dates spanned from March 19, 2015 to Memorial Day (May 25, 2015), summer collections fell between Memorial Day and Labor Day (September 7, 2015), and fall collections occurred from Labor Day to November 18, 2015. We were unable to collect AL during winter due to consistent snow and ice coverage. AL was categorized, counted, and weighed in the laboratory. The AL categories were created by the Ocean Conservancy and Alliance for the Great Lakes to be used in citizen-science data collection during beach clean ups (Hoellein et al. 2015). The seven categories are food-related AL, smoking-related AL, small AL (i.e., AL ≤2.5 cm), medical/personal hygiene, waterway activities, dumping activities (e.g., large appliances and construction materials), and 'other' (e.g., fireworks). We calculated density as number of AL items and AL mass on an aerial basis (No. m^{-2} and g m^{-2}, respectively). The number of days between each collection was recorded and used to determine net accumulation rates of AL by number of items and mass accumulation rates (No. m^{-2} day^{-1} and g m^{-2} day^{-1}, respectively) for each habitat zone (McCormick and Hoellein 2016). We note the net accumulation is the balance between gross accumulation rates and export. Net accumulation assumes the material present on a collection date is the net input of new AL since the preceding collection date, as some amount of the gross accumulation was exported during the days between collection dates (Bowman et al. 1998; McCormick and Hoellein 2016).

Scaling Up Transects to Total Beach Area

Annual net accumulation for the dune restoration area was determined using beach area and total number of items. We calculated total area of all habitats and transects using Google Earth Pro by extending the length of each transect to the edge of the restoration zone and considering the width of each transect to extend to the halfway point between transects. Beach zone area was multiplied by the zone accumulation rate, and the number of days since the previous collection date. Finally, we summed across all collection dates (C; excluding the first collection) and zones to estimate the number of AL items accumulated (Equation 1).

$$\text{No. items accumulated} = \sum_{i=1}^{c}(\text{accumulation rate} * \text{area} * \text{days}) \qquad \text{(Equation 1)}$$

This represents the total number of items that arrived on Pratt beach over the course of one year in each habitat and each transect. We report these values in terms of annual accumulation, but our results are conservative as they do not account for winter accumulation. AL collection was not possible during the winter due to snow cover throughout the beach and shifting ice mounds at the water's edge, limiting access. We would estimate winter accumulation rates to be low given our conclusion that beach visitors are the main source of AL. Other sites with ice and snow would likely experience similar complications for annual AL budget calculations.

Precipitation and Wind Data

We gathered precipitation and wind speed data from the online daily climate database issued by National Weather Service at the closest location we could identify to our study site. All data were recorded at the Weather Forecast Office (WFO) Chicago-O'Hare field station, approximately 20.5 km from the study site (NOAA 2015). In 2015, the annual precipitation daily average was 0.11 inches, and the average wind speed was 9.8 mph. We calculated peak precipitation and wind speed between consecutive collection dates using daily weather data from the WFO. Peak precipitation refers to the heaviest rainfall event between consecutive collection dates. Peak wind speed is defined as the highest recorded wind speed between collection dates. Of the 16 dates where we recorded the peak wind speed, seven dates had wind from the North, five from the West, and four from the South.

Data Analysis

We compared AL density (No. m^{-2}) and AL mass (g m^{-2}) among the four habitats and transects using 2-way ANOVA. AL density and mass were analyzed individually in spring, summer, and fall. Following a significant interaction between habitats and transects, we utilized 1-way ANOVA to compare AL density among the four habitats in each transect individually, and accounted for multiple comparisons with a Bonferonni correction ($\alpha = 0.05/4 = 0.013$). Temporal patterns of AL density and AL mass across all collection dates were analyzed using repeated measures ANOVA. We analyzed AL composition to determine the most abundant categories for each season, transect, and habitat. Small AL was examined separately by material (e.g., glass and other) to determine the dominant material in each habitat. We used simple linear regressions to quantify the relationships between mean AL density (No. m^{-2}) of each habitat and transect, and peak precipitation and wind speed that occurred during the preceding collection interval. All statistical analyses were completed using SYSTAT 13 and SigmaPlot 10.0.

Results

Spatial and Temporal Variation of AL

AL density was different among habitat types and transects, and these patterns were similar across the three seasons. In spring, AL density in the pier zone was higher than the other habitats (2-way ANOVA $p<0.001$; Figure 2A). In summer and fall, there was a significant transect x habitat interaction (2-way ANOVA $p<0.001$ and $p=0.006$, respectively; Figure 2), so we analyzed differences among habitats for each transect individually. The transect 2 section of the pier zone was higher in AL density during the summer than the other habitats (ANOVA $p=0.001$). In the summer measurements of transects 3-5, the pier zone was highest in AL density, the path was intermediate, and the vegetation zones were lowest (Figure 2B). In fall, transects 3 and 5 showed similar patterns as summer where the pier was highest (ANOVA $p=0.007$ and $p<0.001$, respectively), while transects 2 and 4 had no significant differences among habitats (ANOVA $p=0.028$ and $p=0.132$, respectively; Figure 2C). Across all transects and collection dates, the greatest AL density occurred in the pier zone during the fall, and the lowest AL density occurred in the south vegetation zone during spring (Figure 2).

AL mass showed fewer differences among transects or seasons than AL density. AL mass was higher in transect 2 relative to the other transects

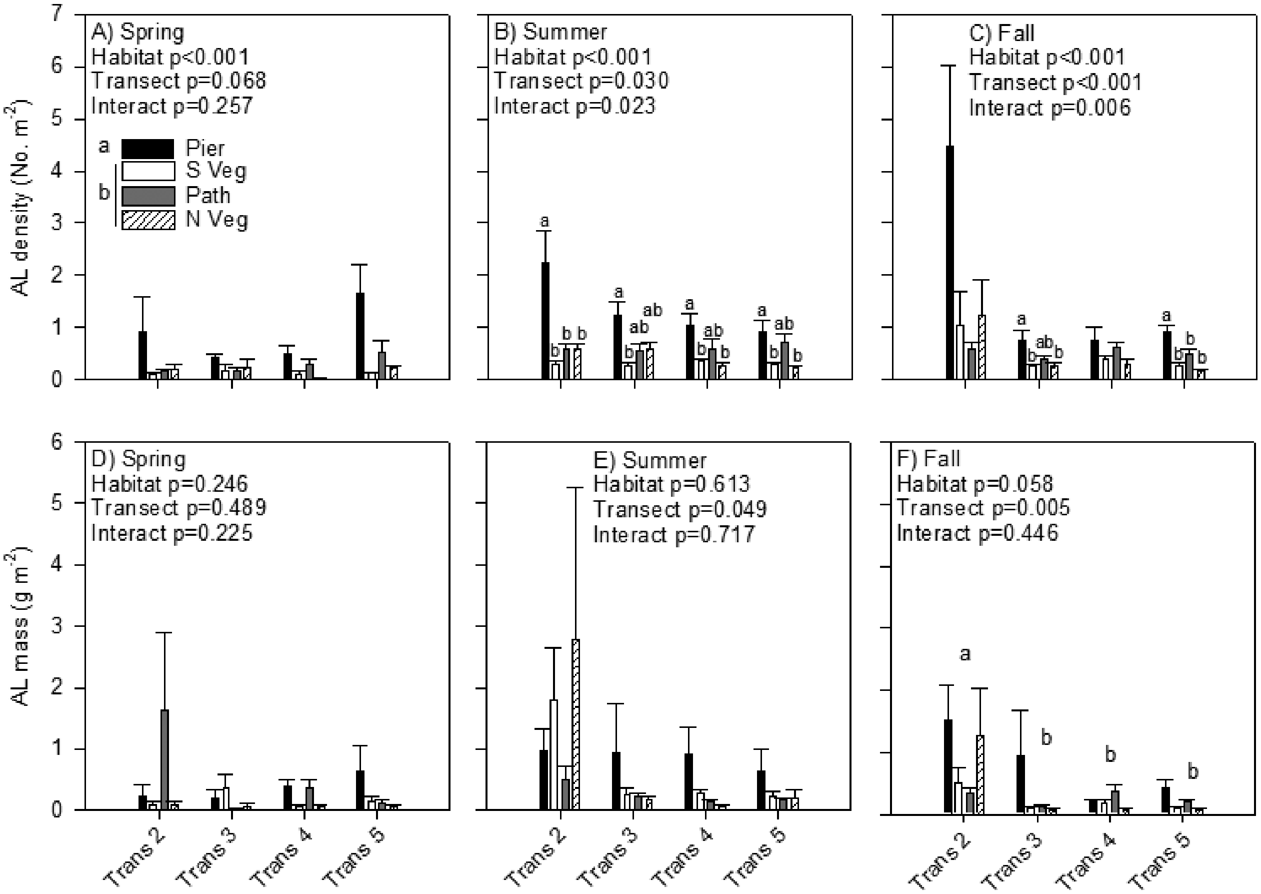

Figure 2. Anthropogenic litter (AL) density for all habitats and transects in (A) spring, (B) summer, and (C) fall. Mass of AL for all habitats and transects are shown in (D) spring, (E) summer, and (F) fall. The p-values are from 2-way ANOVA among habitats and transects in each season. Small letters next to legend in panel A indicate differences among habitats from Tukey's multiple comparison test. Small letters in panels B and C indicate differences among habitats in each transect from Tukey's multiple comparison test, completed after significant habitat x transect interaction. Small letters in panel F indicate differences among transects.

in the fall only (2-way ANOVA p=0.005; Figure 2F). During the fall, AL mass was highest in the pier zone and generally the lowest in the north vegetation zone (Figure 2F). In spring and summer, there was no difference in AL mass among habitats and transects, and there were no significant transect x habitat interactions (Figure 2).

We also considered patterns in AL density and mass over time. Total AL density in the pier zone was higher than the other habitats (R-M ANOVA p=0.036), however, AL density was not significantly different among collection dates (R-M ANOVA p=0.061; Figure 3). In contrast, AL mass showed no differences in habitat (R-M ANOVA p=0.625), but significant differences among collection dates (R-M ANOVA p=0.025; Figure 3), attributed to two peaks of AL mass in early July. There was no significant date x transect interaction in AL density or AL mass (R-M ANOVA p=0.350 and p=0.233, respectively).

Relative Composition of AL by Category

The categories of small AL, smoking-related AL, and food-related AL contributed most to total AL composition across all seasons and habitats. Small AL contributed 55-60% of all collected material, while smoking- and food-related AL represented 20-25% in spring, summer, and fall (Figure 4A). The relative amount of smoking-related AL was higher in fall (~20%) than in spring (~10%) or summer (~15%). By habitat, the contribution of small AL to total AL was relatively consistent at ~55% in the pier, south vegetation, and path habitats, but was ~65% of all AL in the north vegetation (Figure 4B). The amount of smoking- and food-related AL was ~35% in the pier, 20-25% in the south vegetation and path habitats, and ~10% in the north vegetation. The composition of small AL was largely glass (~70% of small items; Figure 4C), with foam, metal, and plastic as the remainder (~30% of small items). Items from waterway activities, medical/personal hygiene, dumping activities, and other miscellaneous items were rare across all habitats and seasons (~5%; Figure 4A, 4B).

Relationship between AL and Weather

We used simple linear regressions to quantify the relationship between weather patterns and AL density in all transects and habitat zones. There

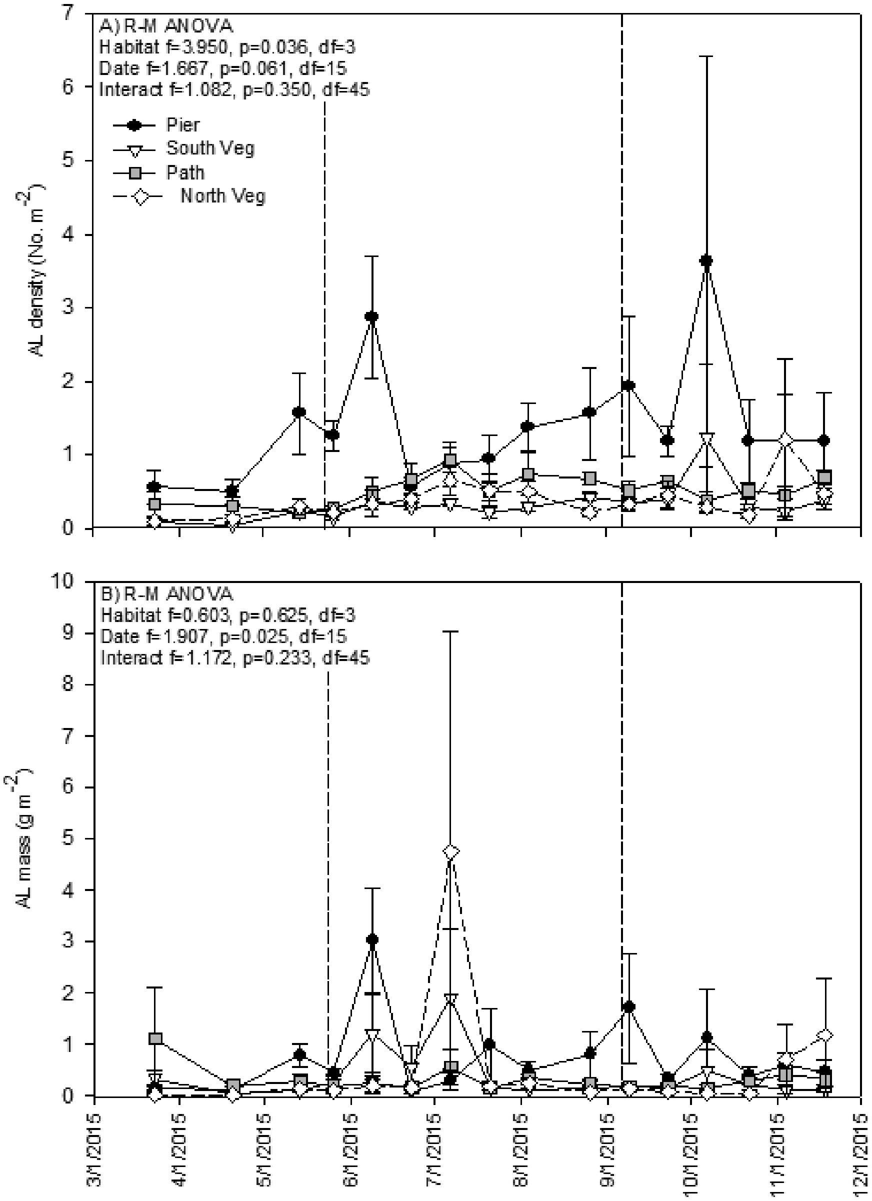

Figure 3. Mean (±SE) anthropogenic litter (AL) (A) density and (B) mass by habitat across all collection dates. From left to right, dashed lines represent changes in season (American holidays of Memorial Day, May 25, 2015 and Labor Day, September 7, 2015, respectively). These dates serve as a reference point, representing the start and end of beach maintenance on municipally maintained beaches. *P*-values are from repeated measures ANOVA.

were no significant linear correlations between AL density and precipitation or wind (Table 1). The strongest linear relationship, albeit statistically insignificant, showed a decreasing trend between AL density in the pier zone and peak precipitation since the previous collection date (R^2=0.191, p=0.091), a trend which may indicate that high precipitation is correlated with lower net AL accumulation.

Scaling Up Transects to the Whole Beach

We scaled up our results to the area covered by each transect and habitat on the beach. The dunes restoration area (total area = 11,366 m^2) had a total net accumulation of 79,915 AL items in 2015. The north vegetation zone was the largest of the four habitats (7,490 m^2, Table 2) and had an annual net accumulation of 50,209 items; south vegetation was the next largest (2,945 m^2) with a net accumulation of 17,537 items; the pier and path zones were the smallest (374 m^2 and 556 m^2, respectively) and had an annual net accumulation of 7,562 items and 4,606 items, respectively. By mass, Pratt beach had a total annual net accumulation of 99,498 g of AL. The north vegetation and south vegetation zones had an annual net accumulation of 67,234 g and 25,131 g, respectively. The pier and path zones had the lowest net accumulation by mass with an annual net accumulation of 4,125 g and 3,008 g, respectively. Finally, the total net accumulation of 'non-small AL' items versus 'small AL' items was different for density and mass. Pratt beach had a total net accumulation of 42,060 non-small items and 37,855 small items. However, the small items represented much of the mass, or 90,361 g, while non-small AL items were 9,138 g.

Discussion

Spatial Patterns in AL Abundance

Patterns in spatial variation of AL followed our hypothesis, as the pier zone had the highest AL density for all habitats and seasons. The prevailing lake and wind currents in Chicago (i.e., the southwest side of Lake Michigan) are from north to south (Beletsky et al. 1999), thus any litter deposited on the beach, especially on the north side of the pier, is likely to accumulate along the pier wall. Like natural materials (i.e., leaf litter and

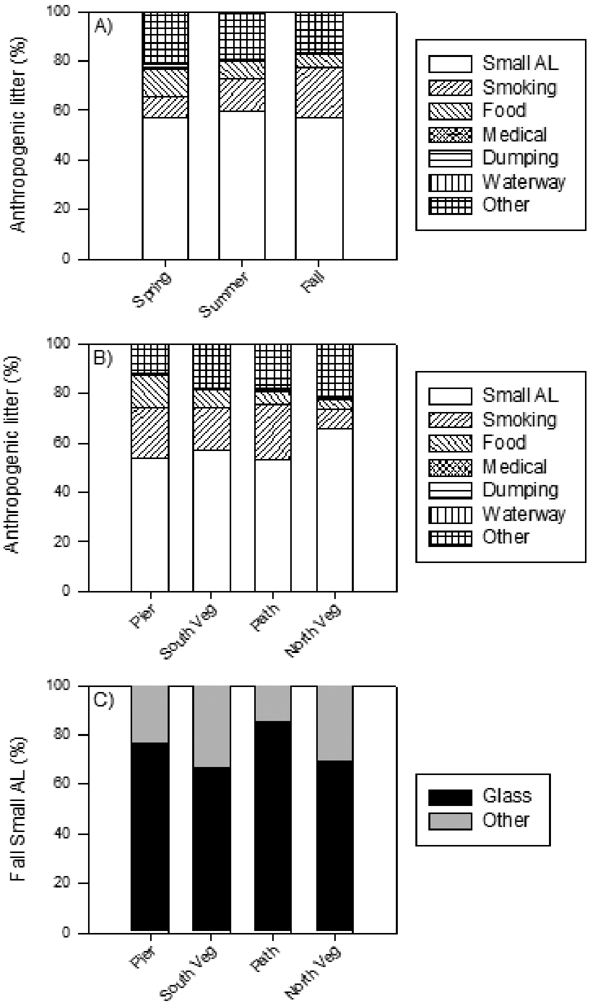

Figure 4. Composition of anthropogenic litter (AL) by (A) season, (B) habitat zone, and (C) AL 1-2.5 cm, analyzed by habitat in fall.

Table 1. R^2 (*p*-value) from simple linear regressions between weather patterns and anthropogenic litter (AL) density (No. m^{-2}) by transect and habitat. Peak precipitation (in) and peak wind speed (mi/hr) were measured between consecutive collection dates.

	Peak Precipitation	Peak Wind Speed
Transect 2	0.068 (0.330)	0.070 (0.321)
Transect 3	0.082 (0.282)	0.084 (0.275)
Transect 4	0.053 (0.392)	0.010 (0.717)
Transect 5	0.043 (0.441)	0.019 (0.607)
Pier	0.191 (0.091)	0.046 (0.426)
South Veg	0.023 (0.576)	0.044 (0.438)
Path	0.139 (0.155)	0.068 (0.329)
North Veg	0.038 (0.472)	0.009 (0.734)

Table 2. Annual net accumulation (number of items) of anthropogenic litter (AL) for all transects and habitats.

	Area (m^2)	Total No. (All Items)	Total No. (Small AL)	Total No. (Non-small AL)
Transect 2	3,605	40,144	25,685	14,459
Transect 3	3,478	20,628	13,368	7,260
Transect 4	1,384	6,004	3,811	2,193
Transect 5	2,899	13,140	8,144	4,996
Pier	374	7,562	4,159	3,403
South Veg	2,945	17,537	10,172	7,366
Path	556	4,606	2,533	2,073
North Veg	7,490	50,209	34,142	16,067

algae), AL in the environment is not stationary, but is redistributed by natural processes throughout the ecosystem and can accumulate on barriers, including natural or anthropogenic structures (Bowman et al. 1998; McCormick and Hoellein 2016). Similarly, some items from the lake were stranded on the beach during periods of high wind and waves, and eventually accumulated along the pier. We observed that AL along the pier was mixed with senesced, filamentous green algae.

We hypothesized that AL density would be highest in Transect 2, which was located nearest to the lake above the high-water mark. However, there were no significant differences among transects in spring, and in fall and summer there was a significant interaction between transect and habitat. This shows that distance from the water and AL density are only related at the pier habitat in transect 2. Because of higher accumulation along the pier at the transect closest to the water, waves seem to increase AL accumulation (Silva-Cavalcanti et al. 2009). In this study, our plan for an additional assessment of the effect of distance from the water's edge on AL distribution was confounded by ongoing lake-level rise throughout 2015. For example, we had initially established another transect closest to the water's edge and collected data there for several weeks, but it remained completely submerged for the remainder of the data collection period and could thus not be considered for analysis here.

Results from studies elsewhere also show that comparing AL density on different beaches, or among different locations on the same beach, can illustrate the effects of visitor density, physical structures, and wind and wave dispersal. A recent analysis of engineered shorelines throughout coastal Chile indicated that artificial breakwaters retain more AL than unmodified shorelines (Aguilera et al. 2016). Hoellein et al. (2015) demonstrated that AL density on beaches throughout Lake Michigan was positively correlated with population density. Similar results were observed on marine beaches in South America (Portz et al. 2011; Thiel et al. 2013), and the Mediterranean (Poeta et al. 2016). Last, Zbyszewski et al. (2014) showed higher plastic AL in proximity to industrial pollution sources, especially downstream of prevailing currents, indicating AL movement via water affects its distribution on Great Lakes shorelines.

Temporal Patterns in AL Density

We hypothesized that summer would have the highest AL density, but found fall had the highest AL density among seasons. This may be related to beach maintenance. Beaches managed by the Chicago Park District receive daily maintenance during the summer, which appears to reduce AL density (Hoellein et al. 2015). However, we observe that good weather conditions continue to draw visitors to Chicago-area beaches for fishing and swimming after regular cleaning ceases in early September, but acknowledge that we do not have beach visitor data. The combination of high visitation rates in September and no regular cleaning schedule could explain higher AL density in the fall than during the summer on sandy beaches with municipal maintenance. This result was similar to Hoellein et al. (2015), who also found AL density was higher in fall on other Lake Michigan beaches by analyzing a citizen science-generated dataset on beaches that have municipal cleaning. Similarly, Topçu et al. (2013) concluded that AL density on tourist beaches was highest in the fall, which they attributed to fishing practices, seasonal climatic variations (e.g., heavy rains), strong wave action, and wind-driven surface currents. While the adjacent public beach receives scheduled maintenance, the dunes restoration area of Pratt beach did not receive any cleaning. Therefore, we hypothesized summer would have higher density as that is the period of greatest visitation. However, it appears that some aspect of seasonality influenced this un-groomed beach in a similar fashion to the adjacent, groomed beaches. Thus, we estimate that the AL density on the study beach was affected by AL from the areas directly surrounding it. This includes beachgoers that could directly litter near the pier zone, as well as the transport of light AL items (e.g., cigarette butts and food wrappers) from nearby beaches via wind. To support this inference, we attempted to relate wind speed and AL density, but found no significant patterns. However, we note our wind speed data were recorded at a National Weather Service field station at O'Hare International Airport, approximately 20.5 km from Pratt beach. Superior results could be attained using wind speed data collected on the beach, and we predict that AL input rates could show a positive correlation with wind speeds in future studies.

Beach Visitors as a Source of AL

We considered smoking-related, food-related, and many of the items in the "other" category (e.g., fireworks, hair ties) to most likely be generated by beach visitors. Anecdotally, we observed many of the smoking- and food-related items to be unweathered suggesting their recent deposition. In accordance with other studies, two of the most common AL categories were smoking- and food-related (Santos et al. 2005; Hoellein et al. 2015). We acknowledge that some smoking and food-related AL may have been generated elsewhere and been moved to the study beach by wind and waves. Previous AL studies on Great Lakes beaches (Hoellein et al. 2014; Hoellein et al. 2015), estuarine shorelines (Thornton and Jackson 1998), and tourist beaches in Latin America (Nagelkerken et al. 2001; Silva-Iñiguez and Fischer 2003; Wetzel et al. 2004; Araújo and Costa 2006; Bravo et al. 2009; Thiel et al. 2013) also concluded that beach visitors are the primary source of AL, based upon the assemblage of AL types and observation of beach-goers' activity. In contrast, studies conducted in more remote areas away from tourist centers found that fishing- and shipping-related activities were the major sources of AL (Nagelkerken et al. 2001; Kusui and Noda 2003; Hinojosa and Thiel 2009; Santos et al. 2009; Thiel et al. 2013).

Our 'small AL' category includes AL items composed of glass or other materials that were ≤2.5 cm in size. Glass represented ~70% of all small AL items. We surmise that these glass particles are most likely from consumer goods (i.e., glass containers), rather than manufacturing or industry sources. We conclude this because there are no major manufacturing centers for glass on Lake Michigan shorelines up-current (i.e., north) of the study site, and because of the irregular shapes of the glass items. We can also draw some inferences about the age and biological interactions of small glass AL. Many of the glass pieces had been present for some time as they were smoothed over from water and sand abrasion. From a biological perspective, these small glass items may represent less of a concern to beach organisms than small pieces of plastic, which could be directly consumed and leach or adsorb persistent organic pollutants (Rochman et al. 2013). Finally, small heavy AL items such as glass pieces were likely to be buried and uncovered by sand throughout the year. Thus, finding small AL in the transect might not always represent input of new AL items, but simply that some previously buried items were revealed between collection dates. We acknowledge this might also occur with larger items or lighter materials, but burial is likely most common with small, dense pieces of glass or plastic. This could be assessed by measuring AL in sand cores, but to our knowledge has not been included in previous AL research. Zbyszewski et al. (2014) noted degradation of plastic on Lakes Erie and St. Clair shorelines due to sunlight and shifting sands. The disparity found between glass and other materials on Pratt beach may be the result of direct deposition of glass items (e.g., beverage bottles) on the beach or in the water near the shoreline.

Comparison of AL Density to Literature Values

Results from this and two recent Lake Michigan AL abundance beach studies suggest that municipal cleaning is effective at reducing AL density (Figure 5; Hoellein et al. 2014; Hoellein et al. 2015), and that citizen science-generated data adequately captured AL density compared to more rigorous, transect-based collection. AL density on the study site was close to an average literature value for marine beaches with no city-sanctioned cleaning (1.83 items m^{-2}; Figure 5; Hoellein et al. 2015). However, an adjacent beach, Hartigan beach, which experienced municipal maintenance had a much lower AL density (0.007 items m^{-2}), when measured using the same transect-based approach as the current study (Hoellein et al. 2015). Finally, similar AL density results were obtained from citizen science and transect-based collections on maintained beaches, which further suggests that AL density can be reduced by effective cleaning strategies (Figure 5; Hoellein et al. 2014; Hoellein et al. 2015).

Management Implications

Due to the protected nature of the dunes restoration area at the study site, the use of large machinery to collect AL is prohibited. Despite the growth of vegetation, accumulation of AL within the site occurs at relatively high rates, consistent with results from marine beaches (Figure 5). Reducing AL density on Pratt beach and similar beaches elsewhere will require a multifaceted approach. We confirm the value of current beach maintenance operations, and suggest that local management agencies enhance AL collection with manual clean-up within protected areas and in sites adjacent to human-engineered structures that may promote AL accumulation. In this way, quantitative analyses of the spatial and temporal patterns of

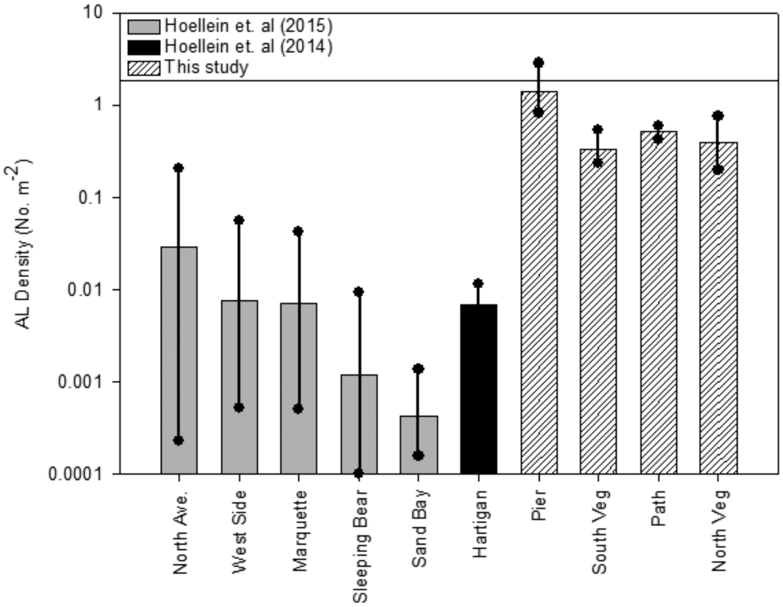

Figure 5. Comparison of mean (± range) AL density on Lake Michigan beaches from citizen science studies (Hoellein et al. 2015) and transect-based collection studies (Hoellein et al. 2014; this study). AL density from Lake Michigan beach studies is compared to a mean AL density for marine beaches worldwide, indicated by a solid line (1.83 items m^{-2}; Garrity and Levings 1993; Thornton and Jackson 1998; Nagelkerken et al. 2001; Kusui and Noda 2003; Silva-Iñiguez and Fischer 2003; Abu-Hilal and Al-Najjar 2004; Bravo et al. 2009; Slavin et al. 2012; Topçu et al. 2013).

AL in urban beaches will directly contribute to the refinement of efficient management practices. Additional prevention measures may include addition of garbage receptacles, adjustments of beach combing technology, and innovative measures similar to the 'vote with your butt' ashtrays installed by the Alliance for the Great Lakes. For this novel approach to litter prevention, beach goers are presented with an opportunity to 'vote' on local topics (e.g., sports teams or food choices) by placing their smoking-related litter on one side or another of a plexiglass ashtray. Future studies should examine resident and tourist populations separately to address disparities in knowledge of local AL management practices. Finally, continued educational outreach and interactive clean-up measures by beach management agencies can draw attention to the harmful effects of AL and provide the necessary incentives to alter beach visitor behavior.

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