Effect of Beach Management Policies on Recreational Water Quality

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Journal of Environmental Management

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Abstract. When beach water monitoring programs identify poor water quality, the causes are frequently unknown. We hypothesize that management policies play an important role in the frequency of fecal indicator bacteria (FIB) spikes (enterococci and fecal coliform) at recreational beach sites. To test this hypothesis we implemented an innovative approach utilizing large amounts of data (n > 150,000 per FIB) to determine associations between the frequency of contaminant spikes and beach management. The large FIB database was augmented with results from a survey designed to document management policies for 316 beaches throughout the state of Florida. The association between FIB and survey data was analyzed using t-tests, ANOVA, factor analysis, and linear regression. Results show that beach geomorphology (beach type) was highly associated with exceedance of regulatory standards. Low enterococci exceedances were associated with open coast beaches (n=211) that have sparse human densities, no homeless populations, low densities of dogs and birds, bird management policies, low densities of seaweed, beach renourishment, charge access fees, employ lifeguards, without nearby marinas, and those that manage storm water. Factor analysis and a linear regression confirmed beach type as the predominant factor with secondary influences from grooming activities (including seaweed densities and beach renourishment) and beach access (including charging fees, employing lifeguards, and without nearby marinas). Our results were observable primarily because of the very large FIB databases available for analyses. Given the availability of these databases, a similar approach can be used to assess the associations between beach management policies and FIB levels within other parts of the U.S. and abroad.

1. Introduction

Beach water quality monitoring programs include sample collection and analysis for the purpose of evaluating levels of fecal indicator (FIB) bacteria. When the levels of FIB exceed a set threshold, beach advisories or closures are issued, as these exceedances could indicate a threat to public health. As a result of these programs, a database is created of long-term FIB monitoring data. These databases tend to grow over time resulting in an untapped resource for analysis.

One common goal of these monitoring programs is a desire to reduce the number of beach advisories by identifying and reducing FIB contributions. These sources of FIB to beaches include point sources, such as leaks from sanitary sewers and effluent from wastewater treatment plants. Non-point sources such as storm water runoff (Molina 2014), and humans and animals that frequent beaches (Wright et al. 2009, Elmir et al. 2009, Elmir et al. 2007, Converse et al. 2012, Sinigalliano et al. 2013) also contribute FIBs. One of the hypotheses underlying this study is that these sources of FIB, in particular non-point sources, can be controlled through beach management practices, thereby resulting in a reduction of beach advisories. Beach management is defined here as infrastructure and a sequence of policies that are implemented to maintain the recreational and ecological value of a beach.

The state of knowledge related to beach management practices and their influences on recreational water quality includes many major gaps. Studies such as Rippy et al. (2013), Russell et al. (2014), Wu et al. (2016), Feng et al. (2016), and Donahue et al. (2017) have examined some of these issues, but focused on relationships between microbial water quality and physical, chemical, and biological factors. The influence of beach management practices and policies on water quality have not been comprehensively addressed.

Beach grooming studies are underrepresented (Nevers et al. 2016, Whitman et al. 2014, Kinzelman et al. 2003, Verhougstraete et al. 2014, Russell et al. 2014); studies that most closely relate to beach grooming studies, focus on sand erosion and issues of coastal zone management (Sutton-Grier et al 2015). Studies of birds (Sinigalliano et al 2013) and some on humans and dogs (Elmir et al 2009, Wright et al 2011) have been conducted, but studies of wildlife and other domesticated animals have not. FIB studies on vehicular traffic; facilities like restrooms and showers; concession stands; solid waste management; and fees to access the beach are not found in the literature. This represents many major gaps in knowledge. The issue of anthropogenic impact, modifications or uses that allow FIBs and pathogens to be introduced into the beach environments, and transport to the beach environment, has also not been well studied.

The primary objective of this study is to evaluate whether beaches characterized by a set of management policies are associated with lower FIB levels. This work is unique in that it evaluates the understudied areas to fill in some of the gaps and indicates areas of future work. It is innovative by classifying beaches based upon major geomorphological characteristics and then evaluating within these characteristics whether specific conditions and policies used to manage a beach were associated with improved water quality. Since beach management policies are in place for long periods of time, on the order of many years, this study used the entire period of record to define a beach's overall average exceedance rate (percentage of time the beach FIB exceeds the regulatory thresholds). This study builds on the work of Feng et al. (2016) and Donahue et al. (2017), by examining the anthropogenic impact on beach water quality due to beach management practices. Earlier studies examined natural and man-made features. This study also evaluated the interaction of these features with new data on beach management practices.

2. Methods

To evaluate beach management policies, a large database of fecal indicator bacteria (FIB) data was consolidated, corresponding to the entire state of Florida as documented through the Florida Healthy Beaches Program (FHBP). Analysis included the establishment of inclusion criteria, which resulted in 316 beaches for evaluation. Beach type was identified based upon the method of Donahue et al. (2017). The data for each beach was converted to a percent exceedance value to track the fraction of times that the beaches exceeded regulatory guidelines. A beach management survey was developed to collect data on management policies. The results were then compared to FIB data to determine which management condition corresponded to lower bacteria levels. The observed influence of beach morphology led to a decision in how each of the responses in the beach management survey were analyzed. For each question within the various categories, the data were analyzed in four groups, 1) all beaches for enterococci, 2) open coast beaches for enterococci, 3) all beaches for fecal coliform, and 4) open coast beaches for fecal coliform. Open coast beaches represented the vast majority of the beach types in Florida (n=211). We also included questions about human and animal densities on a typical Sunday noon and Wednesday noon. Only the results for Sunday are discussed in this paper.

2.1 Analysis of Data from the Florida Healthy Beaches Program (FHBP)

The FHBP (Florida Department of Health 2016) was originally established in August 2000. Through this program FIB data have been collected and reported to the Florida Department of Health (FDOH), which is responsible for maintaining a statewide database. The total number of samples collected through the FHBP for the July 31, 2000 to December 31, 2015 period of record was 189,640 for enterococci and 153,805 for fecal coliform. For a beach to be included for analysis within the current study, the site had to have been included in the FHBP

with a minimum of 120 samples during the 15-year period of record (2000-2015). A value of 120 was chosen after evaluating the continuity of the records for the beaches in the 100 to 400 sample range, and by also considering input from beach managers concerning their views about the permanency of sites in this range.

A total of 316 beaches from the 34 coastal counties (Figure 1) met the criteria for inclusion. There were over 50 other sites with fewer than 120 samples and these data were excluded from our analyses. In some cases, extra exploratory samples were collected following a sample that exceeded the "poor" water quality threshold. In our study, we excluded these exploratory samples from the analysis to minimize bias due to extra sampling conducted during periods of high bacteria levels. After excluding the exploratory samples and data for sites with less than 120 samples, the total number of beach monitoring data points utilized for the analysis was 185,225 for enterococci and 151,000 for fecal coliform.

When issuing advisories, both the geometric mean and single sample maximums are considered. From 2000 until 2015, the FDOH has issued beach advisories or closures when single samples exceeded 104 colony forming units (CFU) per 100 ml for enterococci (See supplemental Table S1). Fecal coliform data was also collected from beaches in Florida during our period of study. Fecal coliforms were recommended earlier by the EPA for both freshwater and saltwater (EPA 2017). From August 2000 through June 2002, closures were issued at 800 CFU/100 mL. This was adjusted to 400 CFU/100mL, which was in effect from July 2002 until June 2011. After June 2011, fecal coliform was dropped from sampling.

To obtain a measure of the frequency with which beaches are closed due to health risks, we converted the numerical measurements of colony forming units to percent exceedance based on the single-sample thresholds for issuing beach advisories. A threshold value of 104

CFU/100 ml was used for enterococci, which is consistent with the threshold value used by Florida beach managers throughout the 2000 to 2015 period of record evaluated in this study. A threshold value of 400 CFU/100 ml was used for fecal coliform which corresponded to the time period when the majority of the sample collection took place for these bacteria. For analyzing data on a county-by-county basis, the percent exceedance value for that entire county was aggregated using a weighted average based upon the number of samples collected at each beach within the county to compute a percent exceedance value for that county. On a beach basis, percent exceedance was computed for the entire period of record, providing one value per beach. The aggregation of the beach monitoring data was considered important for averaging out short-term and seasonal variabilities in FIB measures.

2.2 Beach Management Survey

The survey (copy in supplemental text) was designed with two parts. Part I focused on county-level information including sample collection, sample transportation, and laboratory analysis policies. Part I was sent to the offices of the 34 Florida County Health Departments that participated in the FHBP during the period of record (2000-2015). During the process of distributing the survey, the team learned that sample collection was handled by various entities in Monroe County and as we received responses from both the Upper Keys and the Lower Keys in Monroe County, these responses were classified separately, giving a total of 35 counties surveys instead of 34. For county-level analyses, both the Upper and Lower Keys values were analyzed using the weighted average FIB data for Monroe County as a whole.

Part II covered items that were specific to each beach. The questions included in Part II addressed six categories. These categories included three that addressed sources of fecal indicators within the beach environment (e.g., human use, animal densities and control, and solid

waste management). Additional categories included "grooming" which includes aspects that would alter the sediment distribution at the beach (such as seaweed densities, beach grooming policies, and beach renourishment), "beach access" which includes policies concerning fees charged and how the beach can be used (e.g., concessions at beach), and "drainage" which includes impacts from sources outside the beach environment through storm water drainage and the sanitary infrastructure.

Upon receipt of the responses from the beach managers, they were entered into a master database. Of 316 beaches surveyed, responses were received for 301 beaches. For beaches that did not provide responses and were no farther than an hour's drive (4 beaches), members of the University of Miami team visited the beaches and recorded the responses that could be observed from field visits. This led to a total of 305 beaches with surveys completed (97%). Survey data were consolidated on a county-by-county basis and then sent back to the beach managers for that county asking that they review the responses for the entire county. Corrections to the responses were made in accordance to the second round of responses received from the beach managers.

2.3 Comparison of FIB Data and Beach Survey Results

FIB data were first evaluated spatially by plotting the data in ArcGIS. Once standardized, the survey data was then analyzed against the percent exceedance for enterococci and fecal coliform levels from the FHBP using the statistical analysis suite Statistical Analysis System (SAS)(SAS 9.4, SAS Institute, Cary, North Carolina). The survey responses were standardized into categories, usually "yes", "no," and "no answer" (indicating that the respondent left the response blank), although the open-ended questions required additional categories. For questions that could be divided into two groups, such as "yes" or "no," T-tests were performed, using the Satterthwaite method as the equality of variances is unknown and

assumed to be unequal for our groups. For the open-ended questions, each answer was evaluated and assigned a code, an abbreviated version of the answer provided. Once these codes were developed for all responses to a question, some of the codes that were, for all intents and purposes, the same, were hybridized under new codes that reflected all of the similar answers. These questions were analyzed through ANOVA; the F-values are included in the tables and the p-values are in the text and in the tables. Similar to the way that a T-test indicates whether or not a single variable is statistically different, an F-test such as ANOVA indicates whether a group of variables are statistically different. The F-statistic approaches 1 when where there is no difference in variances among the groups; F-values closer to 1 tend to be accompanied by lower p-values. In this study, F-values significantly greater than 1 and p-values less than 0.05 were considered significant.

2.4 Factor Analysis and Linear Regression

Responses to the questions in the beach survey were analyzed within the six categories (human use, animal policies and control, solid waste management, grooming, beach access, and drainage). ANOVA and T-tests were performed, and the questions that demonstrated a significant effect on FIB levels were selected for further analysis. In each category, the responses to selected questions were assigned a numerical score based on whether the answer would be consistent with an increase or decrease in FIB. The responses were given a negative one if the practice would lower FIB levels, a zero if there was no response and the effect is not known, or a positive one if the practice described would increase FIB levels. These numbers were then averaged for the questions in each category. Once these categories were analyzed, all six scores plus a beach type score were analyzed together through SAS factor analysis to evaluate which had the greatest effect on enterococci and on fecal coliform. Factor analysis was used instead of

multilinear regression or the generalized additive model in that this analysis examines all of the factors used to build a model, keeps only those factors with the strongest contribution, and builds new factors using only those selected. Only two factors were determined to be necessary for the model, as determined by the variance of each factor (eigenvalue), and the proportion of the total variance that each factor accounts for, making a composite of the most significant categories, including beach type. With these factors, a linear regression was performed for both enterococci and fecal coliform. The coefficient of multiple determination (R^2) was evaluated to determine the percentage of the exceedances explained by the model. The p-values were also evaluated, to evaluate which of the factors was most significant.

3. Results

Results are organized into beach-specific results: beach type plus the six included in the surveys (human use, animal densities and control, solid waste management, grooming, beach access, and drainage), and into county-level results, which focused on sample collection, sample transport and laboratory methods. In order to consolidate the information presented, only the questions that had significant associations as determined from the factor analysis and regression are discussed in the main text of this paper. See the supplementary section for discussions about the remaining questions.

3.1 Beach Classification

The spatial distribution of enterococci and fecal coliform percent exceedances for the period of record at each of the 316 beaches shows lower levels of FIB along the northeast coast of Florida and higher levels in bays (Figure 2). With respect to the "Big Bend" area, enterococci

levels frequently exceeded regulatory thresholds. However, this same trend was not as emphasized when evaluating fecal coliform.

This spatial distribution is consistent with the beach classification scheme as described in Donahue et al. 2017, who defined six beach types in Florida based upon their geomorphology as observed from Google Earth imagery and given the wave energy designations of Tanner et al. 1960 and Feng et al. 2016. These beach types included open coast, bay, inlet-channel situated, manmade-structure-protected, marsh surrounded, and back-reef beaches (See supplemental Figure S1 for categorization of beaches).

When the beach classifications were compared to the percent exceedances, certain beach types seemed to be associated with lower exceedance levels (Table 1). Enterococci percent exceedances for open coast beaches were statistically lower than for bay beaches, which in turn were statistically lower than marsh beaches. For fecal coliform, open coast beaches were statistically lower than marsh beaches, which, in turn, were statistically lower than man-made protected beaches. These results indicate that although open coast beaches are lowest in enterococci and fecal coliform exceedance, the relative exceedance between other types of beaches depends upon which FIB is chosen. Marsh beaches tend to fare worse under the enterococci threshold, whereas man-made-structure-protected beaches fare worse under a fecal coliform threshold.

3.2 Human Use

Human use was examined through questions about the densities of visitors and presence of homeless populations.   For enterococci, when considering all results, (Table 2), the "dense" category had the lowest exceedances, followed by "medium", "sparse," and then "zero" categories, which is the opposite of what would be expected if humans are considered sources.

The observed trend, when considering all beaches, may be due to the fact that marsh beaches are more remote and tend to have lower human densities. The open coast beaches, as a whole, tend to have lower FIB levels, but have higher human densities on average, with beach managers at open coast beaches mostly reported dense or medium populations (240/267). Thirteen of 15 beach managers at marsh beaches reported medium to zero (6 medium, 6 sparse, 1 zero).

To remove the impacts of geomorphologic factors (marsh beaches and bays), the associations of human densities were evaluated for "open coast" beaches only (n=211). In this case, the expected trend was observed. The enterococci results in this case show that the "sparse" category had the lowest FIB exceedances (0.64%), followed by "medium" (1.34%) and "dense" (1.73%) category. The exceedances for open coast beaches were statistically different for "sparse" human density beaches relative to "dense" human density beaches ($p = 0.0011$). In this case, when the impacts of beach geomorphological features were removed by considering only open coast beaches, the impacts of human density were observable with beaches characterized by sparse human densities with lower enterococci exceedances relative to beaches with dense human densities.

For fecal coliform, similar trends were observed as for enterococci when evaluating all of the results, with lower percent exceedances for "dense" human densities and higher for "zero" human densities (Table 2). When evaluating open coast beaches only, the results showed a similar trend as for the enterococci, with lower fecal coliform exceedances for "sparse" beaches.

For the presence of homeless populations at the beach (Table 3), results for all groups (all responses, open coast, enterococci and fecal coliform), demonstrate that beaches that reported no homeless populations had lower FIB than those that had homeless populations. The difference in

FIB levels was significant for 3 of the groups: for fecal coliform in the all responses group, and for both enterococci and fecal coliform in the open coast group (Table 3).

Overall, results suggested that the lack of humans is generally associated with lower FIB levels. This was evident for beaches that reported no homeless populations. With respect to beach visitors, the impact of human densities was observed only when evaluating open coast beaches. Beach geomorphology appears to overwhelm the influence of human densities such that these trends were only observed when disaggregating the data by beach type. For open coast beaches, enterococci exceedances were lower for beaches with sparse human densities relative to beaches with high human densities.

3.3 Animal Densities and Control

Animal densities were evaluated in separate categories determined by the type of animal (dogs, other domestic animals, birds, and wildlife other than birds). From these categories, the densities were evaluated in much the same way as human use. In subsequent sections, an emphasis is placed on discussing the results concerning dog and bird densities and policies for control.

3.3.1 Dogs

The first question in this series asked if dogs were allowed at the beach. Survey results indicated that among the responses 68% of the beaches do not allow dogs to visit. Results (Table 3) show statistically lower levels of FIBs (3.19% not allowed; 4.71% where allowed) for enterococci for beaches that do not allow dogs when all beaches are considered (p = 0.037). No statistical differences were observed for the other categories.

For dog densities, results (Table 2) show that the enterococci percent exceedance for "all responses" demonstrated that the "zero" category had the lowest (2.77%) and increasing with "sparse" (4.96%) "medium" (4.00%) and "dense" (7.51%) dog densities. Only the sparse and zero categories were statistically different ("sparse" 4.96%, "zero" 2.77%, p=0.030). For the 211 open coast beaches, none of the responses for open coast beaches were statistically different for enterococci.

For fecal coliform, the "all responses" sections were very similar to the enterococci, with "zero" as the lowest, then "sparse", "medium", and then "dense" as the highest percent exceedance. However, due to the very low levels of exceedances for fecal coliform limiting the range in values, none of the fecal coliform percent exceedances were statistically different.

We then followed up with questions on the policies for dogs at the beach and how this was addressed. There were questions on signage, and whether or not bags were provided. Of these questions, only one (signage and enterococci levels at open-coast beaches) showed statistical differences in FIB exceedances (Table 3) between beaches with and without signage.

Overall, results showed consistently that lower dog densities appear to be associated with lower FIB exceedances, and that policies that address dog waste (address/do not address, signage for dog waste disposal, availability of dog waste bags) are also associated with lower FIB exceedances. However, the FIB exceedances among the different categories evaluated were not always statistically different. These results provide some evidence of the benefits of minimizing dog waste, although the evidence can be considered weak due to lack of statistical differences among the various groupings.

3.3.2 Birds

Survey results indicate that a vast majority of the beaches in Florida (99%) are visited by birds. Statistical differences were observed between beaches with birds versus those without bird visits only when all responses are considered for enterococci. Here beaches where birds visit (n=285) had statistically significantly higher percent exceedances (3.63%) relative to beaches that did not (n=3, 3.34%) (Table 3). The birds observed at the beaches are most commonly gulls. More details about the distribution of bird species is provided in the supplemental text. With respect to the density of birds, open coast beaches (Table 2) demonstrated decreased percent exceedances for enterococci where there were fewer birds.

We then asked if the birds gather in specific areas of the beach. Results (Table 3) show that when all beaches are considered both enterococci and fecal coliform exceedances were statistically different for beaches where birds gather (1.97% for enterococci and 0.89% for fecal coliform) versus beaches where they do not (5.40% for enterococci (ENT) and 2.32% for fecal coliform (COL)) (p=<0.001 ENT; 0.009 COL).

We then asked if there were policies for management of birds at the beaches. There was a significant difference between beaches that have policies in comparison to those that do not for all four categories evaluated. Those with policies were characterized by statistically lower FIB exceedances (Table 3) in comparison to those that do not have policies for managing birds (p = < 0.002 for all categories).

Overall, results showed that lower enterococci exceedances are associated with lower numbers of birds. The answers to our open-ended questions provide interesting insight into how birds behave at the beach, and the sorts of policies designed around birds at the beach. For example, while survey respondents stated that birds may contribute to FIB levels at their specific

beaches, most policies are designed to protect the birds, without consideration of FIB levels. Low exceedances are associated with beaches that have policies that address birds regardless of whether the policies address nuisance birds or the protection of birds.

3.4 Solid Waste Management

Among the 301 responses to our question on whether or not trash cans are available to visitors, the vast majority reported trash cans on the beach (96%), with smaller proportions reporting trash cans nearby (2%) or reporting no trash cans (2%). Results show that beaches with solid waste disposal facilities had statistically higher exceedances for enterococci (3.34%) than those that did not (0.68%, p=<0.001). Fecal coliform results were similar, and the open coast beach results also followed this pattern. For the 276 beaches responding to the question about the trash cans, no statistical differences were observed between beaches reporting covered trash cans (n=150) versus beaching reporting uncovered trash cans (n=126) (Table 4).

Most beaches have trash cans. The availability of trash cans appears to be associated with FIB, with beaches that have trash cans have higher FIB levels. About half of the trash cans at beaches are covered and the other half are uncovered. Distinct trends were not observed with the frequency of trash collection.

3.5 Grooming

This section addresses seaweed, beach grooming, and renourishment policies. The first series of questions focused on seaweed. We asked about the density of the seaweed present at the beaches. Among the respondents, 11% reported zero seaweed, 30% reported sparse, 43% reported medium, and 16% reported dense. Significant differences were seen for enterococci when all beaches and open coast beaches are considered. For "all responses" enterococci,

statistical differences were observed between the "dense" category (7.35%) and all of the others (<3.4%, p <0.001). The "open coast" enterococci also showed significant differences between "dense" (3.76%) and all of the other groups (<1.8%, p < 0.001), as well as between "sparse" and "zero," and "medium" and "zero." For fecal coliform, the "all responses" data showed no significant differences. The open coast fecal coliform data showed significant differences between the "medium" and "zero" categories (Table 2). This, along with the general trend of lower exceedances toward the sparse/zero end and higher exceedances in the dense/medium end, suggests an association between the amount of seaweed on the beaches and FIB levels in the water, with enterococci showing a stronger response relative to fecal coliform.

We then asked if part of the grooming protocol is designed to address seaweed (Table 4). There were no significant differences among any of the "all responses" categories. In the "open coast" section, both the enterococci ("yes" 2.14%; "no" 0.97%, p=<0.001) and the fecal coliform ("yes" 1.15%; "no" 0.21%, p=<0.001) means were statistically different, demonstrating that the "no" group was the lowest (Table 4). This could possibly indicate that disturbing the seaweed causes an increase in FIB levels. Future work would be very beneficial in understanding the relationship between FIBs in the water and beach grooming policies involving seaweed.

Our next question focused on beach renourishment, the addition of sand to the beach. We first asked if the beaches have been renourished. In all cases, the "no" category had higher FIB exceedances. There was a significant difference (p=0.011) between "yes" (2.86%) and "no" (4.76%) in the "all results" enterococci section, but none in the fecal coliform section (p=0.079), as seen in the t-tests (Table 4).

Overall, results showed that amounts of seaweed, grooming, and renourishment have an association with FIB levels. Beaches with naturally lower amounts of seaweed had lower

instances of FIB exceedances, while removal of seaweed at beaches was associated with an increase in FIB exceedances. Beaches that were renourished demonstrate lower FIB levels.

3.6 Beach Access and Use

This section considered beach access, and the ways in which the beaches are used. Policies concerning beach use included (1) maintenance vehicles on the beach, (2) fees to access the beach, (3) lifeguards, and (4) marinas near the beach. All of the factors listed here are related to economics: if an agency that manages the beach charges fees for access, that agency then has funding to pay for lifeguards and maintenance vehicles. Funding can also be provided through amenities such as concession stands and marinas.

We examined whether or not vehicles for maintenance purposes are permitted on the beach (Table 5). The "all responses" enterococci section showed significantly lower FIB exceedances for the "yes" category, (2.95%) but the "open coast" group had lower FIB exceedances in the "no" category (1.30%) (p = 0.181). Overall, mixed results were obtained for this question.

We asked if there was a fee that visitors must pay to access the beach (Table 5). Among the respondents, 31% of the beaches require fees. In all of the categories, beaches where visitors had to pay for access (all responses 2.47% ENT, 0.98% COL; open coast 1.29% ENT; 0.49% COL) were associated with lower FIB levels in comparison to those without fees (all responses 4.11% ENT, 1.76% COL; open coast 1.86% ENT; 0.72% COL) (Table 5). Significant differences were seen in three of the four categories evaluated (p= 0.001 all responses ENT; 0.002 all responses COL; 0.012 open coast ENT) with the exception of fecal coliform at open coast beaches (p=0.115).

We then asked if there are lifeguards at the beach. Among the respondents, 53% reported lifeguards. Significant differences were seen between "yes" and "no" responses for three of four categories evaluated with both FIB in the all responses category showing statistically lower FIB for beaches with lifeguards (p<0.003) and for enterococci in the open coast group (p=0.02).

We then asked if there are marinas near the beaches. On average, the percent exceedance for the "no" category was lower than the "yes" category in every group (Table 5). These differences were statistically significant for three of the four categories (all responses ENT p = 0.0007, all responses COL p=<0.0001, open coast COL p=0.017).

These responses revealed many different policies for beach use and access. These policies varied by beach; some of them have greater impact on the beach environment than others, especially those associated with funding, such as fees for access. These fees allow for the presence of lifeguards which are generally associated with lower FIB. Nearby marinas, although a source of funding, appear to be associated with higher levels of FIB.

3.7 Drainage and Sanitary Infrastructure

This section considers the associations between storm drainage and sanitary infrastructure and FIB levels (Table 6). Our first question asked how storm water is managed at the beaches. We divided the answers into two categories, one where storm water was managed by transporting it away from the beach, retaining it, use of subsurface disposal, or avoiding paved areas at the beach, and another where there is no attempt to manage storm water. For enterococci, results show that the "yes" group was associated with lower exceedances (2.97%) relative to the "no" category (5.15%) in the "all responses" group (p<0.038); for fecal coliform exceedances were lower as well (2.47% for "yes" and 3.13% for "no", p = 0.281), but the differences were not statistically significant. Differences were not statistically significant when

evaluating the storm water management at "open coast" beaches (p = 0.81 ENT and p = 0.94 COL).

The next series of questions focused on potential sources of sewage. The first question in this group asked whether or not there were public restroom facilities at the beaches. The only significant differences (Table 6) were observed among the fecal coliform data, with the "yes" category showing lower fecal coliform percent exceedance (1.38% for all responses and 0.56% for open coast) in comparison to the "no" category (2.62%, p = 0.057 for all responses, 1.30%, p = 0.012 for open coast beaches). Of interest was that enterococci percent exceedances were not associated with the presence of public restrooms, suggesting that fecal coliform may respond more strongly to the presence of restroom facilities in comparison to enterococci.

We then asked if the restroom facilities are open overnight. There were significant differences in all of the categories, with the "yes" response lower than "no" in three of the four analyses. Here, low fecal coliform levels appeared to be associated with restroom facilities open overnight (p = 0.010 for all beaches, p = <0.001 for open coast beaches). Lower enterococci percent exceedances were also associated with restroom facilities open overnight (p = 0.015) when all of the beaches are considered (Table 6).

We then asked if there were public shower or rinsing facilities at the beaches. Significant differences in percent exceedances (p<0.02) were present for the "all responses" groups; analyses showed that the "yes" category had lower exceedances (3.13% for enterococci and 1.27% for fecal coliform) than those in the "no" category (5.83% for enterococci and 2.73% for fecal coliform). Statistical differences were observed for enterococci only in the open coast group (Table 6).

This section demonstrates the associations that drainage and sanitary infrastructure may have with FIB levels at recreational beaches. Attempts to manage storm water were associated with lower FIB levels in the "all responses" categories. Beaches with amenities such as public restrooms demonstrated lower FIB levels, specifically fecal coliform. Beaches with public shower and rinsing facilities also demonstrated lower FIB levels, but the only statistical differences were observed for enterococci levels in the open coast group.

3.8 Factor Analysis and Linear Regression

Two factors were built from the seven categories, using a proportion of each category according to its effect. These factors analyze the categories for potential interdependency. In Factor 1, the drainage score and the numbers of humans score made up the highest proportion; in Factor 2, the beach type score, grooming score, and beach access score made up the highest proportion. With these factors, a linear regression was performed for both enterococci and fecal coliform. Our model resulted in an R-square of 0.300 for enterococci, meaning that it explained about 30% of the exceedances. Both Factor 1 (coefficient of 1.30, p-value 0.0002) and Factor 2 (coefficient of 4.23, p-value <.0001) were significant. For fecal coliform, the R-square was 0.155, demonstrating that it explained about 15%. Factor 1 (coefficient of 0.003, p-value of 0.1) was not significant; Factor 2 (coefficient of 1.55, p-value <.0001) was significant. These results indicate that categories associated with Factor 1 (beach type, grooming, and beach access) were the most significant.

3.9 County-Level Sampling and Analysis Policies

County-level data for the 34 counties in this study focused on assessing associations between FIB and sampling policies (collection time, holding time, day of week sampled,

sampling depth, method of transporting/storing samples) and sample laboratory analysis (laboratory method versus type of lab). The 34-county dataset resulted in a total of 35 surveys due to a split for Monroe County.

For sampling policies, no associations were found with day of the week (23 counties sample on Monday, 6 on Tuesday, 2 on both Monday and Tuesday, and 4 on Wednesday, Supplemental Table S6), sampling depth (knee depth, n=16; waist depth, n=17; knee to waist deep n=1; thigh-deep, n=1, Supplemental Table S7), or cooling method (ice packs, n=15 versus wet ice, n=20, Supplemental Table S8). Holding time (split into more than 2 hours, n=33 or 2 hours or fewer, n=2) also did not appear to be associated with FIB levels (p=0.28, Supplemental Table S8). For sampling time (Supplemental Table S8), the responses were divided into samples collected at noon or earlier, and those collected after noon. The percent exceedance means were not statistically different (p= 0.261) for enterococci (noon or before n=31, percent exceedance 4.12; after noon n=2, percent exceedance 13.1) and did not vary as much for fecal coliform (noon or before 1.58%; after noon 1.32%).

With respect to the analysis methods, differences were not statistically different between the type of lab used (government, n=19 versus private, n=13, p = 0.108. Three responded "other" and were not included in the t-test). With respect to the laboratory methods used (Supplemental Table S8), enterococci were analyzed by two different methods: membrane filtration (MF) (the EPA method 1600 (EPA 2009), n=29) or chromogenic substrate (Enterolert[TM], n=6). Fecal coliform was analyzed by MF only. The only statistically significant differences observed for the county-level sample collection and analysis data is in the method of analyses, with laboratories using chromogenic substrate reporting lower enterococci relative to laboratories using MF techniques (6.01% exceedance for laboratories that use MF versus 2.04% laboratories

that use chromogenic substrate, $p = 0.008$). This difference is present ($p=0.05$) even when the "Big Bend" counties (Wakulla, Dixie, Levy, Citrus, Hernando, Taylor, and Pasco) were removed (EPA method 1600 3.37%; Enterolert[TM] 2.04%). Overall, the only question that demonstrated significant difference was in the type of analysis method used.

4. Discussion

Our study revealed insights into beaches with lower FIB levels through investigation of beaches of different geomorphological type, beach management policies, and water sampling and analysis procedures. Specifically, our beach management survey provided a wealth of information that was previously unavailable on the association between FIB levels and human, dog, and bird densities as well as the ways in which the beach is used, including amenities.

This work also revealed novel information on differences in beach geomorphology throughout the state and the association with these differences and FIB levels. Protected beaches, such as bay or marsh beaches, demonstrated higher FIB exceedance, which is similar to the higher FIB levels seen in embayed beaches in Byappanahalli et al. (2015). Overall, we found that open coast beaches were characterized by low percent exceedances relative to other beach types. This was consistent when both enterococci and fecal coliform were used as indicators. However, for other beach types, in particular marsh beaches, the indicator chosen gave significantly different results, with marsh beaches showing much higher percent exceedances for enterococci (14.5%) than for fecal coliform (2.9%) ($p<0.001$).

The different percent exceedance levels observed for marsh beaches calls into question about which FIB is a stronger indicator of possible public health issues. We found that the switch from a fecal coliform to an enterococci standard resulted in major impacts on the computed percent exceedance for marsh beaches, with percent exceedance increasing by a factor of five

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(from 2.9% to 14.5%). High enterococci and fecal coliform percent exceedances were associated with different questions in our study. The results of this study suggest that fecal coliform may be more strongly associated with human fecal sources due to stronger relationships with human impact, such as the presence of human visitors (including homeless populations), and lack of restroom facilities at the beach. Responses related to the sources of human fecal waste showed relationships with low fecal coliform exceedances, such as the availability of public restroom facilities, as in Korajkic et al. 2010, and if the restroom facilities are open overnight.

Enterococci percent exceedances appear to be more strongly associated with animals (dogs and birds) and environmental sources (seaweed, sand renourishment). In Florida, the change of FIB indicator resulted in a higher frequency of beach closures at marsh beaches; these closures may be a result of higher wildlife influences at these beaches as opposed to human influences. Microbial source tracking studies designed to identify the source of enterococci and fecal coliform (Shanks et al. 2012, Sinigalliano et al. 2010, Brooks et al. 2016, Griffin et al. 2001) to marsh beaches are highly recommended to further explore the hypothesis that enterococci is more sensitive to environmental sources.

When these factors were selected through factor analysis, the results were similar to those observed from T-tests. Drainage and the number of humans made up the highest proportions of Factor 1; Factor 2, was made up of beach type, grooming, and beach access. Our overall analysis revealed that Factor 2 (beach type, grooming, beach access) had the most significant effects on both the enterococci and fecal coliform score. Factor 1 was significant only for enterococci. These results demonstrate once again that enterococci and fecal coliform may not indicate the same sources.

Our study of beach management policies revealed that both enterococci and fecal coliform levels were shown to be lower for beaches with fewer humans, dogs, and birds. Our analysis showed that beaches without homeless populations had lower FIB. For open coast beaches, lower enterococci were associated with beaches that had lower densities of human visitors. Similarly, beaches with low densities of dogs and low densities of birds were associated with lower FIB levels. Our results showed that FIB levels were lowest at beaches where dogs were not allowed and at beaches with policies for addressing dog waste; results on birds were similar, showing that beaches with policies for birds were associated with lower FIB levels. Low densities of dogs and birds, as indicated in studies such as Ervin et al. 2013, demonstrated lower FIB levels. Our results are consistent with studies that quantify the contribution of FIB by humans and animals to beach sites. For example, Elmir et al. (2009) estimated that bathers shed 1.8×10^4 to 2.8×10^6 CFU per 15-minute swim. Wright et al. (2011) quantified the amount of FIB released per dog fecal event at a beach that allows dogs, attributing dogs as the major source. Studies documenting the contribution of birds to FIB at beaches (Oshiro and Fujioka 1995, Edge et al. 2010, Riedel et al. 2015) suggest that birds can also be major contributors. This correlates with many studies on birds, particularly gulls, and increased enterococci levels (Converse et al. 2012, Sinigalliano et al. 2013).

Our analysis of beach access and beach use revealed that beaches where seaweed levels are low, those that are renourished, charge fees to access the beach, have lifeguards ("all responses" only), or lack nearby marinas ("all responses" only), have lower FIB levels. These results echo the results of studies on seaweed (Byappanahalli et al. 2015, Imamura et al. 2011), with similar findings. Seaweed densities were associated with enterococci exceedances (as seen in Quilliam 2014), while grooming of beach sand showed relationships to both enterococci and

fecal coliform. Beach renourishment was also associated with lower levels of enterococci, as in Hernandez et al. 2014, but this association was not seen in fecal coliform. We found that some beach management policies may be incompatible with maintaining low FIB levels at the beaches, such as grooming designed to address seaweed. Beaches with naturally low levels of seaweed had lower FIB levels; higher levels of beach wrack had higher FIB levels, as demonstrated in Nevers et al. (2016). Studies of the contributions of beach sand, as in Whitman et al. (2014) and the associations with grooming have demonstrated that specific grooming practices allowed for lower levels of *E. coli* at Great Lakes beaches (Kinzelman et al. 2003, Verhougstraete et al. 2014). Russell et al. (2014) found results similar to ours, in which "beach grooming was generally associated with either no change or a slightly increase in coastal FIB concentrations." Increased concentrations were also found in a study at beaches that were groomed in York, Maine (Jones et al. 2017). Future work on Florida beaches could follow similar approaches, to understand the effects of these grooming practices on enterococci and fecal coliform. Of specific interest would be to evaluate grooming and wrack disposal methods, as the survey indicated that different methods of disposal are used, including placement around vegetation, burial at the beach, or collection and disposal via trash (see Supplemental text for details). Marinas may contribute to anthropogenic currents and increased FIBs in the area, as described in Ho et al. 2011. Low percent exceedances were also found for beaches where there are provisions for the management of storm water. This finding is consistent with the work of Parker et al. 2010 and Ahn et al. 2005 both of whom found that storm water significantly contributed to elevated levels of FIB.

As the study was conducted we found that beaches were managed through various unrelated agencies. This frequently resulted in independent actions by different groups that can

impact beach quality. To receive the answers to our survey, team members had to contact multiple agencies in each county. Sometimes overlapping agencies existed at the private, municipal, county, state, and national level to carry out and enforce beach management policies. Examples include the departments of health, beach erosion agencies, the National Park Service, departments of environmental protection, state park agencies, public works agencies, solid waste departments, and parks and recreation departments. These multiple agencies resulted in a mix of redundancies, gaps, and conflicting priorities making it difficult to manage the beach as a whole. Through increased standardization and the united effort of agencies as stated in Nevers et al. (2013), policies could be designed to better address FIB levels at recreational beaches, setting forth a list of best practices, similar to the process for setting standards for wastewater treatment facilities, or through a program to lower FIBs through multiple targets, as described in Dorsey 2010. These strengthened policies will need to take into account best practices as well as the individual communities and natural environments at each beach (as recommended in Amorim et al. 2014), and will need to provide a baseline for understanding current environments while planning for future environmental change.

Funding is also an issue for continued monitoring. As mentioned, effective 2011, many beaches were dropped from the Florida Healthy Beaches program altogether due to lack of funding. Other beaches are monitored on a less frequent basis and the analysis of fecal coliform was dropped from all beach monitoring programs throughout the state. In agencies where many interests need to be met, such as the Department of Health, monitoring and management must compete with other programs that also require funding, including school lunch programs, vaccines for children, and help for the disabled. When faced with these choices, water quality

funding is frequently a low priority. Where beaches have their own funding, even though it is frequently not applied toward routine monitoring, water quality tends to be better.

5. Conclusions

Our work identified potential causes of poor water quality at Florida's recreational beaches through an innovative analysis that coupled a very large water quality data set with responses to a beach management survey. Similar analyses could be used by other researchers to evaluate and optimize beach water quality in other areas of the world. The size of the dataset (n>150,000 per FIB) was critical for being able to identify significant associations between FIB and beach management practices.

Our study supports the work of researchers who found that the presence of birds (Sinigalliano et al 2013, Goodwin 2017), humans, and dogs (Elmir et al 2009, Wright et al 2011, Ervin et al. 2014), cause an increase in FIB at recreational beaches.We also found similarities between our results on beach sand, beach grooming studies, and that of work demonstrating that the way in which the beach is groomed can affect FIBs. Beach sand can provide an area in which FIBs can proliferate (Halliday et al. 2011, Phillips et al. 2011).Grooming in areas with heavy beach wrack that involve disturbance of the wrack actually increase concentrations (Imamura 2011, Nevers et al. 2016, Whitman et al. 2014, Kinzelman et al. 2003, Verhougstraete et al. 2014, Russell et al. 2014, Jones et al. 2017). Additionally, our work investigated gaps in areas such as the availability of restrooms and showers; concession stands; solid waste management; and fees to access the beach. We found that these amenities have an effect on FIBs.

Given the associations demonstrated here between beach management and FIBs, our results support the concept of sustainable beach management (James [2000], Micallef and Williams [2002], Russell et al. [2014], and in Lamberti and Zannutigh [2005]). Such

management would streamline or even unify the operations of different agencies that manage beach erosion, wildlife, solid waste, beach patrol and law enforcement, amenities for beach visitors, water quality monitoring, and maintenance. Sustainable beach management will become even more critical in the future given anticipated sea level rise and increased flooding along Florida's coast which will likely require more frequent integration of resources between sister agencies that address beaches. Unification of the agencies that address beaches would allow for an integration of policies that can promote better water quality.

Acknowledgments

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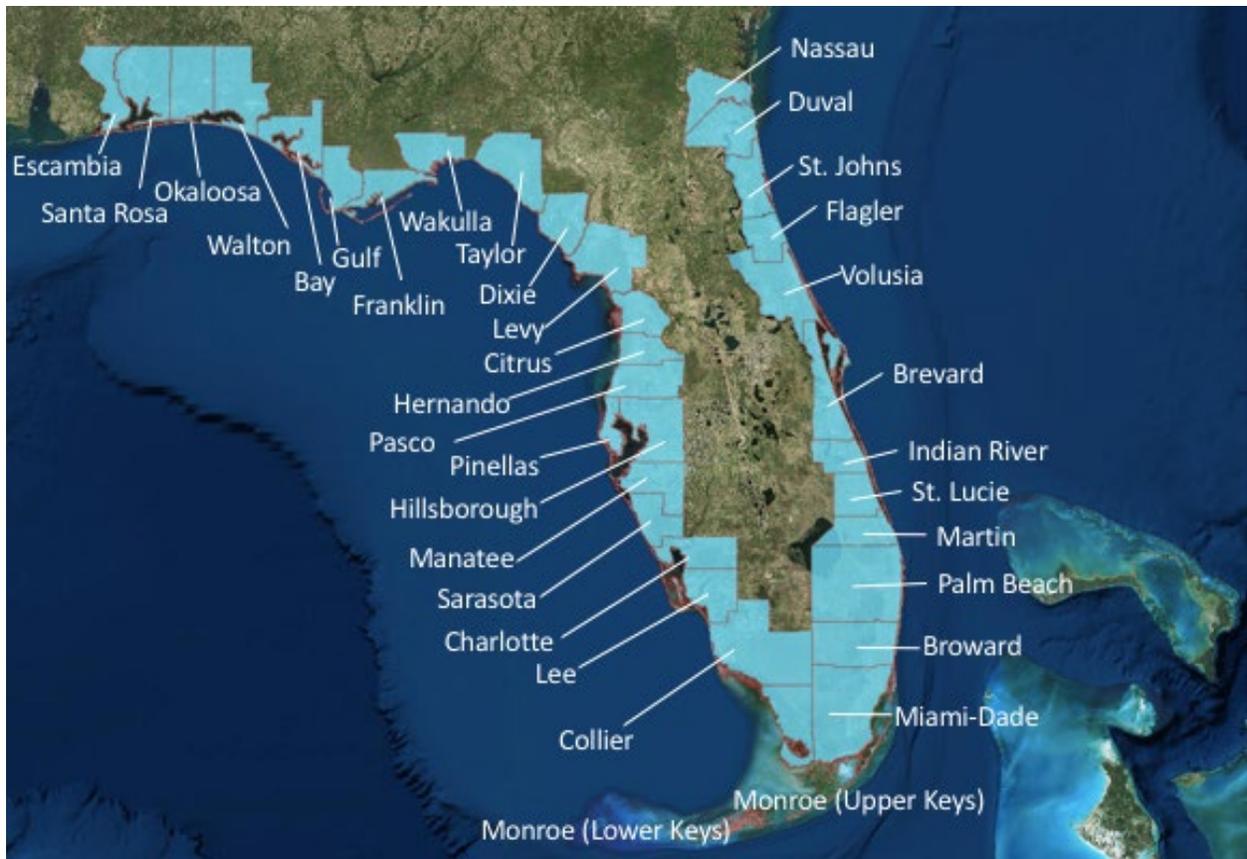
Figure 1. Coastal counties participating in Florida Department of Health's Florida Healthy Beaches Program prior to 2011.
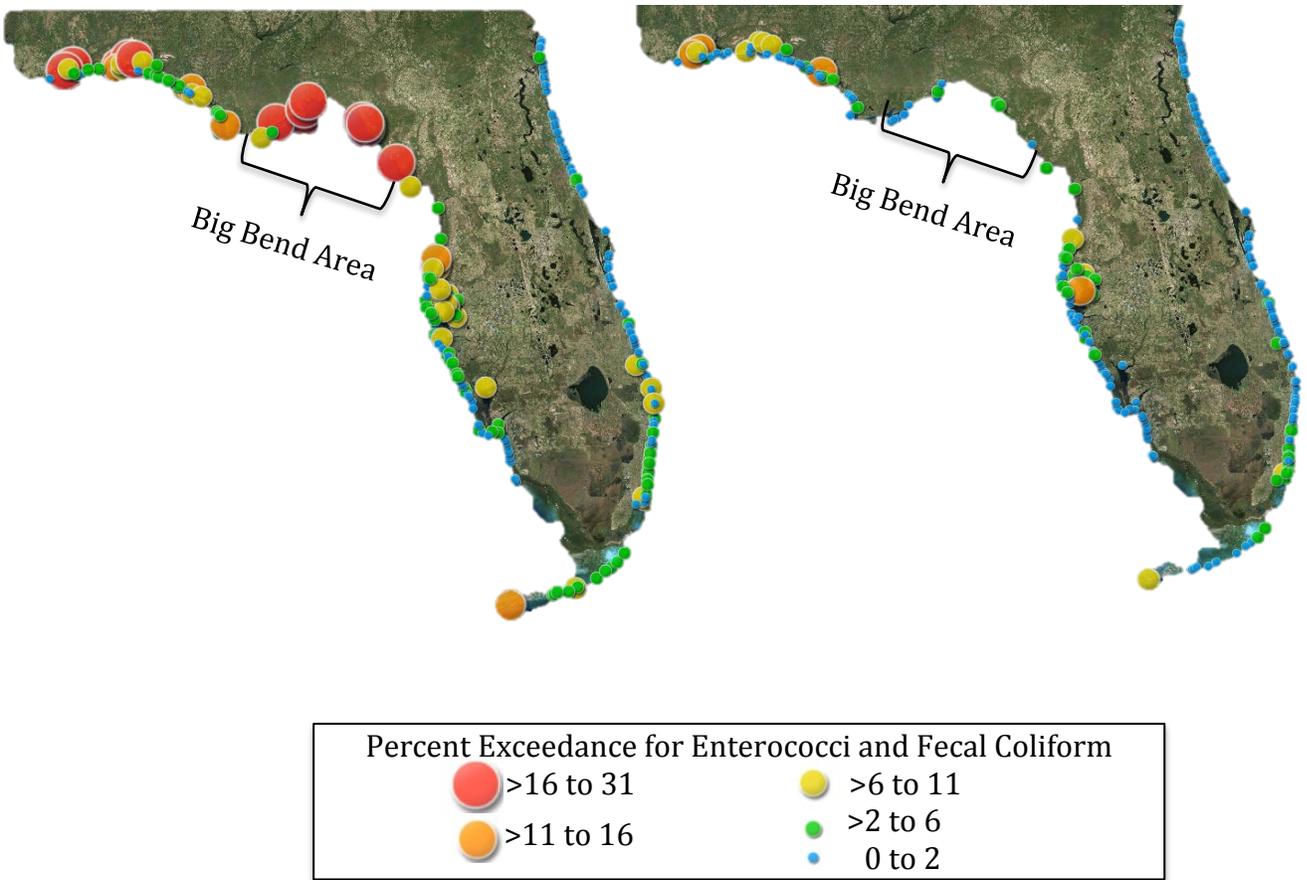
Figure 2. (Left) Percent enterococci exceedances throughout Florida, 2000-2015; (Right) Percent fecal coliform exceedances throughout Florida 2000-2011.

Table 1. Enterococci and fecal coliform percent exceedance statistics by beach type.

Beach Type	ENT				COL			
	Mean % Exceed.	Standard Dev	Range	Statistical Significance*	Mean % Exceed.	Standard Dev	Range	Statistical Significance*
Type 1, Open coast (n=211)	1.65	1.72	0.0 - 16.4 (16.4)	A	0.64	1.03	0.00-5.25 (5.25)	A
Type 2, Bay (n=72)	6.87	5.33	0.0 - 25.2 (25.2)	B	3.84	4.04	0.00-18.2 (18.2)	B, C, E
Type 3, Inlet-channel-situated (n=3)	3.54	1.60	1.69 4.59 (2.9)	A, B	1.43	1.43	0.60-3.09 (2.49)	A, B, D
Type 4, Manmade-structure-protected (n=5)	6.46	5.52	1.17 - 12.9 (11.8)	B	6.09	3.64	3.01-10.75 (7.74)	C, E
Type 5, Marsh-surrounded (n=17)	14.5	10.5	0.69 - 30.5 (29.8)	C	2.94	1.60	1.00-7.14 (6.14)	D, E
Type 6, Back-reef (n=8)	3.50	2.02	0.65 - 7.51 (6.86)	A,B	1.08	0.90	0.00-2.81 (2.81)	A, D

*Beach types sharing the same letter are statistically not different.

Table 2. Statistics of enterococci and fecal coliform percent exceedances survey responses for questions related to density of humans, dogs, birds, and seaweed. ALL=all responses; OC=open coast beaches only.

Question	Mean % Exceed		Mean % Exceed		Mean % Exceed		Mean % Exceed		Mean % Exceed		Statistics
	Dense	n	Medium	n	Sparse	n	Zero	n	No Response	n	
Human Density at Noon Sunday											
Enterococci											
ALL	2.07	104	3.94	136	7.54	26	9.46	1	4.18	49	F=7.40 p=<0.001
OC	1.73	89	1.34	77	0.64	14	N/A	0	2.19	31	F=5.58 p=0.0011
Fecal coliform											
ALL	0.90	104	1.89	136	1.35	26	2.45	1	2.40	49	F=3.59 p=0.007
OC	0.79	89	0.45	77	0.18	14	0.00	0	0.93	31	F=3.36 p=0.020
Dog Density											
Enterococci											
ALL	7.51	1	4.00	54	4.96	81	2.77	147	3.91	33	F=2.72 p=0.030
OC	0.00	0	1.85	34	1.31	50	1.58	107	1.82	20	F=1.25 p=0.291
Fecal coliform											
ALL	2.01	1	1.90	54	1.52	81	1.44	147	2.04	33	F=0.57 p=0.681
OC	0.00	0	0.66	34	0.46	50	0.76	107	0.47	20	F=1.21 p=0.309
Bird Density											
Enterococci											
ALL	3.94	55	3.53	127	3.24	86	1.61	2	4.68	46	F=0.74 p=0.564
OC	2.50	39	1.34	91	1.31	54	0.20	1	2.25	26	F=0.82 p=0.514
Fecal coliform											
ALL	1.20	55	1.29	127	1.91	86	1.64	2	2.36	46	F=2.02 p=0.091
OC	0.48	39	0.59	91	0.76	54	0.20	1	0.86	26	F=0.82 p=0.514
Seaweed Density											
Enterococci											
ALL	7.35	44	2.95	118	3.08	84	3.22	31	3.39	39	F=7.19 p=<0.0001
OC	3.76	20	1.54	85	1.80	57	0.43	25	1.22	24	F=13.98 p=<0.0001
Fecal coliform											
ALL	2.26	44	1.48	118	1.37	84	1.60	31	1.74	39	F=2.97 p=0.0205
OC	0.91	20	0.78	85	0.65	57	0.05	25	0.53	24	F= 2.97 p=0.0205

Table 3. Statistics for enterococci and fecal coliform percent exceedances for select survey questions associated with human use and animal density and control questions.

Question	All Responses					Open Coast				
	Yes	n	No	n	p value	Yes	n	No	n	p value
Human Use										
Homeless Present										
Enterococci	4.21	39	3.45	239	0.237	2.35	23	1.49	165	0.036
Fecal coliform	2.58	39	1.26	239	0.007	1.22	23	0.49	165	0.027
Animal Densities and Control										
Dogs Allowed										
Enterococci	4.71	94	3.19	198	0.037	2.09	61	1.58	137	0.123
Fecal coliform	1.64	94	1.53	198	0.723	0.54	61	0.74	137	0.174
Dogs Visit Anyway										
Enterococci	3.43	120	3.29	88	0.817	1.85	83	1.51	61	0.167
Fecal coliform	1.65	120	1.83	88	0.640	0.96	83	0.67	61	0.150
Dog Policies/Address Dogs										
Enterococci	2.57	155	4.11	25	0.055	1.65	119	2.14	13	0.258
Fecal coliform	1.17	155	2.31	25	0.098	0.69	119	1.28	13	0.127
Dog Signage										
Enterococci	3.75	125	4.15	85	0.632	1.98	82	1.25	55	0.018
Fecal coliform	1.73	125	1.37	85	0.248	0.65	82	0.73	55	0.695
Bags Available										
Enterococci	4.24	98	3.58	109	0.386	2.05	56	1.40	78	0.074
Fecal coliform	1.87	98	1.24	109	0.058	0.63	56	0.67	78	0.812
Birds Visit										
Enterococci	3.63	285	3.34	3	0.0319	1.63	194	2.23	3	0.2511
Fecal coliform	1.54	285	1.14	3	0.1274	0.66	194	1.14	3	0.0871
Birds Gather In Specific Areas										
Enterococci	1.97	127	5.40	55	<0.001	1.17	103	2.25	29	0.080
Fecal coliform	0.89	127	2.32	55	0.009	0.38	103	0.42	29	0.761
Bird Policies										
Enterococci	2.07	59	4.12	211	<0.001	0.90	41	1.69	138	<0.001
Fecal coliform	0.74	59	1.72	211	<0.001	0.25	41	1.62	138	<0.001

Table 4. Statistics of enterococci and fecal coliform percent exceedances when compared to beach management survey responses for beach access questions.

Question	All Responses					Open Coast				
	Yes	n	No	n	p value	Yes	n	No	n	p value
With Trash Cans										
Enterococci	3.34	290	0.68	5	<0.001	1.71	200	0.43	4	<0.001
Fecal coliform	1.56	290	0.48	5	0.001	0.66	200	0.31	4	0.071
Covered Trash Cans										
Enterococci	3.55	150	3.56	126	0.984	1.99	93	1.57	96	0.106
Fecal coliform	1.69	150	1.44	126	0.431	0.64	93	0.74	96	0.524
Grooming Protocol Addresses Seaweed										
Enterococci	3.53	114	4.02	106	.517	2.14	76	0.97	73	<.0001
Fecal coliform	1.95	114	1.27	106	.048	1.15	76	0.21	73	<.0001
Sand Renourished										
Enterococci	2.86	163	4.76	101	0.011	1.29	120	1.39	53	0.618
Fecal coliform	1.35	163	1.99	101	0.079	0.51	120	0.59	53	0.583

Table 5. Statistics for enterococci and fecal coliform percent exceedances for select survey questions associated with beach access and use.

Question	All Responses					Open Coast				
	Yes	n	No	n	p value	Yes	n	No	n	p value
Maintenance Vehicles on Beach										
Enterococci	2.95	251	7.10	47	0.005	1.73	183	1.30	20	0.181
Fecal coliform	1.43	251	2.03	47	0.251	0.69	183	0.36	20	0.049
Charge Fees										
Enterococci	2.47	92	4.11	206	0.001	1.29	64	1.86	139	0.012
Fecal coliform	0.98	92	1.76	206	0.002	0.49	64	0.72	139	0.115
Lifeguards										
Enterococci	2.14	157	4.69	69	<0.001	1.43	137	2.16	28	0.017
Fecal coliform	1.08	157	1.98	69	0.002	0.65	137	0.68	28	0.800
Marinas Near Beach										
Enterococci	4.11	108	2.29	112	<0.001	1.76	64	1.50	91	0.368
Fecal coliform	2.28	108	0.75	112	<0.001	0.78	64	0.35	91	0.017

Table 6. Statistics for enterococci and fecal coliform percent exceedances for select survey questions associated with drainage and sanitary infrastructure.

Question	All Responses					Open Coast				
	Yes	n	No	n	p value	Yes	n	No	n	p value
Storm Water Management										
Enterococci	2.97	141	5.15	62	0.038	1.43	101	1.37	39	0.811
Fecal coliform	2.47	141	3.13	62	0.281	0.53	101	0.52	39	0.937
Public Restrooms										
Enterococci	3.57	261	3.89	38	0.701	1.64	177	1.94	27	0.345
Fecal coliform	1.38	261	2.62	38	0.057	0.56	177	1.30	27	0.012
Public Restroom Open Overnight										
Enterococci	3.03	238	3.22	57	0.015	1.25	54	1.65	79	0.273
Fecal coliform	1.27	238	1.60	57	0.010	0.160	54	0.72	79	<0.001
Public Shower/Rinsing Facilities										
Enterococci	3.13	238	5.83	57	0.015	1.79	170	1.15	30	0.017
Fecal coliform	1.27	238	2.73	57	0.010	0.66	170	0.66	30	0.996

Table S1. Water quality standards.

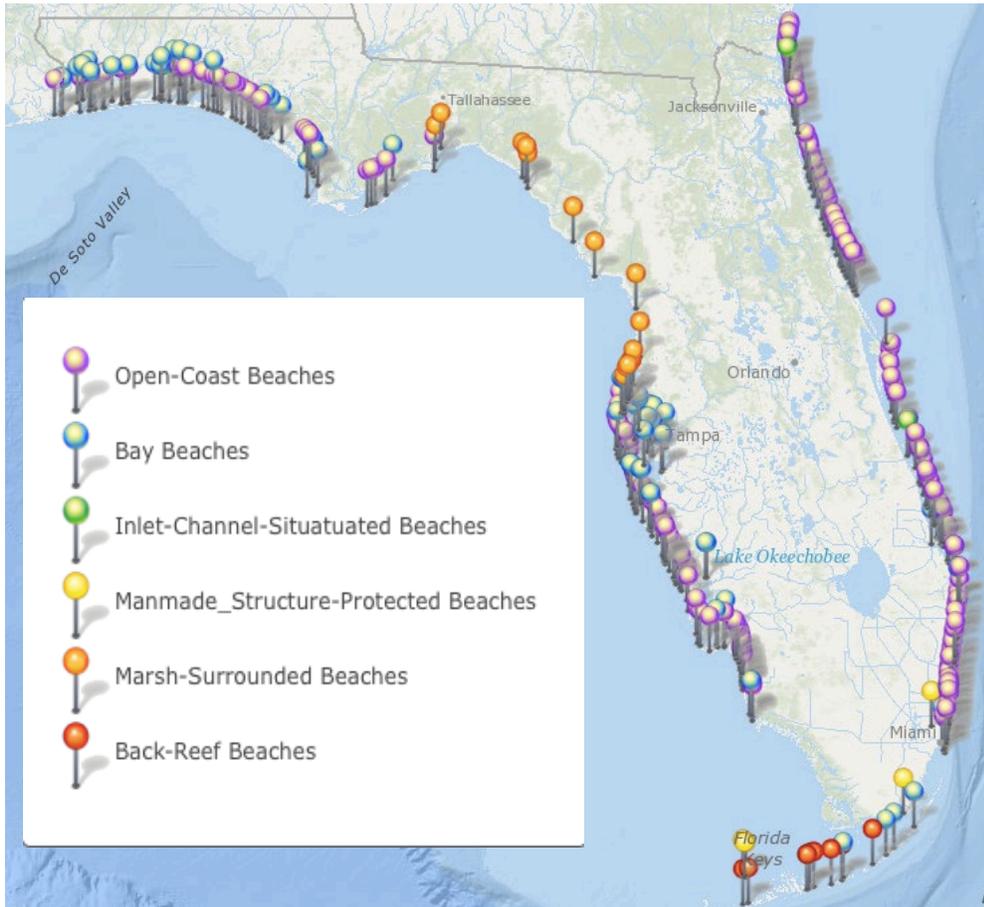| Category	Enterococci, CFU/100 ml		Fecal Coliform, CFU/100ml		
	Jul. 31, 2000 to Dec. 31,2015	Jan. 1, 2016 to present	Aug. 2000 – Jun. 30 2002	Jul. 1 2002 – Jun. 30 2011	Jul. 1 2011-2016
Good	0-34	0-35	0 – 799	0 – 199	Fecal coliform dropped
Moderate	35-103	35-70		200 – 399	Not applicable
Poor	104 or greater	71 or greater	800	400	Not applicable

Figure S1. Classifications for beaches in Florida participating in the Florida Healthy Beaches Program.

Animal Densities and Control

Below we provide a brief summary of the results for "other domestic animals" and for "other wildlife".

Respondents reported that the only "other domesticated animals" that visit the beaches were horses; among the respondents (n=284), horses were reported to visit 15% of Florida beaches and their presence at the beach was not associated with FIB exceedances ($p = 0.649$ enterococci [ENT], 0.063 fecal coliform [COL]). For the "other wildlife" category we found that 28 different species of wildlife were reported ranging from 20 different mammals to 8 different reptiles. Among the mammals, animals reported most commonly were raccoons (86%; 145 beaches), feral cats (45%; 76 beaches), and coyotes (30%; 51 beaches). Common reptiles include turtles (terrestrial and sea turtles, 65%; 109 beaches), snakes (20%; 33 beaches), and iguanas (18%; 30 beaches). Wildlife at Florida's beaches is quite diverse, with additional reports of foxes, hogs, armadillos, bobcats, and even hyenas and bears in isolated cases. Given the propensity of "other wildlife" at beaches, many beaches have policies in place specific to them, especially as the wildlife reported included both protected animals and nuisance animals. Of survey responses, we found that beaches with wildlife management policies, whether designed to protect endangered or native animals, or to keep nuisance animals (raccoons, feral cats, iguanas) out, was associated with lower FIB percent exceedances ($p=0.006$ ENT, <0.001 COL). More details are available in the supplemental text.

Dogs

We asked if dogs visit the beach regardless of whether or not they are allowed. Among the respondents, 58% report that dogs visit the beach regardless of beach policy, suggesting that the dog policy is not followed at 26% of the beaches. No statistical differences were observed in

FIB levels among the four combinations of beach type (all/open coast) and FIB (enterococci and fecal coliform) evaluated (Table 4).

Other Domesticated Animals

Domestic animals could be any animals that people own as pets, but our respondents' replies were focused on horses. Only one response mentioned animals other than horses, and this response mentioned beach policy on trapping feral cats. Since feral cats are not domesticated, we classified this response as a beach where other domesticated animals are not allowed.

Our first question in this series was the number of other domesticated animals (i.e., horses) at the beach on an average Sunday. This was accompanied by the choices "zero," "sparse," "medium," or "dense," with pictures to illustrate each category.

A significant difference was shown in enterococci levels at open coast beaches for Sunday between beaches that are sparsely populated by other domesticated animals (2.59 % exceedance, n = 20 for Sunday, 2.56 % exceedance and those with a medium population (0.41 % exceedance, n = 10 for Sunday). This difference is the opposite of what would be expected, as the beaches where the beach managers reported medium populations had lower percent exceedances than the beaches where beach managers reported sparse populations of other domesticated animals. This may indicate that there are confounders other than the beach type, or that the numbers of other domestic animals do not have an association with the enterococci levels at the beaches. The numbers of beaches where other domesticated animals are allowed is very small (44 "all responses", 36 "open coast," and spatial clustering was observed, as beaches that allow other domesticated animals and reported a "medium" density tend to be segregated in a particular county (e.g., Nassau County, the most northeastern county in Florida) where FIB levels tend to be low.

Our next question asked whether or not other domesticated animals were allowed on the beach. Results (Supplemental Table S2) show a significant difference between "no" and "yes" in the fecal coliform levels at the open coast beaches. However, the levels are the opposite of what would be expected (as emphasized above) with lower levels of fecal coliform for beaches that do allow other domesticated animals at the beach.

We then asked whether other domestic animals come to the beach although they are not allowed. Results (Supplemental Table S2) show that very few beaches (n = 3) have other domesticated animals visit beaches where they are not allowed and no statistical differences were observed in FIB levels for these beaches relative to those that do not allow other domesticated animals.

We also inquired as to management of fecal events by other domesticated animals. This resulted in responses that were similar to how dog fecal events are handled: burial, no known process in place, not an issue, owners are responsible, and specific trash receptacles.

Overall, for other domestic animals, 15% of the beaches allow them. Where they are allowed, they do not seem to be associated with FIB exceedances.

Table S2. Domesticated Animals and Wildlife, All Responses and Type 1 Open Coast.

	All Responses					Open Coast				
	Yes	n	No	n	p value	Yes	n	No	n	p value
Domesticated Animals Allowed										
Enterococci	2.95	44	3.30	240	0.649	1.53	36	1.74	163	0.666
Fecal coliform	0.90	44	1.61	240	0.063	0.14	36	0.79	163	<0.001
Domesticated Animals Not Allowed, Visit Anyway										
Enterococci	2.66	3	3.34	193	0.337	4.23	120	1.63	1	1.84
Fecal coliform	2.26	3	1.83	193	0.337	1.23	120	3.78	1	0.83
Wildlife Visit										
Enterococci	3.41	168	4.06	115	0.270	1.36	120	2.22	163	0.004
Fecal coliform	1.24	168	2.03	115	0.013	0.58	120	0.86	163	0.110
Protocols for Managing Wildlife										
Enterococci	2.41	106	4.21	132	0.005	1.47	76	1.10	85	0.042
Fecal coliform	0.92	106	1.66	132	0.009	0.60	76	0.41	85	0.145
Have Buffer Zones or Protected Areas										
Enterococci	3.16	177	5.01	69	0.013	1.44	137	2.37	28	0.156
Fecal coliform	1.16	177	2.14	69	0.010	0.66	137	0.50	28	0.479

Other Wildlife

The last series of questions in the Animal Densities and Control section focused on wildlife.

Our first question was again similar to the approach we took for dogs, other domestic animals, and birds, to ask how many are at the beach on an average Sunday at noon. For the "all results" and "open coast" beaches, no statistical differences were observed for any day, nor for either FIB.

We then asked whether or not wildlife other than birds visit the beaches. Results (Supplemental Table S2) show that there was a significant difference in the fecal coliform data for the "all responses" group, and in enterococci for the "open coast" beaches. These differences are interesting to note, as the "no" responses have higher FIB levels in all of the categories. It could be that beaches without wildlife may be in more urban settings and tend to have more human visitors, which may also bring FIBs with them.

We then inquired as to what kinds of wildlife visited the beaches. Similar to the responses we received for the birds, we received reports of so many different kinds of wildlife that we were unable to perform a statistical analysis. Respondents reported a large variety of animals, including marine animals, mammals, insects, and reptiles, as shown in Figure S2.

We then asked if there was a protocol for managing the wildlife at the beaches. Results (Supplemental Table S2) show significant differences in three of the four categories. For the all responses category, the p values were particularly low and for these beaches lower percent exceedances were observed for beaches that had protocols in place for managing other wildlife. Statistically significant differences were observed in the enterococci exceedances for open coast beaches. In this case, the beaches without protocols for managing wildlife had lower enterococci levels.

We asked the beach managers to describe their protocols for managing wildlife. This open-ended question resulted in a wide variety of answers, all of which fit into two basic categories: policies for protecting endangered or native animals, and policies for keeping nuisance animals (exotic or feral) out. To protect native or endangered animals, respondents mentioned wildlife sanctuaries where the animals are not to be disturbed, for example, protection of sea turtle nests. Visitors are not allowed to feed the wildlife. There is also management for listed species, and habitat restoration after oil spills, posting of signs for sea turtle nests, and community education, along with beach ordinances and relocation of injured birds. Gopher tortoises are carried to safety if found in the road. To keep the beaches free of nuisance wildlife, such as raccoons, opossums, feral cats, and coyotes, trapping was reported at many beaches ("trap/neuter/release" programs for feral cats, and trapping and removal of iguanas), along with animal-resistant trash receptacles in more natural areas. Aggressive raccoons approaching

humans for food are relocated. Some policies affect both categories at the same time. For example, to protect endangered animals, some beaches monitor the nuisance animals, particularly raccoons, to see if they are depredating sea turtle nests.

Our next question concerned whether or not there are buffer zones or protected areas like sand dunes that could serve as areas of refuge for wildlife near the beach. Beaches with buffer zones (Supplemental Table S2) had lower FIB levels in almost every case, except for the "open coast" fecal coliform group.

Our next question asked, if there was an area of refuge, how this area and the wildlife there are managed. Again, as this was an open-ended question, there were multiple varied responses. Some of the respondents described the areas, and some described the management policies. Areas of refuge described include wooded buffer zones (e.g. Australian Pine forest); others described sand dunes, such as vegetated dunes with sea grapes and sea oats, and mangroves, which house some wildlife. Description of management policies included how seagrasses and sea oats are planted, permission is required to trim dune vegetation, there is no entry to the dunes, public areas are mowed, natural areas are maintained by fire and exotic invasive plants are removed. Some beaches leave these areas alone to a natural state; other dune and coastal grassland areas are designated protected sensitive areas; the public is prohibited from entering and the sand dunes can be roped off. One hundred forty-one beaches provided these in-depth descriptions of multiple different beach environments.

Our last question in the wildlife section asked whether there were other notable items about wildlife at the beaches. This open-ended question resulted in responses that were similar to the discussions of management of wildlife and areas of refuge, describing management and protection programs. Responses also revealed the activity of the animals, where they can be

found, and at which times of day. This is particularly interesting in the case of nuisance animals: raccoons on the beach at night and in the early morning; reports that cats stay in the dunes, and come out to trash cans to get food. Other beaches have very little in the way of wildlife policies, describing that not much is done. These descriptions came from 37 beaches; 279 did not respond to this question.
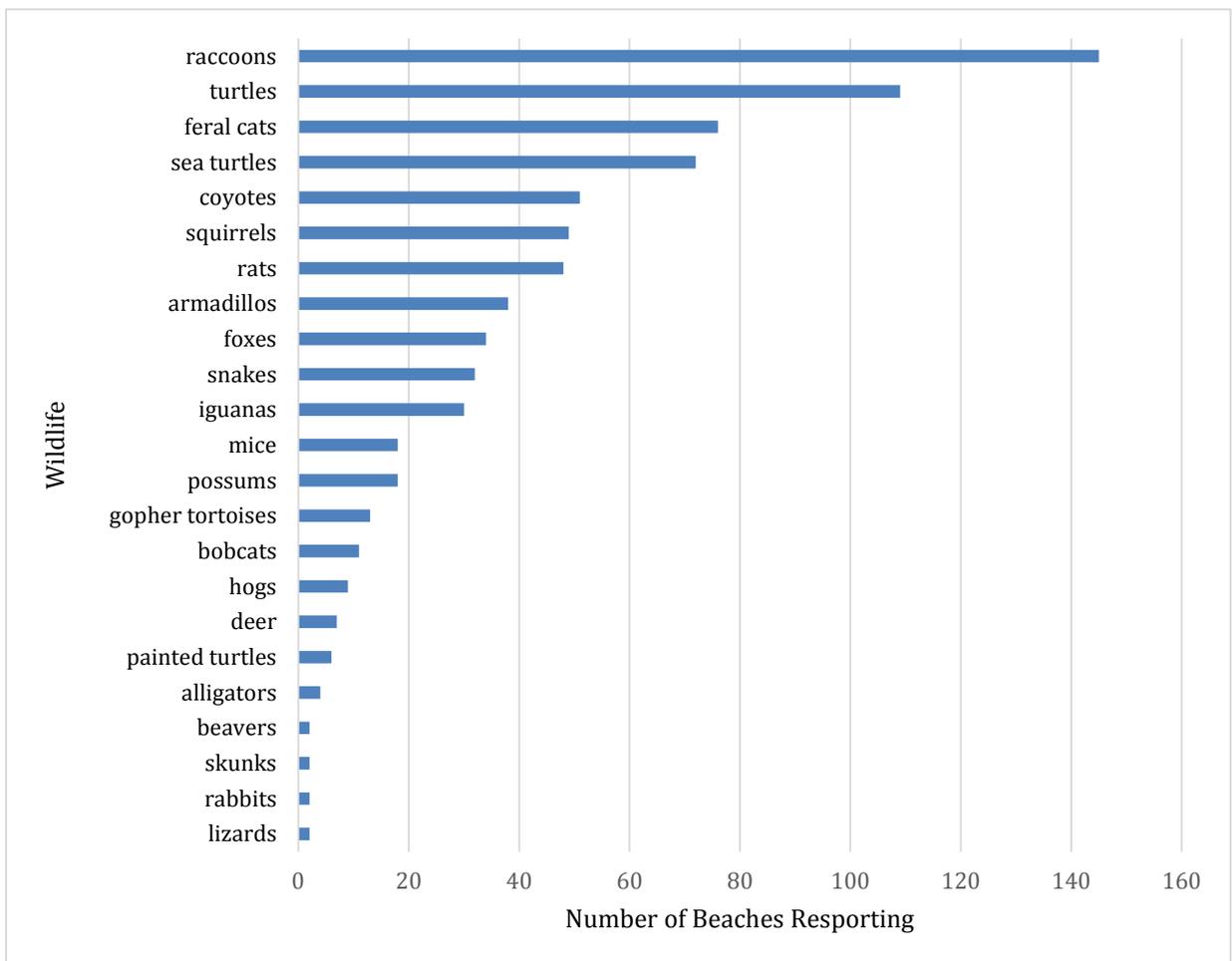

Figure S2. Wildlife reported at the beaches, all responses. Animals not included in the figure, as there was only one report of each animal, were anoles, black racers, black bears, hyenas, otters, pigs, and rodents.

Birds

An interesting finding is that the majority of respondents reported that the birds gather in certain locations (127 beaches of 182), which may be useful for beach management purposes. A related question asked if the numbers of birds change on a seasonal basis. The vast majority of the respondents said yes (83% for all respondents).

Our next question focused on the species of birds that visit the beach. Fifty-one different species of birds were reported (Figure S3). The birds reported most frequently were gulls (92%), terns (69%), pelicans (41%), and herons (33%).
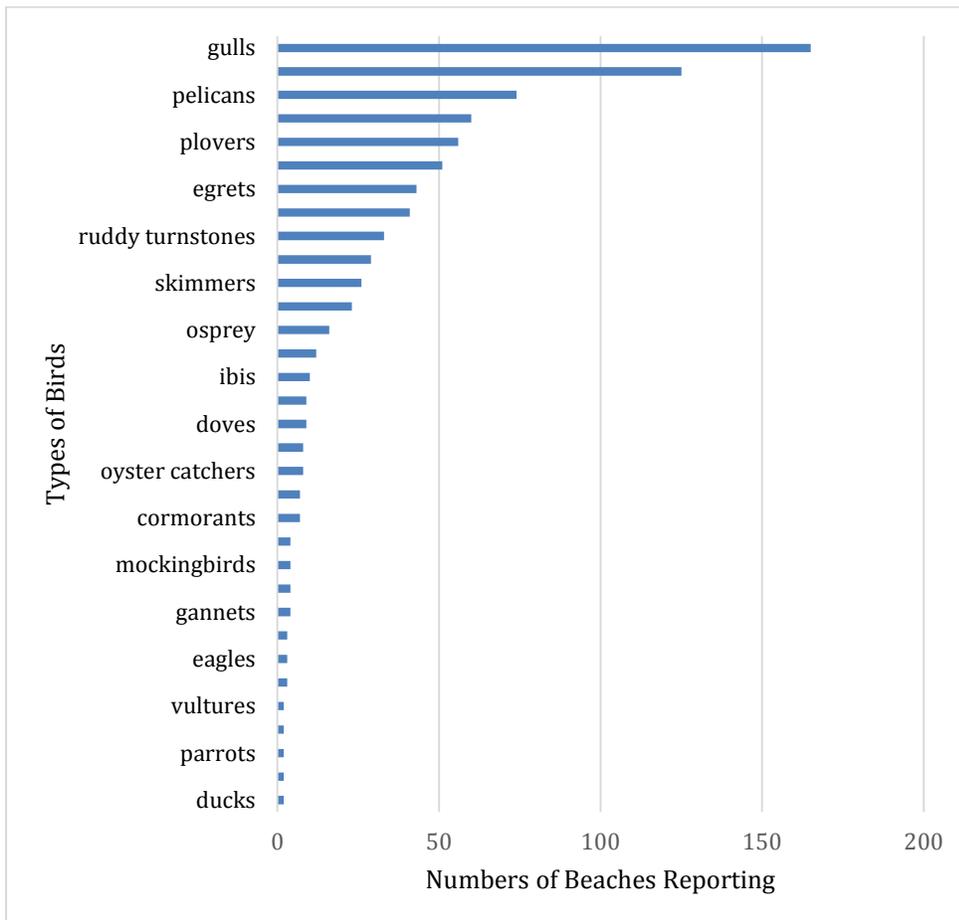

Figure S3. Types of birds reported at all beaches. Birds not included in the figure, as the bird was only reported once were: wrens, woodpeckers, whimbrels, owls, kites, kingfishers, grebes, grackles, frigatebirds, flamingos, finches, falcons, cardinals, blue jays, blackbirds, binecks, avocets, and American kestrels.

Our next question focused on the types of bird policies at the beaches. Most policies focused on bird protection. These policies included the presence of bird sanctuaries where the public is not allowed to feed birds, protective fencing around nests, and closing off areas of the beach used by shorebirds. One policy cited the removal of feces, which addresses bird fecal material, but only insofar as docks are pressure-washed to remove the feces (the feces were reported to be washed into the water as a result). When the data were stratified by type of bird policy, no statistical differences were observed.

Our last question in the bird section asked for any other notable items about birds at the beaches. Notable answers, especially from a beach management standpoint included observations of visitors seen feeding birds, that birds are denser in the morning, and that the number of birds change based upon food sources, weather, and the number of humans.

Solid Waste Management

We received multiple responses to our question about how far the garbage cans are located from the shoreline. The percent exceedances, whether for enterococci or fecal coliform, were not statistically different between the different categories of distance of trash cans from the beach, except for in the open coast fecal coliform group, which showed a difference between trash cans placed 15-50 feet from shoreline (1.41%) and those placed 50-150 feet (1.70%).

Frequency of trash collection also varied by individual beach, from daily, weekly, or a collection schedule that fluctuates based on holidays or the season. Among the 225 responses, 174 responded with a number of days ranging from three times a day to every other day; 34 responded on a scale of weeks ranging from every five days to two to three times a week, and 17 reported a fluctuating schedule that ranged from "as needed" to more on holidays. None of the

percent exceedances, whether for enterococci or fecal coliform, were statistically different when comparing the FIB corresponding to beaches with different frequencies of solid waste collection.

Beach Grooming and Seaweed

We asked how severe the seaweed condition is at the beaches. This was an open-ended question, but most respondents chose to use "sparse," "medium," and "dense," as in the prior survey questions. Some added "severe" and "not severe" in their replies. This was especially interesting as the beaches where the seaweed condition was identified as "severe" had the highest FIB levels (12.4% ENT, 2.20% COL) of all of the categories, though only enterococci in the "all responses" category was statistically significant (Supplemental Table S3).

Table S3. Severity of seaweed at the beaches, All Responses (ALL) and Type 1 Open Coast (OC).

Question	Mean % Exceed	n	Mean % Exceed	n	Mean % Exceed	n	Mean % Exceed	n	Mean % Exceed	n	Mean % Exceed	n	Mean % Exceed	n	Statistics
	Dense		Medium		Not Severe		Severe		Sparse		Varies		No Response		
Enterococci															
ALL	4.74	5	2.15	19	3.63	21	12.42	12	4.33	24	3.01	57	3.35	178	F=7.32 p=<0.0001
OC	0.86	3	1.74	14	1.96	17	3.65	5	1.68	12	1.45	34	1.59	126	F=0.19 p=0.9785
Fecal coliform															
ALL	1.45	5	1.44	19	1.83	21	2.20	12	1.30	24	1.58	57	1.60	178	F=1.44 p=0.2017
OC	1.33	3	1.45	14	0.86	17	1.60	5	0.55	12	0.27	34	0.58	126	F=3.55 p=0.0023

The next question was a follow-up question, asking about grooming methods for the beaches that are groomed. This open-ended question resulted in multiple responses that were condensed to descriptions of frequency or of the actual process. Frequency descriptions included daily grooming, raking once a week or a few times per week, monthly sand raking; regular grooming with a rake; raking or grooming as needed; and cleanup from the oil spill (2010-2012). Descriptions of process included manual cleanup of litter and garbage disposal services; occasional raking for trash (not sand grooming purposes); raking of seaweed above the high tide line; use of a mechanical beach raker or grooming system; regrading done for driving areas; use of a sanitizer to pick up cigarette butts and litter, bury seaweed, and leave a level surface; and use of a tractor and rake or a tractor and blade to address seaweed and a sifter to pick up small litter that the ground crews cannot pick up. Other responses described how grooming is either suspended during turtle season or that they do not groom near the nests. As many of these groups only include 1 or 2 beaches, this is just a snapshot of what is done to groom beaches. It provides interesting insight into the variety of approaches to beach management, based on the individual needs of the environment and the impact of human use (Russell et al. 2014, Lamberti and Zannutigh 2005).

Table S4. Regular beach grooming, shower and rinsing facilities, All Responses and Type 1 Open Coast.

Question	All Responses					Open Coast				
	Yes	n	No	n	p value	Yes	n	No	n	p value
Regular Beach Grooming										
Enterococci	3.70	110	3.33	163	0.546	1.90	78	1.17	106	0.0003
Fecal coliform	1.75	110	1.32	163	0.153	0.91	78	0.40	106	0.0016
Public Shower/Rinsing Facilities Flow Toward Shoreline										
Enterococci	2.35	10	2.66	236	0.521	2.07	7	1.64	175	0.346
Fecal coliform	0.71	10	1.20	236	0.062	0.64	7	0.59	175	0.863

Beach Access and Use

We then focused on whether or not concession stands are present at the beaches. Among the respondents, 39% reported concession stands; significant differences were found between the "yes" and "no" groups in both the enterococci and the fecal coliform "all responses" sections (p <0.001 ENT, 0.002 COL). The "open coast" groups also showed a difference between "no" and "yes" (p = 0.0051 ENT, 0.0029 COL). All of the "yes" responses in all categories were lower than the "no" response (Supplemental Table S5), suggesting that beaches with concessions were associated with lower FIB levels.

Our next question asked for the respondents to provide details on the types of concession stands that are present at the beaches. This open-ended question resulted in four categories: (1) traditional concessions including stands that provide food, chairs, or jet skis; (2) pavilions with restrooms, picnic areas, and water fountains; (3) residences, describing homes, condos, resorts, and camping; and (4) restaurants and bars near the beach or on nearby piers. ANOVA showed no significant differences in the "all responses" group; in the "open coast" enterococci group, there was a difference between the "restaurant" category (3.53%) and the "pavilion" category (0.72%) (Supplemental Table S6). This was not seen in the fecal coliform group. The "restaurant" results were very interesting, as there are many factors (trash, birds, wildlife) that restaurants introduce. FIB levels can be driven up by factors associated with restaurants: feces from birds, rodents, and runoff from trash containment areas).

Table S5. T-test for concession stands, frequent boating activity, and public vehicles, All Responses and Type 1 Open Coast.

	All Responses					Open Coast				
Question	Yes	n	No	n	p value	Yes	n	No	n	p value
Have Concession Stands										
Enterococci	2.54	113	4.43	174	0.001	1.38	95	2.08	99	0.005
Fecal coliform	1.05	113	1.90	174	0.002	0.45	95	0.90	99	0.003
Frequent Boating Activity										
Enterococci	3.73	182	3.03	108	0.232	1.60	120	1.63	79	0.912
Fecal coliform	1.46	182	1.31	108	0.628	0.64	120	0.56	79	0.580
Public Vehicles Permitted										
Enterococci	1.75	55	3.61	240	<0.001	0.90	45	1.90	159	<0.001
Fecal coliform	0.42	55	1.75	240	<0.001	0.06	45	0.83	159	<0.001

Table S6. Types of concession stands at beaches, all results and Type 1 Open Coast.

Question	Mean % Exceed		Mean % Exceed		Mean % Exceed		Mean % Exceed		Mean % Exceed		Statistics
	Concessions	n	Pavilions	n	Residences	n	Restaurant	n	No Response	n	
Enterococci											
ALL	2.50	54	2.16	15	0.69	7	6.93	8	4.02	232	F=2.78 p=0.0269
OC	1.61	46	0.72	9	0.69	7	3.53	4	1.72	145	F=2.59 p=0.0366
Fecal coliform											
ALL	1.06	54	0.82	15	0.09	7	3.29	8	1.77	232	F=2.52 p=0.0424
OC	0.63	46	0.25	9	0.09	7	1.14	4	0.68	145	F=1.13 p=0.3415

We also focused on boating activity. Our first question was whether or not there was frequent boating activity offshore of the beaches. None of the categories were statistically significant (Supplementary Table S5), but the higher exceedance levels in the "yes" category for almost all of the groups indicate that offshore boating activities may slightly contribute to FIB exceedances.

Another question asked whether or not the public is allowed to bring vehicles on the beach (Supplementary Table S5). There were significant differences in all categories between "yes" and "no." However, the beaches where cars are allowed demonstrate lower exceedances of

bacteria than those where cars are not allowed. For example, for the enterococci group, the "all responses" yes category had a 1.75% percent exceedance, while the no category was at 3.61% (p<0.001). This association may be due to the small number of beaches that actually allow cars, or to a confounding variable, such as the spatial location of these beaches. Most of the beaches that allow vehicles on the beach (44 of 55 for all responses) are in northeast Florida, and have lower percent exceedances overall. These low numbers may also be due to the possibility that these beaches could welcome a large number of visitors, both in cars and out, and the facilities, management processes, and maintenance may be scaled to meet this demand.

Drainage and Sanitary Infrastructure

Our final question in this section asked if the shower/rinse water potentially flows towards the shoreline or if it is drained away. The answers resulted in two categories: beaches with policies that help to minimize impacts to the shoreline water and beaches without these policies. No statistical differences were observed in any of the groups evaluated (Supplemental Table S4).

County-Level Sampling and Analysis Policies

Table S7. Sampling day during the week, all counties.

Question	Mean % Exceed		Mean % Exceed		Mean % Exceed		Mean % Exceed		Statistics
	Monday	n	Monday and Tuesday	n	Tuesday	n	Wednesday	n	
Enterococci	6.62	23	5.41	2	2.13	6	2.66	4	F=0.90 p=0.4517
Fecal coliform	1.59	23	4.63	2	1.03	6	1.39	4	F=3.47 p=0.0279

Table S8. Sampling depth, all counties.

Question	Mean % Exceed		Mean % Exceed		Mean % Exceed		Mean % Exceed		Statistics
	Knee-deep	n	Knee or waist-deep	n	Thigh-deep	n	Waist-deep	n	
Enterococci	6.16	16	2.77	1	3.55	1	4.81	17	F=0.17 p=0.918
Fecal coliform	2.05	16	0.19	1	1.98	1	1.33	17	F=0.90 p=0.451

Table S9. T-test for cooling method, holding time, sampling time, and type of laboratory analysis, all counties.

Question	Mean % Exceed		Mean % Exceed		Statistics
Cooling Method					
	Ice pack	n	Wet ice	n	
Enterococci	5.64	15	5.10	20	.829
Fecal coliform	1.41	15	1.82	20	.422
Holding Time					
	More than 2 hrs	n	Two or fewer hrs	n	
Enterococci	4.86	33	13.1	2	0.278
Fecal coliform	1.67	33	1.32	2	0.782
Sampling Time					
	Noon or before	n	After noon	n	
Enterococci	4.12	31	13.1	2	0.261
Fecal coliform	1.58	31	1.32	2	0.834
Type of Laboratory					
	Government		Private	n	
Enterococci	5.76	19	2.92	13	0.108
Fecal coliform	1.75	19	1.58	13	0.781
Type of Laboratory Analysis					
	EPA 1600	n	Enterolert	n	
Enterococci	6.01	29	2.04	6	0.008

Table S10. Summary table.

Question	Result Associated with Lower FIB
human density	Lower density
dog density	Lower density
dog policies	Policies for addressing dog waste Stronger association with lower FIB levels than bags or signage
bird density	Lower density
bird policies	Policies for addressing birds, even if not focused on FIB levels
seaweed	Lower natural density Collection of seaweed at beaches with naturally high density increases FIB levels
renourishment	Beaches that are renourished
fees	Charging fees
lifeguards	Lifeguards
marinas	Beaches without nearby marinas
storm water management	Managing storm water
public restrooms	Availability of public restrooms