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Quantifying the effects of boat wakes on intertidal oyster reefs in a shallow estuary

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QUANTIFYING THE EFFECTS OF BOAT WAKES ON INTERTIDAL OYSTER REEFS IN A SHALLOW ESTUARY

by

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ABSTRACT

There have long been concerns about the negative impacts of recreational boating activity in the Indian River Lagoon system (IRL), especially in Mosquito Lagoon (ML), the northernmost part of the IRL. My research is focused on the impacts of boat wakes on intertidal reefs formed by the eastern oyster, *Crassostrea virginica*. There has been a 24% loss of oyster habitat in ML since 1943, where natural oyster reefs have been replaced by dead oyster reefs which do not serve the same ecological function. While there is anecdotal and correlative evidence that this loss is a result of boat wakes, no studies to date have confirmed dead reefs can be a direct result of boat wakes. Therefore, I addressed the following questions: (1) What wake heights are generated by a range of boat types, and (2) What amount of oyster movement and erosion occurs as a result of these boat wakes?

A series of boat pass experiments addressed the first question; these results were utilized in experiments at Florida Institute of Technology's wave tank to observe sediment erosion and oyster movement as a result of specific wake heights. Model selection was used for both the field and wave tank experiments to determine which variables contributed most to explaining the wake heights, erosion, and oyster movement that occurred. Wake heights ranging from 0.05 cm to 20.80 cm were documented contacting the oyster reefs from the boat passes, with a mean of 2.95 cm. Boat type was less important than speed or distance when determining wake height. My wave tank results document that wake heights as small as 2 cm contacting oysters are capable of moving individual and clusters of oysters. Minimum distances for boats to travel in order to maintain wakes smaller than 2 cm at reefs are suggested for management purposes based on regression equations. This could minimize the amount

of movement that occurs when oysters are subjected to boat wakes. The results of this study can help resource managers implement boating policies in Mosquito Lagoon, and contribute greatly to conserving this important ecosystem engineer.

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INTRODUCTION

Background

While there are many benefits, there are also direct and indirect negative impacts associated with recreational boating on marine and estuarine ecosystems throughout the world (e.g., Bejder et al., 2006; Fonseca and Malhotra, 2012; Wasson et al., 2001; Williams et al., 2002; Zacharias and Gregr, 2005). Direct physical impacts include changes in sedimentation and hydrology, boat strikes of marine organisms, and chemical pollution (e.g., engine emissions, anti-fouling agents, sewage dumping) (Burgin and Hardiman, 2011). Indirect biotic impacts can include the spread of non-native species and interactions of boat wakes with organisms (Burgin and Hardiman, 2011).

Indirect impacts caused by the wakes generated from recreational vessels have been shown to be detrimental to many diverse organisms (Bickel et al., 2011; Bishop, 2005, 2008; Gabel et al., 2012; Lorenz et al., 2013). For example, the volume of water filtered by mussels decreased with increasing shear stress from boat wakes (Lorenz et al., 2013). Epifaunal and macro-invertebrates experienced displacement and dislodgement from various shoreline substrates and seagrasses, resulting in potential changes in faunal assemblages with increased boating pressure (Bishop, 2008; Gabel et al., 2012). This could ultimately influence the ability of a seagrass bed to act as a nursery ground for fisheries (Bishop, 2008). There is also evidence that planktonic copepods had higher mortality rates in turbulent waters as a result of boat wakes, which could influence bottom-up trophic interactions in high boating activity areas (Bickel et al., 2011). Algal assemblages were also altered as a result of boat wakes due to changes in bottom-up processes along ferry routes in the Canadian southern Gulf Islands (Demes et al., 2012).

The relative damage, or alterations, that a boat wake can produce is a function of the energy of the wake upon impact (Stumbo et al., 1999). The energy of the wake can be derived from the height of the wake at impact using **Eq. 1**, based upon linear wave theory (Denny, 1988).

$$E = \frac{1}{8}\rho g H^2 \tag{1}$$

In this equation, E is energy, ρ is fluid density (~1000 kg m^{-3} freshwater, ~1025 kg m^{-3} brackish water), g is the acceleration of gravity (9.81 m s^{-2}), and H is wave height (Denny, 1988). Since ρ and g are relatively constant, the wave energy density can be computed by knowing the wave height. Therefore, it is important to consider what factors influence the height of a wake when examining the ecological impacts of a wake. The initial height of a boat wake depends on a variety of factors, including the shape of the hull, the speed of the boat, the ratio of speed to boat length, and whether the boat is on plane or not (Maynord, 2005; Stumbo et al., 1999).

There are three defined modes of operation for planing boats as defined in Maynord (2005): displacement, semi-planing (also known as ploughing), and planing. Displacement mode is when the boat weight is offset by the buoyant force of the water, and is obtained at lower speeds (Maynord, 2005). Semi-planing is when the bow of the boat is high in the water and large wakes are created, while planning is when a lift force maintains the hull position flat and out of the water with little contribution from the buoyant force of the water (Maynord, 2005). Due to the design of their hulls, pontoon boats are not capable of reaching the planing mode unless they are fitted with external planing fins (Nickell, 1993). In general, wake heights tend to increase as speed increases up until a point, and then decreases once a boat is in planing mode (Maynord, 2005).

Study Area

Florida has the most registered boats of any state (2012: 870,031), encompassing 7.1% of all registered boats in the United States (US Coast Guard, 2012). Additionally, boating in Florida is becoming increasingly popular, which is exemplified by a 73% rise in recreational boat registrations between 1985 and 2005 in counties bordering the Indian River Lagoon (IRL), on the east coast of central Florida (Sidman et al., 2007). Therefore, we have chosen to focus on the impacts of boat wakes in Mosquito Lagoon, an estuary in Volusia County, which is part of the Indian River Lagoon system (IRL).

The IRL is one of 28 estuaries in the U.S. Environmental Protection Agency's National Estuary Program (NEP), and was designated as an "Estuary of National Significance" in 1990. This designation indicates that the IRL's waters, natural ecosystems, and economic activities are critical to the environmental health and economic well-being of the United States (US EPA, 2014). The IRL has been valued at approximately $3.7 billion annually, and supports 15,000 jobs (SJRWMD, 2014a). The IRL has also been recognized as one of the most biologically diverse estuaries in the United States, primarily as a result of its overlap between temperate and sub-tropical climatic zones (IRLNEP, 2008).

Mosquito Lagoon is the northernmost part of the IRL (**Figure 1**), has an average depth of less than 1.5 meters, and a salinity range from 25 to 45 ppt (Walters et al., 2001). Canaveral National Seashore, part of the United States National Park System, is located within the southern half of Mosquito Lagoon (NPS, 2014). Mosquito Lagoon is comprised of three important habitats: (1) seagrasses (multiple species, primarily *Halodule wrightii*), (2) salt marshes, composed of mangroves and marsh cordgrass (*Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*, *Spartina alterniflora*), and (3) oyster reefs (*Crassostrea virginica*). Each of these habitat types has been experiencing declines worldwide as a result of various stressors (Beck et al., 2011; Fletcher and Fletcher, 1995; Garvis et al., in review; Grizzle et al., 2002; Valiela et al., 2001; Waycott et al., 2009). Seagrass beds currently experience an average global decline of 1.5% annually, with a global coverage loss of 29% since 1879 (Waycott et al., 2009). Global declines of mangroves are at 35% (Valiela et al., 2001), and 85% for shellfish reefs (Beck et al., 2011). In the IRL, the declines are even worse. Approximately 75% of saltmarsh habitat, including mangroves, was lost between the 1950s and the 1970s, due primarily to mosquito impoundments (SJRWMD, 2014b). Although seagrass abundances are highly variable, 11% of IRL seagrasses were lost from the 1970s to 1992 (Fletcher and Fletcher, 1995). Approximately 60% of IRL seagrasses were then lost from 2009 to 2012 due primarily to abiotic factors, algal blooms, and decreases in water quality (SJRWMD, 2014a). There has been a 24% loss (15 hectares) of oyster habitat in Mosquito Lagoon since 1943, where the natural habitat oyster reef habitat was replaced by dead oyster reefs or dead seaward edges of otherwise live oyster reefs (i.e. dead margins), which do not serve as ecosystem engineers (Garvis et al., in review).

The 2008 Indian River Lagoon Comprehensive Conservation and Management Plan (CCMP) states that boating activity in the IRL is one of the significant stressors resulting in negative impacts to the natural resources of the lagoon (IRLNEP, 2008). One goal of the CCMP is to, “Monitor boating impacts to Indian River Lagoon natural resources. Where appropriate, establish resource protection zones and monitor their effectiveness,” which recognizes that the impact of recreational boating has become an issue of importance in the area (IRLNEP, 2008). Likewise, the Canaveral National Seashore Water Resources Management Plan stresses the concern that increased recreational boat traffic may have severe impacts to the aquatic resources in the area (Walters et al., 2001).

There has been a multi-disciplinary project seeking to utilize a “community-based social marketing plan” to protect Mosquito Lagoon from boating impacts. In a collaboration between biologists and social scientists at the University of Central Florida, innovative social marketing approaches are being utilized to encourage recreational boaters in the area to voluntarily adopt more ecologically responsible boating habits (Bowerman and DeLorme, 2014). Ecologically responsible boating habits include those that would minimize the amount of shoreline erosion and dead oyster reef formation as a result of boat strikes and wakes, in addition to the avoidance of shallow areas with seagrass beds where propeller scarring is likely. Responsible boating would include travelling at speeds that minimize wake heights, although data to make recommendations is still needed.

Study Species

While boating activity may impact many species in Mosquito Lagoon, our particular interests are the impacts of recreational boating activity on the eastern oyster *Crassostrea virginica*. *C. virginica* is a keystone species in estuaries, ranging along the Atlantic coast from Canada to Brazil and the Gulf of Mexico (Bergquist et al., 2006; Gunter and Geyer, 1955). It provides a multitude of ecosystem services that are valued at up to $99,000 per hectare per year (Grabowski et al., 2012). These ecosystem services include water quality improvement through filtration and de-nitrification, shoreline stabilization, carbon sequestration, and habitat provisioning for many invertebrate and fish species (Grabowski et al., 2012).

In Mosquito Lagoon, *C. virginica* forms only intertidal reefs. The reefs are composed of a combination of single oysters and clusters of oysters. Larvae of *C. virginica* frequently settle on existing live and disarticulated oyster shells, thus resulting in the formation of three-dimensional, fused clusters. There are three main states of the oyster reefs in Mosquito Lagoon: natural, dead, and restored. Additionally, reefs can be partially dead or partially restored. Natural reefs, for the purpose of this study, are defined as oyster reefs that are not restored and have no, or minimal, formation of dead margins. Dead margins occur when the seaward edge of a natural reef has started to develop a dead mound, but the back-reef area is still an intact assemblage of oysters. Dead reefs are areas where there has been substantial piling up of dead oyster shells and clusters that have resulted in dead mounds where natural reefs once existed. Restored reefs are areas where a natural reef has transformed into a dead reef, or where dead margins have formed, and subsequent restoration efforts have taken place. For restoration, the dead margins or dead reefs have been leveled and stabilized, disarticulated oyster shells have been deployed and weighed down to promote new reef formation through larval recruitment.

Unfortunately, there has been a decline in live oyster reefs in Mosquito Lagoon (Garvis et al., in review; Grizzle et al., 2002). Using analysis of historical aerial photographs, Grizzle et al. (2002) found that the percentage of dead margins on oyster reefs in Canaveral National Seashore has been increasing over time, from 0.3% in 1943 to 27.6% in 2000. The dead area on a single reef ranged from <10% of the reef area to as high as 100% of the total reef area, indicating that some reefs were affected more than others (Grizzle et al., 2002). Grizzle et al. (2002) determined that all oyster reefs containing dead margins were only found adjacent to channels with boating activity. Additionally, many dead margins were present in channels that were too narrow to generate significant wind-driven wave action (Grizzle et al., 2002). An increase of 16.4% from 1995 to 2000 of the extent of dead margins also correlated to an increase in registered boaters in the counties that border Mosquito Lagoon (Grizzle et al., 2002). Garvis et al. (in review) expanded upon the study performed by Grizzle and colleagues to include all of Mosquito Lagoon, added in years 2000 – 2009, and determined that there has been a 24% loss (15 hectares) of oyster reef habitat in Mosquito Lagoon since 1943, and, more specifically, a 40% loss (~9.5 hectares) of natural reef coverage in Canaveral National Seashore. Again, Garvis et al. (in review) was able to show that the first dead margins on oyster reefs appeared on reefs in the heavily navigated Intracoastal Waterway (ICW), followed by dead margins appearing along Shipyard Channel in Mosquito Lagoon by 1951, and gradually increasing from there over time, along additional boating channels.

Dead reefs, and dead margins on the seaward edges of otherwise live reefs, have negative impacts on the ecology of *C. virginica* and the biodiversity of the oyster reefs (Stiner and Walters, 2008; Wall et al., 2005). Wall et al. (2005) showed that while oyster larvae continued to recruit to reefs that had formed dead margins, the percent survival of the larvae was significantly lower than on live, natural reefs. They found that the reefs with dead margins had higher sediment loads in the water column, which corresponded to reduced spat survival (Wall et al., 2005). Additionally, Stiner and Walters (2008) found that there was a significant difference in the distribution of species richness, density, and biomass between reefs with dead margins and live, natural reefs. The highest diversity on reefs with dead margins was on the live back-reef area, while on live reefs it was in the fore-reef area (Stiner and Walters, 2008).

While these studies show a strong correlation between boating activity and the formation of dead reefs, there have not yet been any studies that document the mechanism by which boat wakes turn live reefs into dead margins and dead reefs. It appears that boat wakes cause oysters and disarticulated shells to become dislodged from the sediment, move, and ultimately pile up above the intertidal zone. This forms mounds of shells above the mean high water line which prevents feeding as well as future larval settlement. A better understanding of how dead margins are formed, and whether the boat wakes observed in Mosquito Lagoon are capable of impacting oyster reefs, can provide valuable insight for conservation and restoration efforts. Additionally, data can provide a basis for implementing boating standards and regulations within waterways. Therefore, my goal was to quantify the movement of single oysters and clusters of oysters in Mosquito Lagoon as a result of boat wakes. I addressed the following questions in order to accomplish this: (1) What wake heights do different boat types generate that contact intertidal oyster reefs in Mosquito Lagoon? (2) What amount of oyster movement and erosion occur as a result of these boat wakes?

METHODS

Baseline Data on Boating Near Oyster Reefs in Mosquito Lagoon

Before conducting a field study related to boating activity in Mosquito Lagoon, observations of motorized boating activity near oyster reefs in Mosquito Lagoon were needed. For this, twenty oyster reefs (ten restored reefs, ten natural reefs along boating channels) were visited twice each between September 2012 and June 2013. Each visit lasted 40 minutes. Observers recorded the number and type of boats that passed the reefs. The speed of the boats was recorded using a Stalker Pro II Sports radar gun, and the distance the boat passed by each reef was recorded using a Nikon Laser1200 Long Range Precision Rangefinder. Whether the boat was on plane or not was also recorded.

Field Study Data Collection

A field study was designed to determine the wake heights of multiple boat types that contacted intertidal oyster reefs in Mosquito Lagoon. Five restored oyster reefs were selected at random using Geospatial Modeling Environment software (Beyer, 2014) and an existing shapefile of all restored oyster reefs in Mosquito Lagoon (Garvis et al., in review). The selected reefs and their coordinates were Athena (28.939565N, 80.845332W), RCW (28.941851N, 80.85852W), Seahorse (28.944601N, 80.853809W), Rainbow (28.943074N, 80.860553W), and Victory (28.942152N, 80.865079W) (**Figure 2)**. Each of the five reefs was considered a replicate. Restored reefs were chosen for the purpose of this study because they show similar characteristics to natural reefs in the area, but had previously formed dead margins indicating that they were subjected to sufficient pressures to previously result in dead reef formation. Boat passes were conducted at each site to include all possible combinations of four pre-determined variables. Variables considered were hull type, speed of boat, distance of boat from oyster reef, and whether or not the boat was on plane. The levels used for each variable were based on the results of the baseline boating activity observations.

The length of the boats tested in our trials, as well as horsepower of the engine, was based on availability. A Boston Whaler (17', 40 hp outboard engine) was provided by the UCF Biology Department; a pontoon (Monark 223 Fish & Swim, 22'5", 60 hp outboard engine) and flat bottom skiff (Griffis & Sons Stumpnocker, 16', 35 hp outboard engine) were provided by a generous volunteer. A v-hull boat was not used in this study because the boating channels near test reefs were too shallow at low tide for a v-hull to safely navigate.

Each boat was tested under varying speeds which fell into one of three categories: idle (<5mph), slow (6-15 mph), and fast (16-25 mph). Boats passed the oyster reefs at two different distance categories (close, far); distances considered close versus far depended on the geography of each individual site. A buoy was placed in the center of the channel seaward of each oyster reef, and all passes on the far side of the buoy were considered "far," while passes on the near side were considered "close." Passes were conducted with boats both on plane and not on plane. However, pontoon boats were not run on plane, as this hull type does not typically allow for planing. Additionally, at very low speeds, it was not possible for the boats to get on plane, and likewise at the faster speeds, it was not always possible to stay off plane. By running all possible trials, we were able to obtain wave heights at all three of the defined modes of operation (**Table 1**).

Five replicates of every possible combination of these variables were completed, for a total of 121 runs. All five replicates were completed in one day for the pontoon boat (4/24/14), while the skiff and whaler both required two days for completion (4/23/14 & 4/25/14 and 4/12/14 & 5/5/14, respectively). Each boat type completed all necessary passes at each reef within one session before proceeding to the next site. All passes were performed within 3 hours of low tide, while the oyster reefs were at least partially exposed to the air. The order of the passes at each site was randomized prior to data collection.

The surface level of the water was measured during all boat passes using an Ocean Sensor Systems wave logger. Data were collected continuously at a recording frequency of 10 Hz and were recorded to a compact flash memory card. While the wave logger recorded water levels in *count* units, a linear response curve that related counts to water level (in cm) was produced based on calibration prior to logger deployment. This allowed a time-series of water level to be produced from which a statistical wave-by-wave analysis could be performed to compute wave height.

For each pass, two observers standing at the edge of the oyster reef recorded the actual speed the boat was travelling using a Stalker Pro II sports radar gun, the distance from the reef of the boat while passing using a Nikon Laser1200 Long Range Precision Rangefinder, the time the wake first contacted the wave logger, wind speed while the boat passed using a Kestrel 2000 wind meter, and the number of visible waves in each wake.

Baseline Data on Oyster Reef Characteristics in Mosquito Lagoon

Before conducting any experiments related to oyster movement in a wave tank, observations of oyster reef characteristics in Mosquito Lagoon were needed. That way, the parameters of variables used would be indicative of what can typically be found on natural oyster reefs. For this, data was collected at five natural reefs (28.94000842N, 80.84766688W; 28.94228983N, 80.85213944W; 28.9424086N, 80.85771624W; 28.93767697N, 80.86220353W; and 28.9420343N, 80.86716034W). These reefs were selected at random using Geospatial Modeling Environment software in ArcGIS with an existing shapefile of all natural oyster reefs in Mosquito Lagoon (Garvis et al., in review). Five 0.25m^2 quadrats were deployed haphazardly at each reef. In each quadrat the number of single live oysters, single disarticulated oyster shells, and clusters of oysters were counted. Each cluster was weighed and measured (length x width x height). The number of live oysters and dead oyster shells were counted for each cluster. The depth (cm) that each oyster cluster and each single oyster were buried in the sediment was also recorded. The water displacement of oyster clusters was measured in the laboratory for 19 clusters. A frequency distribution of the size of oyster clusters (using weight as a proxy for size) and depths that the clusters were buried assisted in determining what size clusters would be used in the wave tank, as well as how deep they would be buried in the sediment. Laser transect surveys at these five natural reefs, as well as the five restored reefs used for the boat pass observations, were also performed to determine the average seaward slope at oyster reefs in Mosquito Lagoon.

Wave Tank Experiment Data Collection

The wave tank at the Florida Institute of Technology (FIT) Surf Mechanics Laboratory was used for experiments designed to quantify oyster movement and sediment erosion around the base of the oysters as a result of varying wave energies in a controlled environment. The tank (9.08 m long, 0.57 m wide, 0.91 m deep) generated waves using a piston paddle located 0.6 m from the back wall of the tank. Piston paddles, as opposed to flap paddles, generate more realistic shallow water waves, such as those found at oyster reefs in Mosquito Lagoon (Hugues, 2005).The tank was constructed of 5 cm clear acrylic and supported with metal beams at 1.22 m intervals along its length. This particular wave tank has been used for prior ecological studies, including assessing the efficacy of living shorelines in attenuating wave energy produced from recreational boat wakes (Manis et al., 2014).

Sediment was collected at low tide from oyster reefs in Mosquito Lagoon, and placed in the wave tank on top of a platform that was built to represent the average seaward slope found at oyster reefs in Mosquito Lagoon (0.41:5.18 m). The platform acted as a false bottom to reduce the amount of sediment necessary, and sediment covered the entire platform at a depth of 150 cm of sediment. The water level in the tank, at a depth of 0.41 m, was at the top of the sediment line, mimicking low tide (**Figure 3**). All trials were run at this water level in order to minimize any reflection off the back of the wave tank. Between each run, any sediment that moved was regroomed to its original position, and sediment was added to the tank to compensate for any erosion resulting in lost sediment.

Variables tested to determine their influence in moving individual oysters and clusters of oysters, as well as eroding the surrounding sediment, included: wave height, number of wakes, size of the oyster/cluster, and the depth that the oyster/cluster was initially buried in the sediment (**Table 2**). For each trial, every combination of these variables was run in a pre-randomized order (30 runs). Each trial was replicated three times for a total of 90 runs. All runs were completed between 7/7/14 and 8/4/14.

The wave heights used (2, 4, and 8 cm) were determined based on the results of the boat pass field experiment. Wave height was altered in the wave tank by adjusting the distance the piston paddle moved. The 2 and 4 cm waves were run with the paddle moving at a speed of 3 Hz, while the 8 cm waves were run with the paddle moving at a speed of 2 Hz. This resulted in a wave period of approximately 4 seconds for all of the 2 and 4 cm waves, and a period of approximately 6.5 seconds for the 8 cm waves. The actual height of each wave was measured using an Ocean Sensor Systems wave logger placed 2 m from the paddle, recording at 10 Hz. Each “wake” in the wave tank was a wave train comprised of 15 waves, based on the boat pass experiment observations. The effects of a single “wake” as well as three “wakes” were tested. This was to mimic the effects of a single boat pass as well as repetitive boat passes. The water in the wave tank was allowed to settle completely between each wake before movement of the paddle was initiated again.

The effects of wake energy on a single oyster, as well as a small cluster and large cluster were observed. The single oyster used for all wave tank trials was 11 x 4 x 2.5 cm, weighed 60.67 g, and displaced 43 mL of water. The small cluster was 6 x 8 x 4.5 cm, weighed 109.82 g, and displaced 66 mL of water. The large cluster was 9.5 x 5 x 12 cm, weighed 298.60 g, and displaced 151 mL of water. The individual oyster and clusters used for the trials were collected from Mosquito Lagoon. After collection, they were measured, weighed, left outside to desiccate for two weeks, and then adjusted back to their initial weight with the addition of AMACO brand self-hardening clay placed inside the shells which were then glued closed (Gorilla Glue™). All shells were glued closed to mimic live oysters at low tide. This allowed for repeated usage of the single oyster and the two clusters for all trials, to avoid additional variation of cluster characteristics between trials. Water displacement of all clusters was recorded after the glue had set.

For each run with the single oyster, the oyster was placed on top of the sediment at a distance of 48 cm from the end of the tank furthest from wave propagation. The single oyster was never buried in the sediment because single live oysters were not found buried in the sediment in the field. After the oyster was subjected to the waves, the distance that the oyster moved was measured in centimeters. Erosion, if any, was determined by the area and depth of sediment scouring around the oyster. The average depth of scouring was calculated based on 5 random point measurements. To determine the surface area of scouring, a picture was taken after each run using a digital camera mounted in a platform above the tank with a US nickel placed next to the scouring in each picture for standardization. The eroded surface area was then calculated using ImageJ software (2014).

All procedures for runs with the oyster clusters were similar to the individual oyster runs described above, except for the added variable of burial depth. The clusters were either placed on top of the sediment, or were buried between 1.5 and 4 cm into the sediment. The initial burial depth was recorded each time, and an angle locator was used to ensure the cluster was initially standing upright (90° angle). Oysters were initially upright because that is the position that best allows for filtration in nature, and the majority of oyster clusters on natural oyster reefs are found at angles between 20° and 90° (Stiner and Walters, 2008).

Data Analyses

For the field data collection, each day of data collection constituted a separate dataset of water surface levels to be analyzed. Using Matlab R2014b (Mathworks, 2014), the data were split into sections, with each section beginning at the time recorded of when the boat wake for each pass initially hit the wave logger (**Figure 4**). H_{max}, H_{mean}, T_{max} and T_{mean} were calculated for each section. All analyses of wake data were performed using only H_{max} (maximum wave height) because it was the most reliable metric obtained based on our methods. When the data was split into sections, these sections also contained the time between passes when there was no boat wake present. The nature of this analysis resulted in H_{mean} values for the boat wakes to be much lower than they would be if the analysis was performed on only the wake itself. H_{max} was deemed reliable because during each section there was only one wake present, and the wake would naturally generate a H_{max} for that time period. These wave heights helped determine wave heights for the wave tank experiment, and were also used in model selection.

Model selection analysis was performed in R (version 3.1.0) to determine the most influential factors in determining the wake height. Due to pontoon boats not having the ability to run both on and off plane, model selection had to be broken into two separate models. First, we analyzed the data including all boat types, but not including the variable of whether the boat was on plane or not. The second model excluded pontoon boats and included the predictor variable of whether the boat was on plane. For all analyses, H_{max}, the speed of the boat, and the distance of the boat from the reef were log transformed for normality. For the model excluding pontoon boat data, H_{max}, the speed of the boat, and the distance of the boat from the reef were also centered around the mean in order to decrease the variance inflation factor. All model selection utilized linear models, and were performed utilizing the AICmodavg package with the criteria of lowest AICc value to determine the most informative model. The random effect of site was added to each of the most informative models to account for any variability having to do with the location blocking term.

For the wave tank experiment, the response values of “distance moved” and “erosion” were analyzed using model selection in R (version 3.1.0) as described above. Distance moved and erosion were both Log_{10} transformed in order to account for heterogeneity of variances. Four models were analyzed for this data, including: probability of movement occurring, the level of movement when it occurred, probability of erosion occurring, and the level of erosion when it occurred. The probability of movement occurring and the probability of erosion occurring were performed using general linear models with a binomial distribution. The level of movement and the level of erosion, as appropriate, were analyzed with linear models under normal distributions. The random effect of replicate number was added to each of the most informative models to account for any variability associated with the replicate blocking term.

RESULTS

Baseline Data on Boating Near Oyster Reefs in Mosquito Lagoon

Of 71 boats observed, approximately 42% of the boats were Boston Whaler, Carolina Skiff, or boats with similar hulls (typically a cathedral hull with three v shapes along the hull). Sixteen percent were flats fishing boats, where the hull of the boat is flat, 14% were v-hulls, and 10% were pontoon boats where the hull of the boat is a platform with an air filled pontoon on each side for buoyancy. Other boat types observed less frequently included sailboats, Jon boats (aluminum, flat bottomed hull), and motorized canoes. A mean (± SE) of 3.2 ± 0.32 boats passed during each 40-minute observation period, with a maximum of 13 boats passing a reef during each 40-minute observation period. The mean speed of all boats (± SE) was 16.9 ± 1.1 mph, although 25% of the boats travelled slower than 8.1 mph, and 75% of the boats travelled slower than 24 mph. The fastest boat to pass any of the oyster reefs during observations was a v-hull boat with a 115 hp engine, travelling at 33 mph towing a water skier. The mean distance of the boats from oyster reefs (± SE) was 65.1 ± 6.3 m, although the distance was highly variable based on the landscape of each site. Seventy-two percent of the boats were travelling on plane, while 28% of the boats were not on plane.

Field Study Results

The mean H_{max} (± SE) contacting oyster reefs of all boat passes was 2.96 ± 0.31 cm. The minimum H_{max} was 0.05 cm and the maximum H_{max} was 20.80 cm. The average wind speed (± SE) during boat passes was 4.3 ± 0.2 mph. The average number of waves per boat wake (± SE) was 14.94 ± 0.76.

Model selection to determine which of the tested variables was most influential in determining the observed H_{max} results provided additional insights. For the first model, which included all boat types but eliminated whether the boat was on or off plane, we found that the most informative model to fit the data included the variables of boat speed (slope ± SE = 0.53 ± 0.17; p = 0.003), and distance from the reef (slope ± SE = -0.60 ± 0.17, p < 0.001) (**Table 3**). Our data did not provide evidence that boat type played a significant role in determining H_{max}. We found that as the speed of the boat increased, the H_{max} of the wake height increased exponentially, and as the distance from the reef increased, the H_{max} decreased exponentially (**Figure 5**). This relationship is described by **Equation 2**.

$$H_{max}(cm) = e^{1.92 + 0.53*Speed(mph) - 0.60*Distance(m)} \quad (2)$$

For the second model, which included whether the boat was on or off plane but excluded all pontoon data, we found the most informative model included the distance from the reef (slope ± SE = -0.55 ± 0.19, p<0.006), the speed of the boat (slope ± SE = 1.97 ± 0.44, p<0.001), and whether the boat was on plane. Additionally, there was an interaction between the boat speed and whether the boat was on plane (**Table 4**). As with the first model, we found that as the distance the boat passed by the reef increased, the H_{max} of the wake decreased exponentially (**Figure 7, Table 4**). We also found that as the speed of the boat increased, the H_{max} of the wake height increased exponentially, but this happened at a steeper rate when the boat was not on plane, as opposed to when it was on plane (**Figure 7, Table 4**). These responses can be explained for boats that are not on plane with **Equation 3**, and for boats that are on plane with **Equation 4**.

$$H_{max} = e^{1.67+1.97*Speed(mph)-0.55*Distance(m)} \quad (3)$$

$$H_{max} = e^{1.06+0.29*Speed(mph)-0.55*Distance(m)} \quad (4)$$

Baseline Data on Oyster Reef Characteristics in Mosquito Lagoon

There was a strong linear correlation between cluster weight and water displacement of oyster clusters ($r^2 = 0.93$) and weight was used as a proxy to indicate cluster "size." Per quadrat, there was a mean (± SE) of 6.00 ± 1.08 living single oysters, 42.32 ± 2.38 disarticulated oyster shells, and 25.08 ± 1.38 clusters of oysters (n = 25 quadrats). The mean weight (± SE) of individual clusters was 211.55 ± 7.52 g. The minimum cluster weight was 11.80 g, while the maximum weight was 2,059.00 g.

For further analysis of the depth the clusters were buried, oyster clusters were grouped into two classes: small clusters (71.6 – 94.7 g), and large clusters (255 – 456 g). Clusters used in the wave tank experiment were based on these classifications. On average in the field, 25% of the clusters found in a quadrat would fall into the "small" category or smaller, 15% would fall into the "large" category, and 50% of the clusters were between these size categories. Intermediate weight clusters were not included to ensure there was clear distinction between small and large clusters in the experiment. For small clusters, the 25%-75% quartile range of burial depths was 1.5 to 3.5 cm. For large clusters, the 25%-75% quartile range of burial depths was 1.5 to 4.0 cm.

The mean seaward slope (± SE) of oyster reefs was 0.41:5.40 (± 1.62) m for natural reefs and 0.41:5.00 (± 1.44) m for restored reefs. There was no significant difference in slope between natural and restored reefs (ANOVA, p = 0.86), so an average slope of 0.41:5.18 m was used in the wave tank.

Wave Tank Experiment Results

Probability of individual oyster/cluster moving

The single oyster had a mean frequency (± SE) of 0.94 ± 0.02 of moving, the small cluster had a mean frequency of 0.58 ± 0.05, and the large cluster had a mean frequency of 0.53 ± 0.05.

A summary of the most informative model of the data collected can be found in **Table 5**. Based on this model, there is evidence that the size of an oyster/cluster and the depth that they were buried contributed to movement potential. As the depth that clusters were buried increased, the probability of movement decreased. There was also evidence for an interaction term, indicating that this happened at a faster rate for small clusters than it did for large clusters (**Figure 8, Table 5**).

Movement

For oysters/clusters that moved (n=57), when subjected to one wake the mean distance moved (± SE) of the single oyster was 16.82 ± 2.25 cm, of the small cluster was 7.89 ± 0.99 cm, and of the large cluster was 9.00 ± 1.01 cm. When subjected to three wakes, the mean distance moved (± SE) of the single oyster was 36.67 ± 1.67 cm, of the small cluster was 9.76 ± 1.96 cm, and of the large cluster was 12.65 ± 1.59 cm.

The most informative model suggested that the wake height, number of wakes, and cluster size contributed to determining the level of movement (**Table 6**). **Equation 5** describes the distance moved for large clusters, **Equation 6** for small clusters, and **Equation 7** for single oysters, all when subjected to one wake (**Table 6, Figure 9**).

$$Distance\ Moved\ (cm) = 10^{0.58+0.05*WakeHeight(cm)} \tag{5}$$

$$Distance\ Moved\ (cm) = \ 10^{0.43+0.05*WakeHeight(cm)} \quad (6)$$

$$Distance\ Moved\ (cm) = \ 10^{0.96+0.05*WakeHeight(cm)} \quad (7)$$

Distance moved for each shell type when subjected to three wakes was described using **Equation 8** for large clusters, **Equation 9** for small clusters, and **Equation 10** for single oysters (**Table 6, Figure 10**).

$$Distance\ Moved\ (cm) = \ 10^{0.81+0.05*WakeHeight(cm)} \quad (8)$$

$$Distance\ Moved\ (cm) = \ 10^{0.66+0.05*WakeHeight(cm)} \quad (9)$$

$$Distance\ Moved\ (cm) = \ 10^{1.19+0.05*WakeHeight(cm)} \quad (10)$$

Frequency of erosion

The most informative model indicated that, of the variables tested, the size of the oyster/cluster best described whether erosion would occur or not (**Table 7**). The bases of single oysters were less likely to erode than the bases of clusters (**Figure 12, Table 7**). Large clusters had a mean frequency of erosion (± SE) of 0.81 ± 0.04 and small clusters had a mean frequency of 0.89 ± 0.03, while single oysters had a mean frequency of erosion (± SE) of 0.17 ± 0.04.

Erosion

When erosion occurred (n=64), the mean erosion (± SE) for large clusters was 9.80 ± 1.09 cm^3, for small clusters was 4.30 ± 0.86 cm^3, and for single oysters was 1.39 ± 0.09 cm^3. The most informative model indicated that the level of erosion was most influenced by the size of the cluster (**Table 8**). Single oysters and small clusters had less erosion occur than large clusters (**Figure 13, Table 8**).

DISCUSSION

While previously there was only anecdotal and correlative evidence that boat wakes were capable of forming dead oyster reefs or dead margins (Garvis et al., in review; Grizzle et al., 2002; Walters, 2014), there is now direct evidence showing that wake heights found in Mosquito Lagoon are capable of causing both individual oysters and oyster clusters to move as sediment erodes around their bases. We have shown, by combining field and wave tank data, that wake heights as small as 2 cm are capable of moving not only single oysters but also oyster clusters. Additionally, within our trials, there was no evidence that boat type played a significant role in determining the heights of wakes that were produced. Only 10% of the oyster clusters we found on natural reefs in Mosquito Lagoon were larger than those that were used in our experiment. While this experiment was conducted in a controlled environment, we would expect to see similar results in the field given that the parameters we used were indicative of what can be found in Mosquito Lagoon. Other studies looking at ecological effects of boat wakes have found similar results in the field as they did with their wave tank experiments (Gabel et al., 2008; Gabel et al., 2012).

Before an oyster or an oyster cluster can be piled up to form a dead margin, erosion must occur in the surrounding sediment, resulting in dislodgement of the oyster/cluster. Our experiments showed that wake heights as small as 2 cm are capable of producing sufficient erosion for dislodgement and movement to occur. How much erosion occurred in the sediment surrounding the oyster clusters was dependent on the cluster size. The single oyster in our experiments had very little erosion occur because it was never buried in the sediment. While our data did not find sufficient evidence to indicate that increases in H_{max} influences erosion levels, Nanson et al. (1994) showed, while working in the Gordon River in Tasmania, that as the maximum wave height (H_{max}) of a boat wake increased, the level of erosion also increased. Additionally, they showed that although there are other, more complicated, parameters of a boat wake that can be used in analyses, none were significantly better estimators of erosion than H_{max} (Nanson et al., 1994). We did find evidence that along with cluster size, wake height and the number of wakes a reef influenced the distance that an oyster or cluster moved. Therefore, our results indicate that in order to decrease the number of dead oyster reefs and dead margins that form in Mosquito Lagoon, it is important that we minimize boat wake heights and wake frequency. If less erosion occurs around oyster clusters, they will remain buried in the sediment at deeper depths. Our models then show that as depth of initial burial increases, the probability of the oyster or cluster moving significantly decreases.

While it may be difficult to decrease the frequency of boat passes, our field experiment shows that boater and management efforts could reduce wake heights generated from recreational boats. Other studies (e.g., Bishop, 2008), have recommended banning of power boats in sheltered areas adjacent to ecologically important organisms. However, in areas such as the Indian River Lagoon, where tourism and recreation are important to the economy (SJRWMD, 2014a), it is important to consider alternatives. Based on our findings, it should be recommended that boats travel at speeds or distances away from the oyster reefs that will reduce their wake heights to below 2 cm when the wakes reach the oyster reefs. **Table 9** summarizes suggested minimum distances from a reef that each boat type should maintain at speeds commonly found in Mosquito Lagoon in order to minimize their impacts. These values are based on the regression equations derived from the wake height models (**Figures 5 – 7, Equation 2 – 4)**. Management authorities could also use these equations to derive recommendations for a variety of different speed and distance scenarios, as they deem appropriate.

The depth that oyster clusters are initially buried in the sediment is a significant factor in determining whether they ultimately move or not. It is important to consider additional factors besides boat wakes that could decrease that depth. Given the method that some harvesters manually dislodge intertidal oyster clusters and then discard the remaining oysters in the cluster without reburying them, they could be having a larger impact than previously thought (personal observation). In Canaveral National Seashore, an annual average of approximately 1,990 bushels (1 bushel = 9.3 gallons) of oysters were reported on catch logs from commercial fisherman over the years of 2009-2013 (K. Kneifl, pers. comm.). Other studies have shown that harvesting can have negative effects on oyster reefs (Lenihan and Micheli, 2000). Lenihan and Micheli (2000) found through experimental harvesting that harvesting not only reduced the density of oysters on harvested reefs, as would be expected, but also reduced the survival of the un-harvested oysters on these reefs. Future research on harvesting practices in Mosquito Lagoon could provide valuable insight into the effect of harvesting on reef sustainability.

Another factor that could be contributing to the erosion and movement of oysters/clusters is that of wind-generated waves, as opposed to boat wakes. Our boat passes were conducted on relatively calm days (average wind speed ± SE of 4.3 ± 0.2 mph, with a maximum speed of 11.3 mph) in order to have a clear distinction between wind-generated waves and boat-generated wakes. However, it should be acknowledged that wind speeds do reach higher levels than those present during our boat wake study, and the degree to which they contribute to the formation of dead margins and dead reefs is not yet known. Houser (2010) looked at how a shoreline at Fort Pulaski in Savannah, Georgia changed as a result of wind-generated waves versus boat-generated waves, and found that boat wakes accounted for only 5% of the total wave energy impacting the shoreline, however due to larger heights and longer periods, they were approximately 25% of the cumulative wave force in the area. This shows that although wind-driven waves can be more abundant in an area, boat wakes can have a non-proportional effect on the shoreline or organisms that they contact. Additionally, Houser (2010) expressed the importance of seasonality when considering wind generated waves versus boat wakes. It is possible that during certain seasons, wind-generated waves contribute more to erosion (such as in the winter months when wind energy is greatest), while in other seasons boat-generated wakes would be the main contributor. It is possible to use models to better understand the wave climate in Mosquito Lagoon, however it is important to consider that shallow- water estuaries are uniquely challenging for models to accurately predict wave climates due to their complex geography and unsteady conditions (i.e., Chen et al., 2005). Therefore, it is not only necessary to obtain detailed data on wind patterns and bathymetry at oyster reefs in Mosquito Lagoon, but it will also be necessary to perform additional field experiments to determine the relative contribution of wind waves versus boat wakes to the observed levels of sediment erosion and oyster/cluster movement.

It is particularly important to gain a more thorough understanding of the impacts of boat wakes on oysters, as oyster reefs act as ecosystem engineers. Negative impacts to oyster reefs reach far beyond the scope of just the oysters themselves. With increasing dead reef formation, the ecosystem services that *C. virginica* provides (i.e., water filtration, shoreline stabilization, nitrogen fixation, and feeding and nursery grounds for other species) are greatly reduced. The combined work of Boudreaux et al. (2006) and Stiner (2006) showed that the presence of dead margins on oyster reefs in Mosquito Lagoon affected the ability of the reefs to sustain biodiversity. Smyth et al. (2013) have shown that *C. virginica* increased organic matter decomposition and denitrification resulting in oyster reefs being a net sink of nitrogen, while in the absence of live *C. virginica*, sediments are generally a net source of nitrogen. Thus, the formation of dead margins and transformation of live oyster reefs to dead reefs in Mosquito Lagoon could have a detrimental effect on nitrogen fixation in the lagoon waters. A meta-analysis by Kellogg et al. (2014), however, emphasized that the data related to the ability of oyster reefs to mitigate eutrophication is largely lacking, and that more research on this topic is important.

As the level of recreational boating continues to increase in the Indian River Lagoon (Sidman et al., 2007), now is the time to fully understand the ecological implications of this human impact on this estuary, and all shallow- water estuaries. Boat wakes can have negative impacts on various estuarine species that are not naturally exposed to water turbulence at the same levels associated with the wakes, and it is important to try to minimize those impacts. Although oyster reef restoration in Mosquito Lagoon has been largely successful (Walters, 2014), preventative measures to reduce the need for restoration must be the ultimate goal. In order for resource managers and policy makers to put preventative policies in place, they must first be provided with the necessary data. This study has provided a baseline for understanding some of the impacts of boat wakes in Mosquito Lagoon.

Figure 1: **Map of Mosquito Lagoon**. Canaveral National Seashore boundaries are marked.

Figure 2: **Map of oyster reef study sites**. Each reef was a replicate for the controlled boat passes.

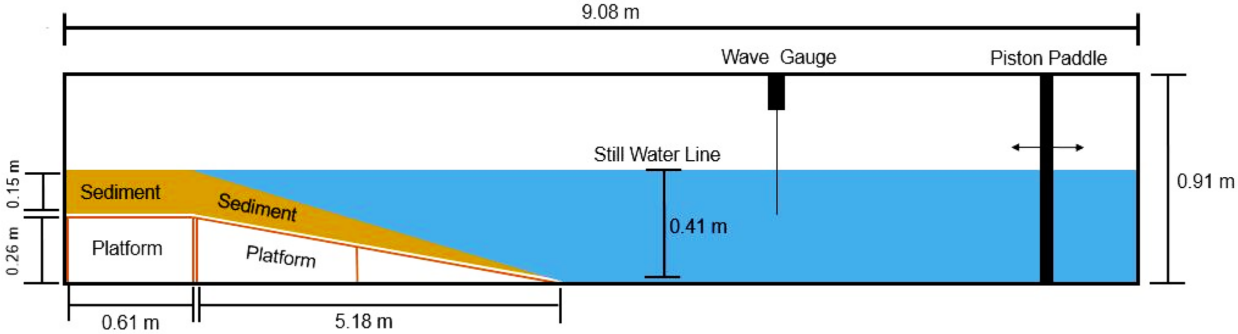

Figure 3: **Wave tank setup (not drawn to scale)**. The platform was built at a slope of 0.26:5.18 m so that when covered with sediment, the final slope was 0.14:5.18 m.

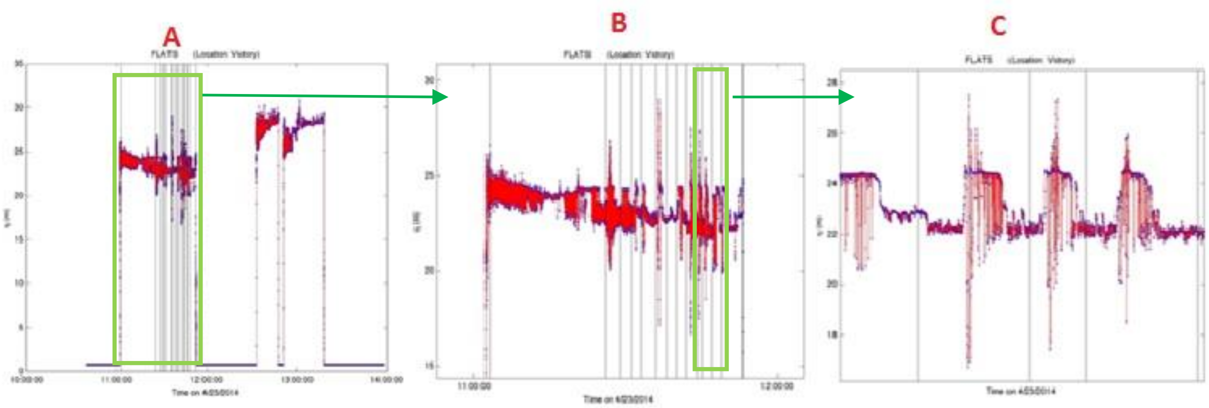

Figure 4: **Example of logger output during boat pass trials**. A: free surface of water at two reef site locations for the flats boat. B: the first site zoomed in for Victory Reef. Vertical lines indicate the start of each new boat pass as indicated by the time recorded of when the wake hit the logger. C: Details of wakes from 4 boat passes.

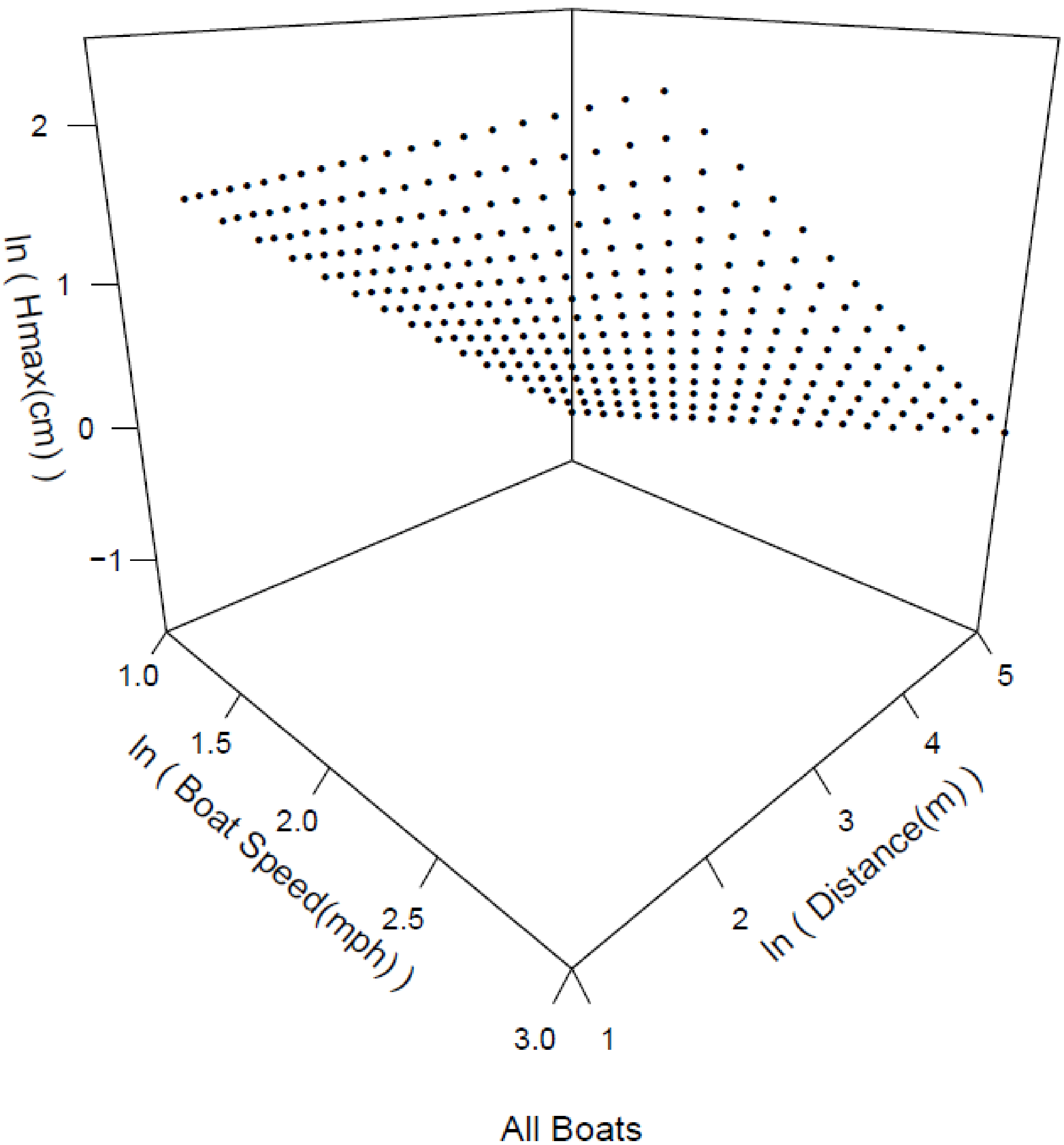

Figure 5: **H_{max} as a function of boat speed and distance for all boat types**. H_{max} is the maximum height of the water as recorded with wave gauges during boat passes. **Equation 2** describes the relationship between H_{max}, speed, and distance.

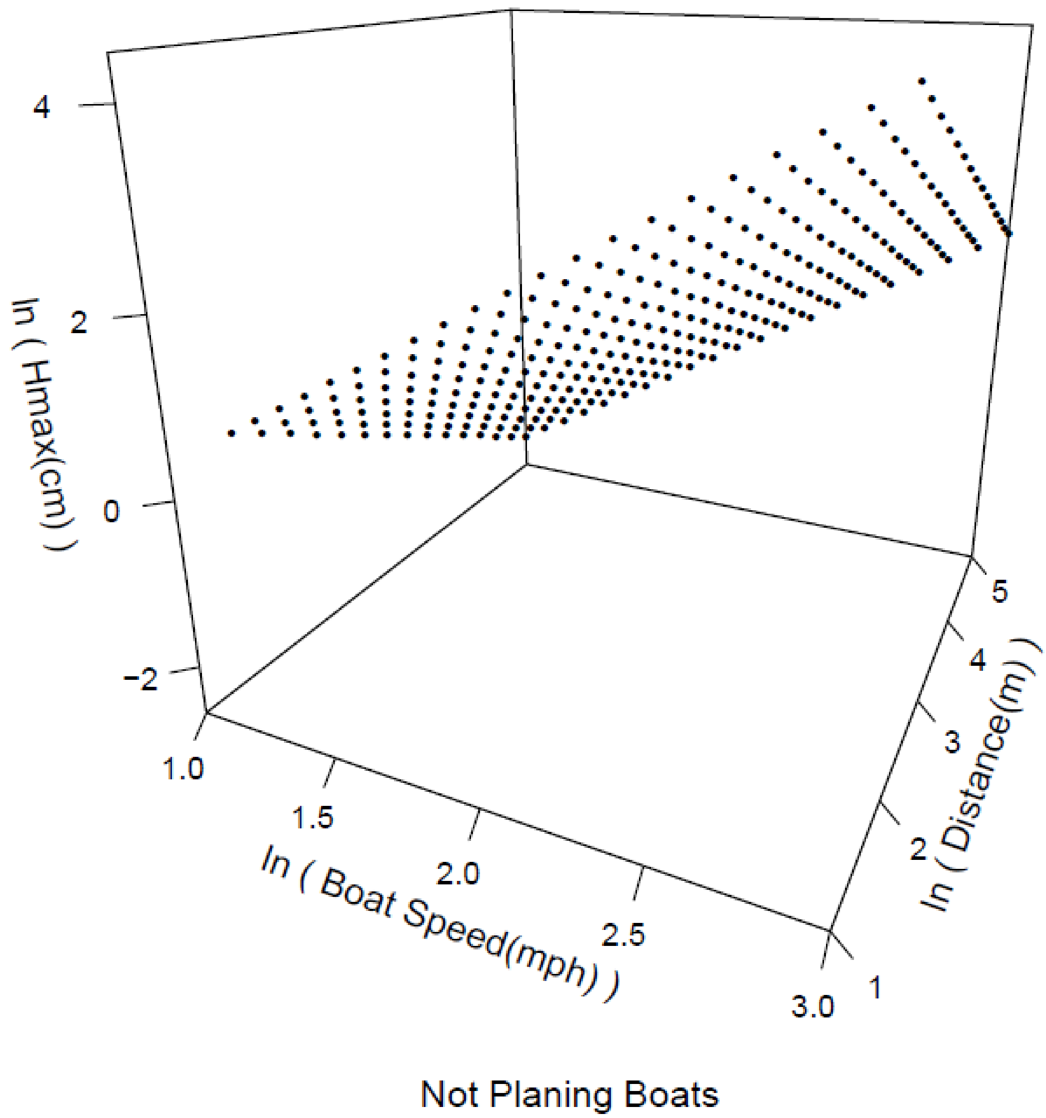

Figure 6: **H_{max} as a function of speed and distance for Whaler and flats boats while not on plane**. H_{max} is the maximum height of the water as recorded with wave gauges during boat passes. **Equation 3** describes the relationship between H_{max}, Speed, and Distance.

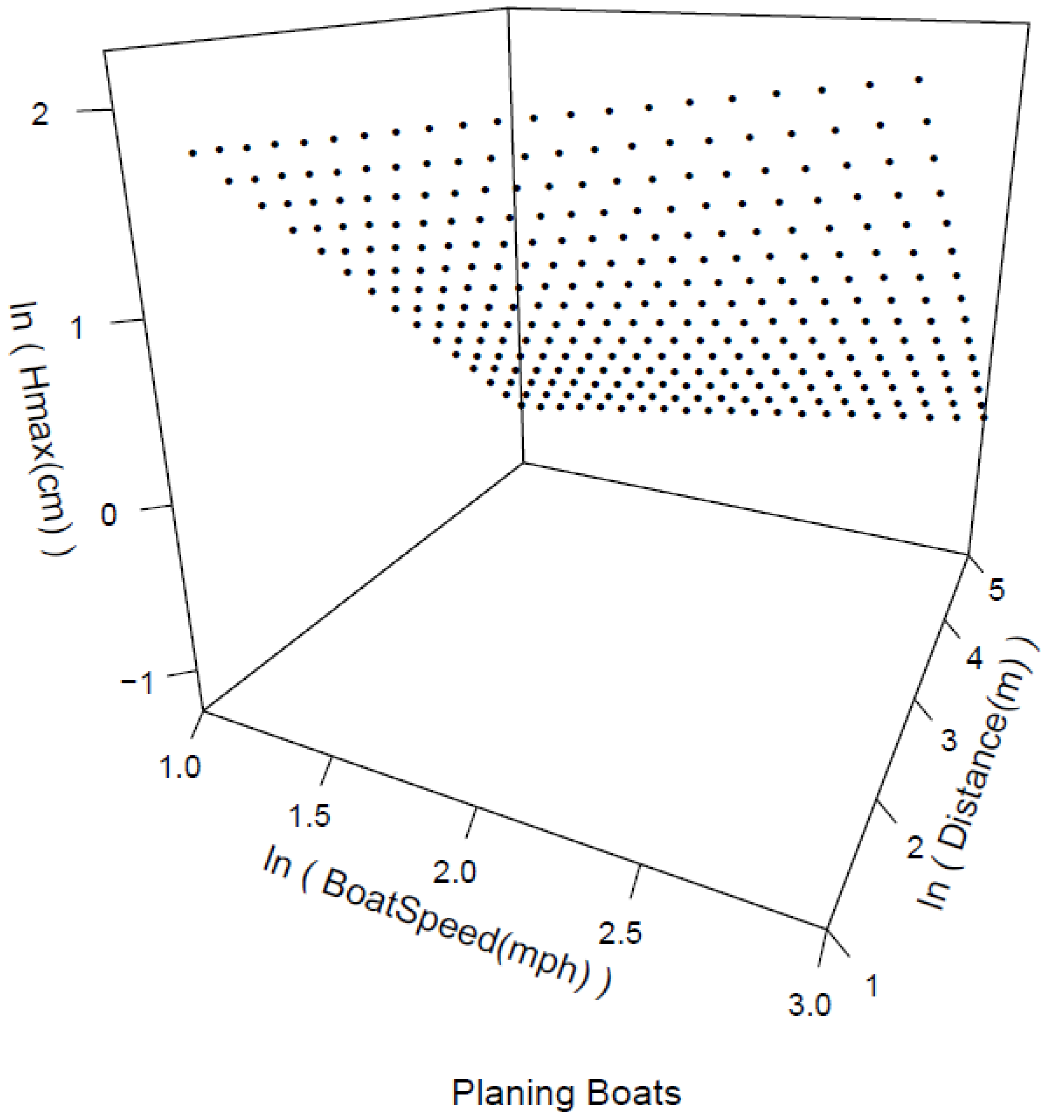

Figure 7: H_{max} as a function of speed and distance for Whaler and flats boats while on plane. H_{max} is the maximum height of the water as recorded with wave gauges during boat passes. **Equation 4** describes the relationship between H_{max}, speed, and distance.

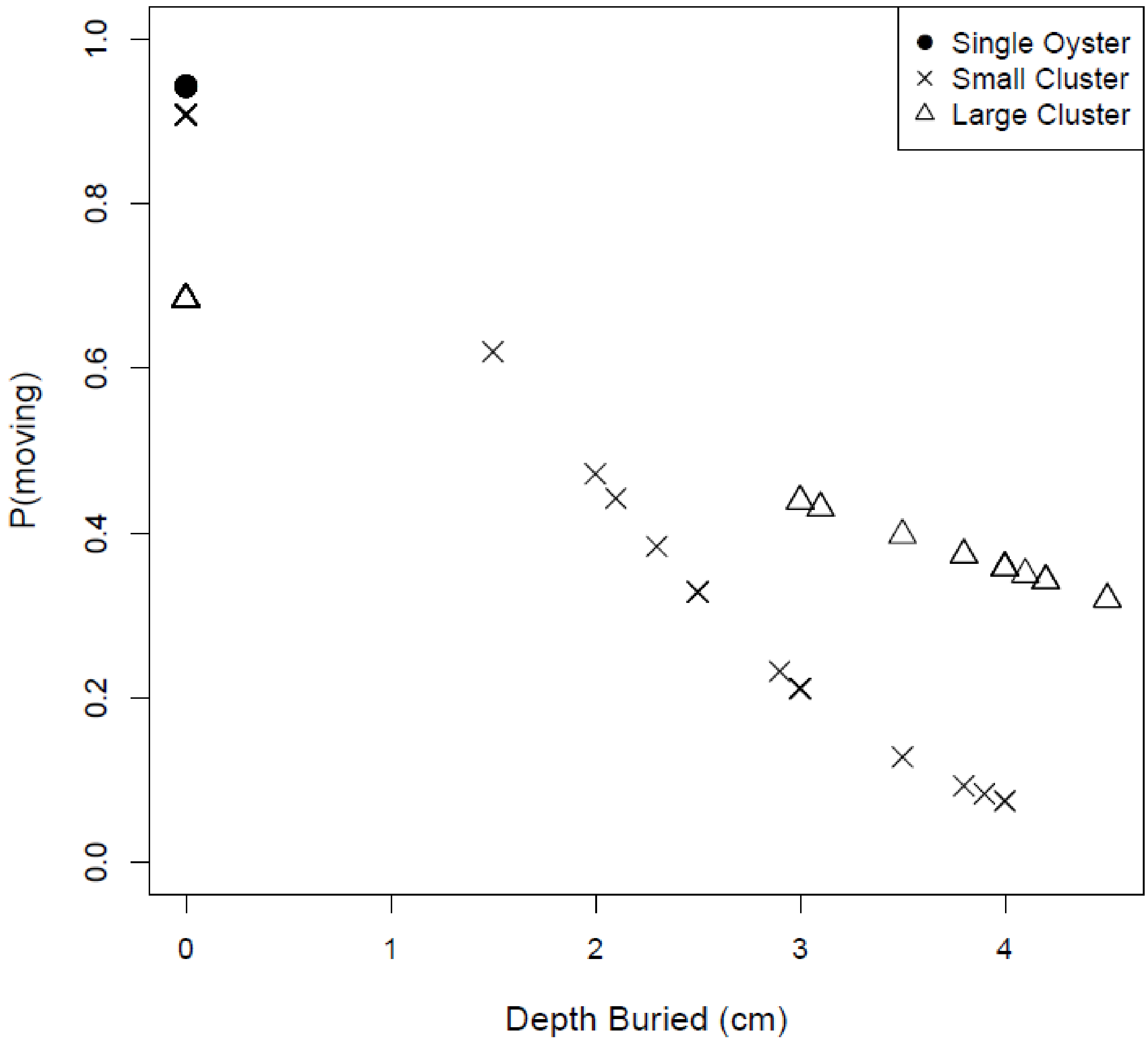

Figure 8: **Probability of an oyster or cluster of oysters moving as a function burial depth**. Single oysters were never buried.

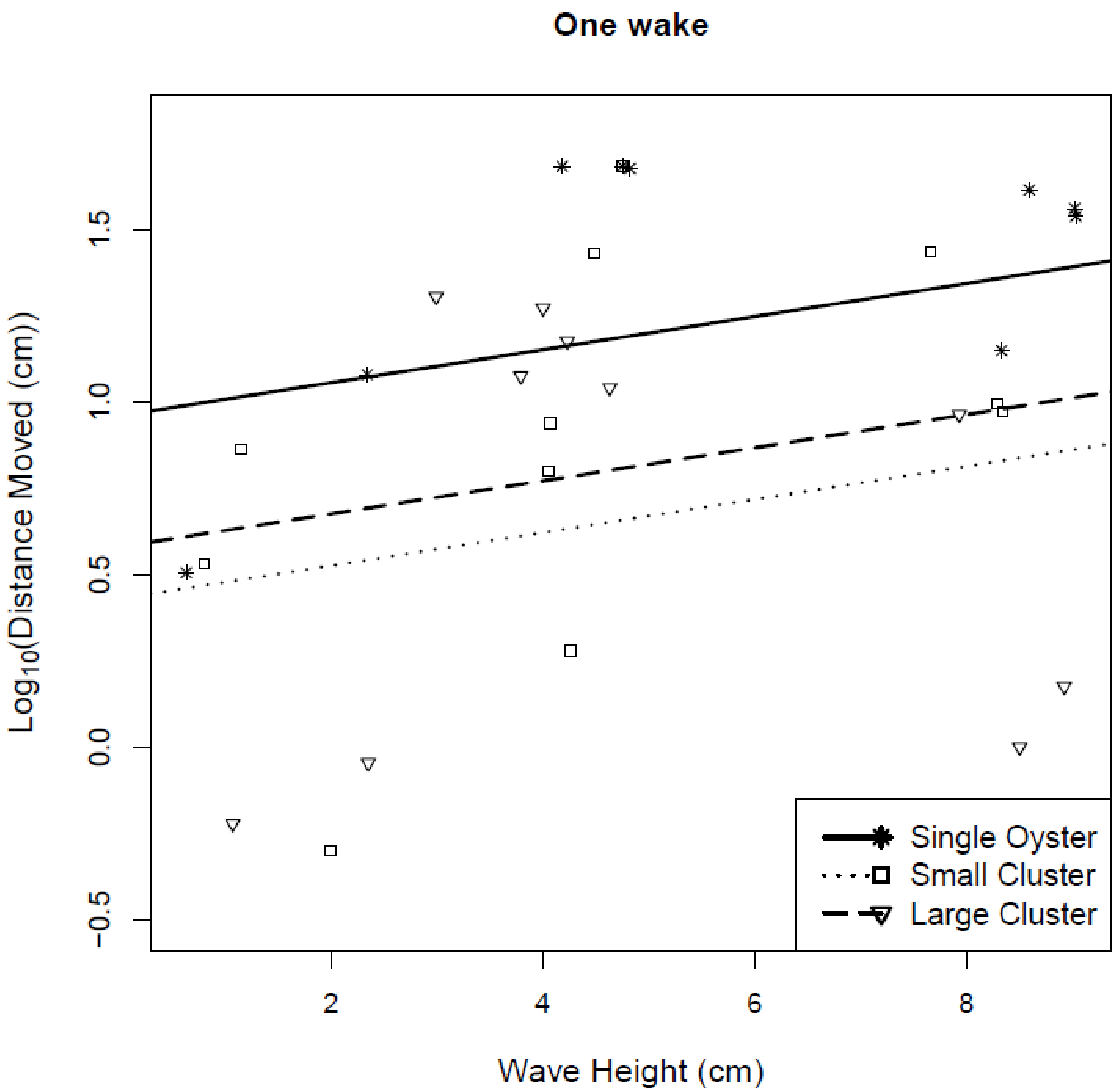

Figure 9: **Distance moved as a function of oyster/cluster size for 1 wake**. Results are shown only for the oysters/clusters that did move (n=57). **Equations 5 – 7** describe the relationship between distance and wave height for each size oyster/cluster.

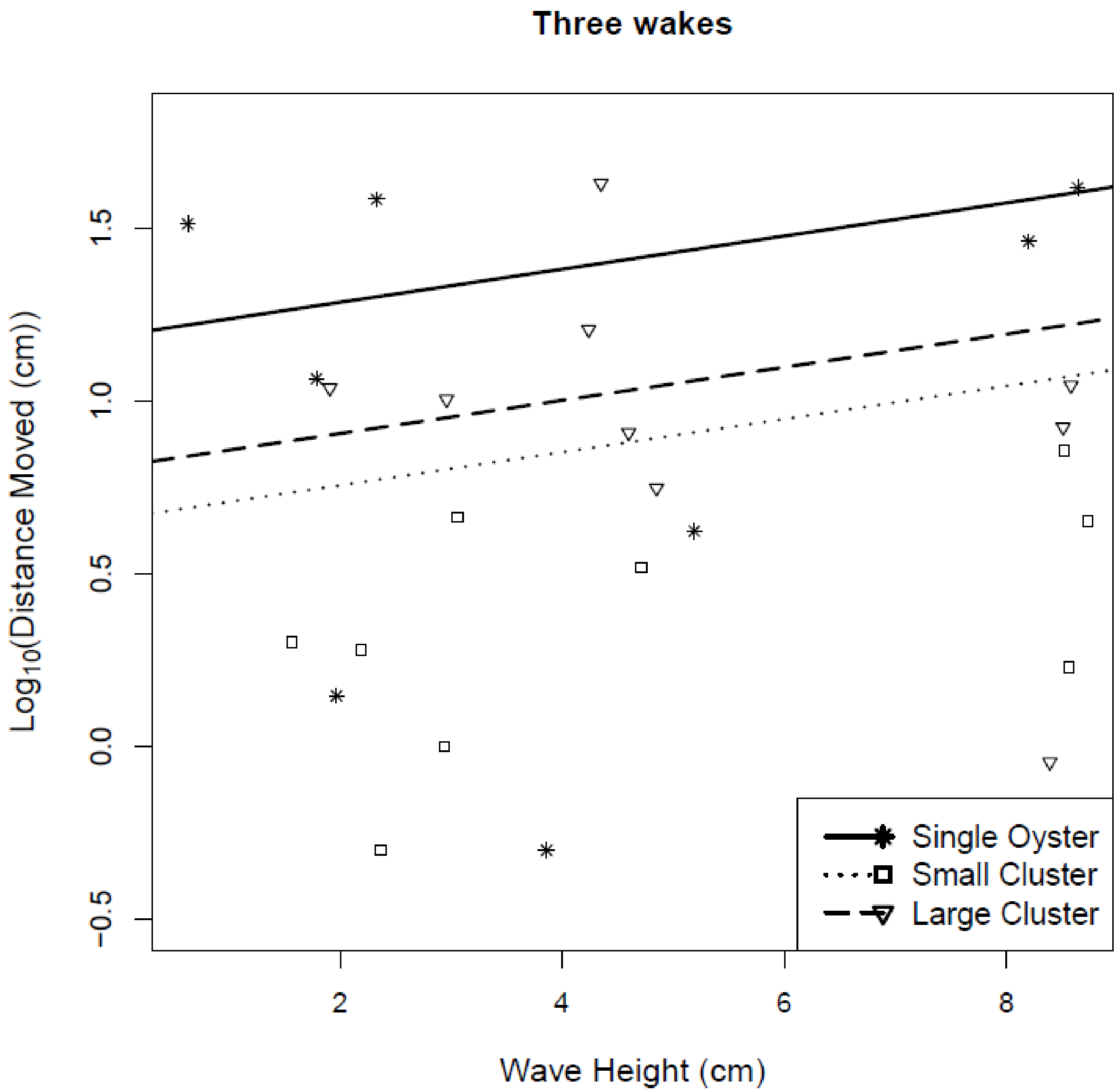

Figure 10: Distance moved as a function of oyster/cluster size for 3 wakes. Results are shown only for the oysters/clusters that did move (n=57). **Equations 8 – 10** describe the relationship between Distance and Wave Height for each size oyster/cluster.

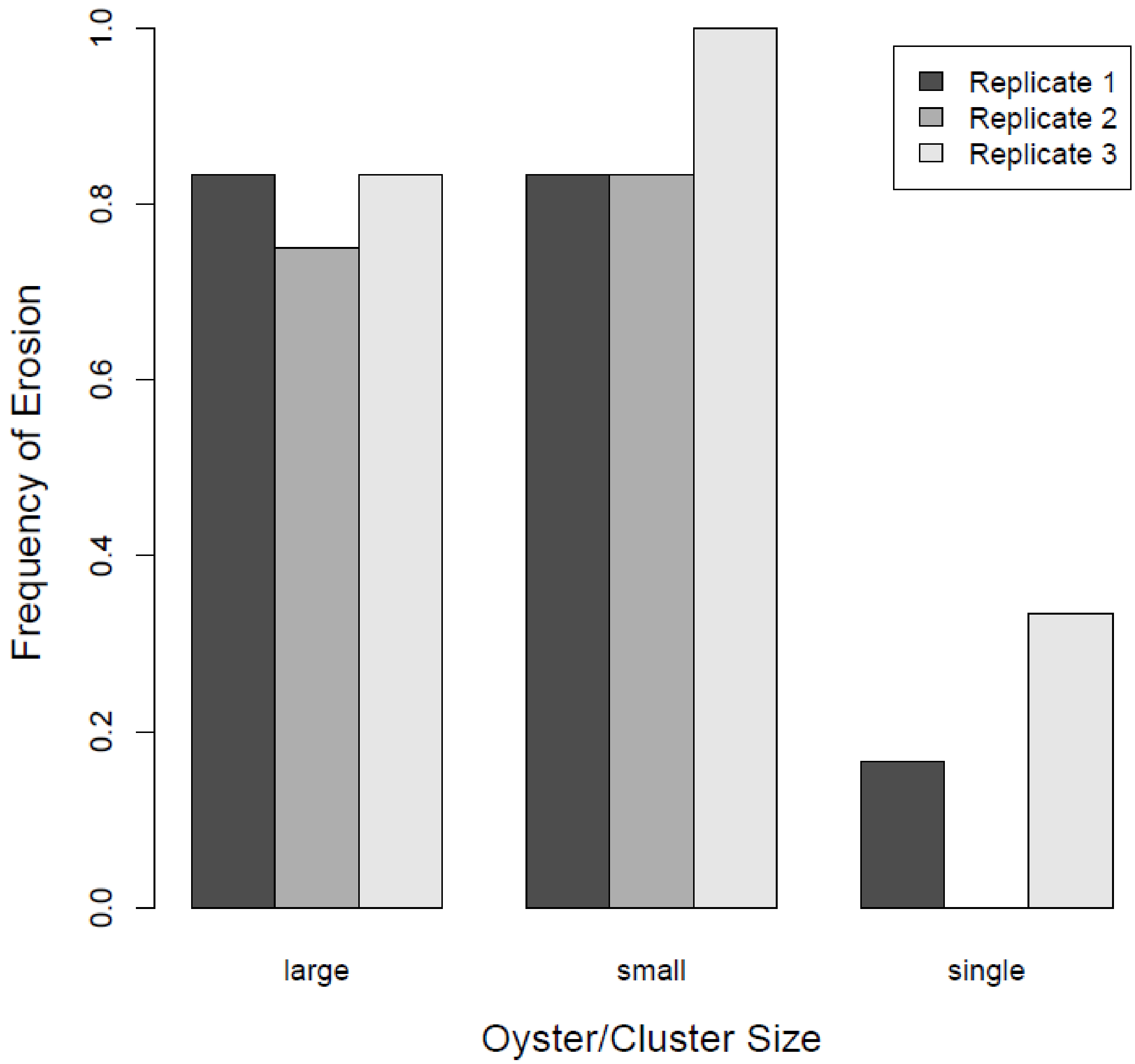

Figure 11: **Frequency of erosion around a single oyster or cluster**. The different color bars indicate replicate trial numbers.

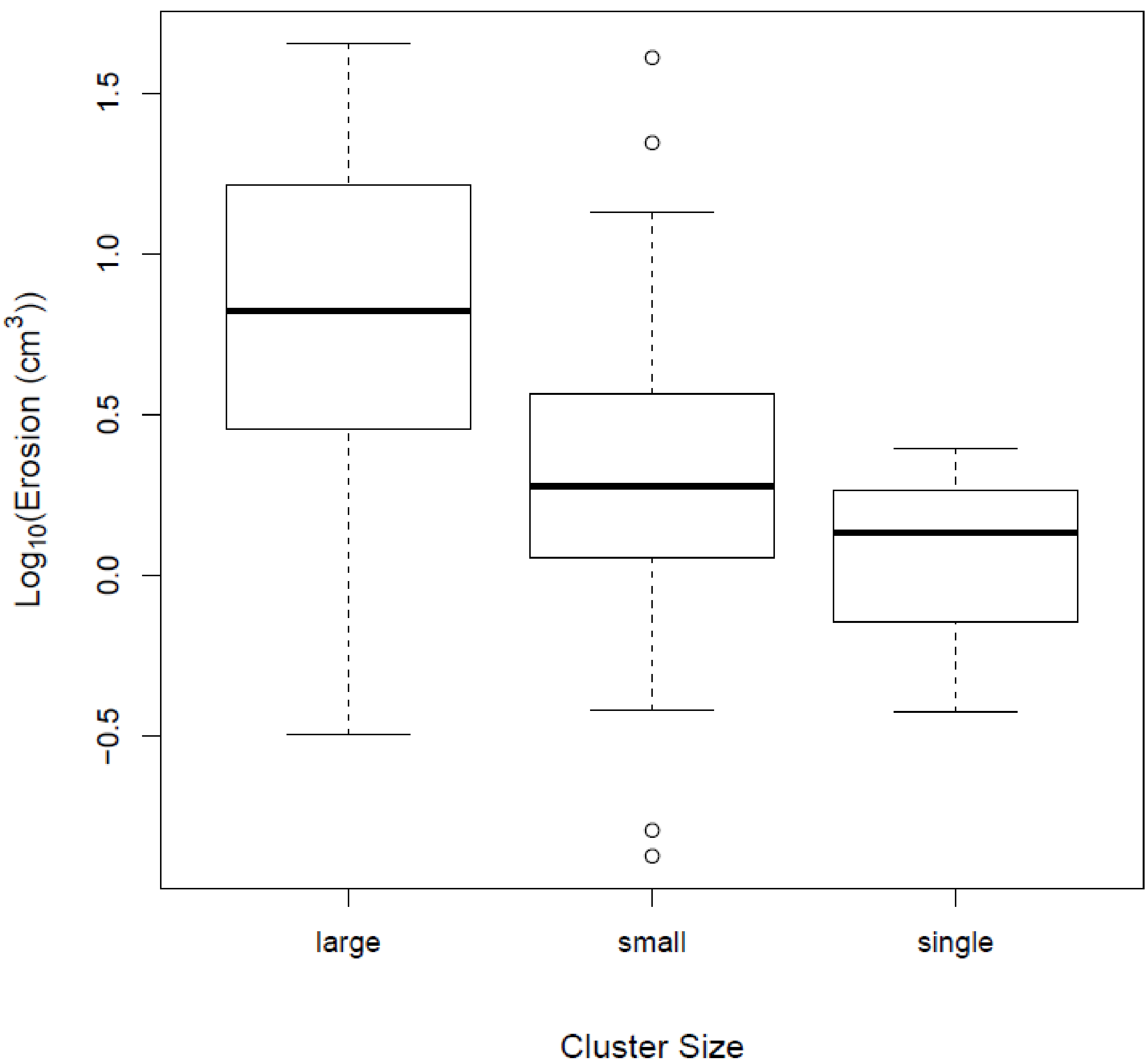

Figure 12: **Three-dimensional area of erosion (cm^3) as a function of oyster/cluster size**. Data are shown only for when erosion occurred (n = 64).

TABLES

Table 1: **Variables considered for controlled boat passes**. Each possible combination of all variables was tested with 5 replicates. Pontoon boats were never tested on plane because pontoon boats do not typically have a planning mode.

Boat Type	Speed (mph)	Distance	Planing
Whaler & Flats	<5	Close	Yes
			No
		Far	Yes
			No
	6 - 15	Close	Yes
			No
		Far	Yes
			No
	16 - 25	Close	Yes
			No
		Far	Yes
			No
Pontoon	<5	Close	No
		Far	No
	6 - 15	Close	No
		Far	No
	16 - 25	Close	No
		Far	No

Table 2: **Variables considered for wave tank trials**. Each combination of these variables was tested in the FIT wave tank with 3 replicates. Single oysters were never buried because single, live oysters are rarely found buried in the sediment on natural oyster reefs. A simulated boat wake consisted of a wave train of 15 waves.

Oyster Type	Burial Depth (cm)	Wake Height (cm)	# Wakes
Single	0	2	1
			3
		4	1
			3
		8	1
			3
Small Cluster or Large Cluster	0	2	1
			3
		4	1
			3
		8	1
			3
	1 - 4	2	1
			3
		4	1
			3
		8	1
			3

Table 3: **Model selection for boat passes**, including all boat types but excluding variable of planing. Model is lm(logH_{max} ~ logBoatSpeed + logDistance + Site). Site was a random effect. AICc of model was 328.48 with an AICc weight of 0.31.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1.92647	0.66936	2.878	0.004832
logBoatSpeed	0.52983	0.17451	3.036	0.003011
logDistance	-0.60231	0.17291	-3.483	0.000719
Site	-0.11523	0.08457	-1.362	0.175911

Table 4: **Model selection for boat passes**, not including pontoon boat but including variable of whether the boat is on plane or not. Model is lm(logH_{max} ~ logBoatSpeed * Planing + logDistance + Site). Site was a random effect. AICc of model was 246.76, with an AICc weight of 0.32.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	1.67296	0.37216	4.495	2.48E-05
clogBoatSpeed	1.97389	0.44493	4.436	3.09E-05
Planing - Yes	-0.61286	0.27916	-2.195	0.03123
clogDistance	-0.54814	0.19703	-2.782	0.00683
Site	-0.17528	0.09953	-1.761	0.0823
clogBoatSpeed : Planing	-1.68496	0.50861	-3.313	0.00142

Table 5: **Model for probability of moving**. Model to determine the probability that an oyster/cluster would move was glm(Probability ~ ClusterSize * DepthBuried + Replicate, family = binomial). Replicate was a random effect. AICc of model was 93.98, with an AICc Weight of 0.25.

	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	0.4764	0.8393	0.568	0.5703
ClusterSize - single	2.0678	1.1461	1.804	0.0712
ClusterSize - small	1.5235	0.9257	1.646	0.0998
DepthBuried	-0.3393	0.1821	-1.863	0.0624
Replicate	0.1477	0.3377	0.437	0.6618
ClusterSize - small :DepthBuried	-0.8691	0.3923	-2.215	0.0268

Table 6: **Model for distance moved**. For the oysters/clusters that did move (n = 57), the best model to determine how far they would move was lm($\log_{10}$Distance Moved ~ WakeHeight + NumberWakes + ClusterSize + Replicate). Replicate was a random effect. The AICc was 99.43, with an AICc weight of 0.07.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	0.58755	0.25201	2.332	0.0237
WaveHeight	0.04825	0.02638	1.829	0.0732
NumberWakes - 3	0.23198	0.14377	1.614	0.1128
ClusterSize - single	0.38128	0.18116	2.105	0.0403
ClusterSize - small	-0.15323	0.1716	-0.893	0.3761
Replicate	-0.06634	0.08784	-0.755	0.4536

Table 7: **Model for probability of erosion occurring**. Model to determine the frequency that an oyster/cluster would have erosion occur around its base was glm(Probability ~ ClusterSize + Replicate, family=binomial). Replicate was a random effect. AIcC of model was 83.08, with an AICc Weight of 0.12.

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**
(Intercept)	0.6686	0.8	0.836	0.403
ClusterSize - single	-3.0959	0.7749	-3.995	6.47E-05
ClusterSize - small	0.6664	0.6814	0.978	0.328
Replicate	0.3919	0.3682	1.065	0.287

Table 8: **Model for erosion**. For the oysters/clusters that did have erosion (n = 64), the best model to determine how far they would move was lm($\log_{10}$Erosion ~ Cluster Size). Replicate was a random effect. The AICc was 109.38, with an AICc weight of 0.18.

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	0.56472	0.19156	2.948	0.00455
ClusterSize - single	-0.74064	0.33066	-2.24	0.02882
ClusterSize - small	-0.46501	0.13941	-3.336	0.00146
Replicate	0.08984	0.08142	1.103	0.27426

Table 9: **Example of recommendations for minimizing erosion/dislodgement of oysters**. These recommendations are minimum distances to travel from a reef (m) based on various speeds of travel, in order to reduce a wake hitting exposed oyster reefs below 2 cm. Distances were derived from the regression equations in Figures 5 – 7. Numbers marked with an "*" indicate scenarios which are unlikely to occur because boats will likely not be planning if travelling 5 mph, or not planning if travelling 20+ mph.

	Not Planing			Planing		
	5 mph	**10 mph**	**20 mph**	**5 mph**	**10 mph**	**20 mph**
Flats & Whaler	20 m	38 m	73 m*	3 m*	6 m	11 m
Pontoon	6.5 m	11 m	20 m	n/a		

APPENDIX: AIC TABLES

AppendixTable 1: AIC Table for Boat Wake Model Selection without Pontoon Boat. Table was generated using AICmodavg package in R (version 3.1.0).

Model	K	AICc	Delta_AICc	AICcWt	Cum.Wt
lnHmax ~ lnBoatSpeed*Planing +lnDistance	6	246.76	0	0.32	0.32
lnHmax ~ lnBoatSpeed*lnDistance +lnBoatSpeed*Planing	7	247.97	1.21	0.18	0.5
lnHmax ~ lnBoatSpeed*Planing +lnDistance*Planing	7	248.76	2	0.12	0.61
lnHmax ~ lnBoatSpeed*Planing +BoatType +lnDistance	7	249.03	2.27	0.1	0.72
lnHmax ~ BoatType*lnBoatSpeed +lnBoatSpeed*Planing +lnDistance	8	249.54	2.78	0.08	0.8
lnHmax ~ lnBoatSpeed*lnDistance +lnBoatSpeed*Planing +BoatType	8	250.29	3.53	0.05	0.85
lnHmax ~ lnBoatSpeed*Planing +lnDistance*Planing +BoatType	8	251.1	4.34	0.04	0.89
lnHmax ~ BoatType*lnDistance +lnBoatSpeed*Planing	8	251.38	4.62	0.03	0.92
lnHmax ~ BoatType*Planing +lnBoatSpeed*Planing +lnDistance	8	251.44	4.68	0.03	0.95
lnHmax ~ lnBoatSpeed*lnDistance	5	254.6	7.84	0.01	0.96
lnHmax ~ lnBoatSpeed +lnDistance	4	254.9	8.14	0.01	0.96
lnHmax ~ lnBoatSpeed*lnDistance +Planing	6	255.7	8.94	0	0.97
lnHmax ~ lnBoatSpeed +lnDistance +Planing	5	256.04	9.28	0	0.97
lnHmax ~ lnBoatSpeed*lnDistance +BoatType	6	256.15	9.39	0	0.97
lnHmax ~ BoatType + lnBoatSpeed +lnDistance	5	256.36	9.6	0	0.98
lnHmax ~ BoatType*lnBoatSpeed +lnDistance	6	256.46	9.7	0	0.98
lnHmax ~ BoatType*lnBoatSpeed +lnBoatSpeed*lnDistance	7	256.46	9.7	0	0.98
lnHmax ~ lnBoatSpeed*lnDistance +lnDistance*Planing	7	256.58	9.82	0	0.98
lnHmax ~ lnBoatSpeed*lnDistance +BoatType +Planing	7	257.48	10.72	0	0.99
lnHmax ~ BoatType*lnBoatSpeed +lnBoatSpeed*lnDistance +Planing	8	257.56	10.8	0	0.99
lnHmax ~ BoatType*lnBoatSpeed +lnDistance +Planing	7	257.59	10.83	0	0.99
lnHmax ~ BoatType +lnBoatSpeed +lnDistance +Planing	6	257.72	10.96	0	0.99
lnHmax ~ lnDistance*Planing +lnBoatSpeed	6	258.36	11.6	0	0.99
lnHmax ~ lnBoatSpeed*lnDistance +lnDistance*Planing +BoatType	8	258.44	11.68	0	0.99
lnHmax ~ BoatType*lnDistance +lnBoatSpeed*lnDistance	7	258.48	11.72	0	0.99
lnHmax ~ BoatType*lnDistance +lnBoatSpeed	6	258.69	11.93	0	0.99
lnHmax ~ BoatType*lnBoatSpeed +BoatType*lnDistance	7	258.85	12.09	0	0.99
lnHmax ~ BoatType*Planing +lnBoatSpeed*lnDistance	8	259.6	12.84	0	0.99
lnHmax ~ BoatType*Planing +lnBoatSpeed +lnDistance	7	259.64	12.88	0	1
lnHmax ~ BoatType*lnDistance +lnBoatSpeed*lnDistance +Planing	8	259.89	13.13	0	1
lnHmax ~ lnDistance	3	259.96	13.2	0	1
lnHmax ~ BoatType*lnBoatSpeed +lnDistance*Planing	8	260.05	13.29	0	1
lnHmax ~ BoatType*lnBoatSpeed +BoatType*lnDistance +Planing	8	260.06	13.3	0	1
lnHmax ~ BoatType*lnBoatSpeed +BoatType*Planing +lnDistance	8	260.06	13.3	0	1
lnHmax ~ lnDistance*Planing +BoatType +lnBoatSpeed	7	260.1	13.34	0	1
lnHmax ~ BoatType*lnDistance +lnBoatSpeed +Planing	7	260.12	13.36	0	1
lnHmax ~ BoatType +lnDistance	4	260.25	13.49	0	1
lnHmax ~ lnBoatSpeed*Planing	5	260.33	13.57	0	1
lnHmax ~ BoatType*lnDistance +BoatType*Planing +lnBoatSpeed	8	262.07	15.31	0	1
lnHmax ~ BoatType*Planing +lnDistance*Planing +lnBoatSpeed	8	262.08	15.32	0	1
lnHmax ~ lnDistance +Planing	4	262.1	15.34	0	1
lnHmax ~ BoatType +lnDistance +Planing	5	262.45	15.69	0	1
lnHmax ~ BoatType*lnDistance	5	262.51	15.75	0	1
lnHmax ~ BoatType*lnDistance +lnDistance*Planing +lnBoatSpeed	8	262.56	15.8	0	1
lnHmax ~ lnBoatSpeed*Planing +BoatType	6	262.59	15.83	0	1
lnHmax ~ BoatType*lnBoatSpeed +lnBoatSpeed*Planing	7	263.24	16.48	0	1
lnHmax ~ BoatType*Planing +lnDistance	6	264.29	17.53	0	1
lnHmax ~ lnDistance*Planing	5	264.37	17.61	0	1
lnHmax ~ BoatType*lnDistance +Planing	6	264.77	18.01	0	1
lnHmax ~ lnDistance*Planing +BoatType	6	264.78	18.02	0	1
lnHmax ~ BoatType*Planing +lnBoatSpeed*Planing	7	264.91	18.15	0	1
lnHmax ~ BoatType*lnDistance +BoatType*Planing	7	266.63	19.87	0	1
lnHmax ~ BoatType*Planing +lnDistance*Planing	7	266.68	19.92	0	1
lnHmax ~ BoatType*lnDistance +lnDistance*Planing	7	267.17	20.41	0	1
lnHmax ~ lnBoatSpeed +Planing	4	270.85	24.09	0	1
lnHmax ~ lnBoatSpeed	3	271.74	24.98	0	1
lnHmax ~ BoatType*lnBoatSpeed +Planing	6	272.55	25.79	0	1
lnHmax ~ BoatType + lnBoatSpeed +Planing	5	272.58	25.82	0	1
lnHmax ~ BoatType +lnBoatSpeed	4	273.16	26.4	0	1
lnHmax ~ BoatType*lnBoatSpeed	5	273.53	26.77	0	1
lnHmax ~ BoatType*Planing +lnBoatSpeed	6	274.45	27.69	0	1
lnHmax ~ BoatType*lnBoatSpeed +BoatType*Planing	7	274.94	28.18	0	1
lnHmax ~ BoatType	3	275.96	29.2	0	1
lnHmax ~ Planing	3	277.56	30.8	0	1
lnHmax ~ BoatType +Planing	4	277.96	31.2	0	1
lnHmax ~ BoatType*Planing	5	279.77	33.01	0	1

AppendixTable 2: AIC Table for Boat Wake Model Selection Including All Boats. Table was generated using AICmodavg package in R (version 3.1.0).

Model	K	AICc	Delta_AICc	AICcWt	Cum.Wt
lnHmax ~ lnBoatSpeed*lnDistance	5	328.33	0	0.33	0.33
lnHmax ~ lnBoatSpeed +lnDistance	4	328.48	0.15	0.31	0.64
lnHmax ~ lnBoatSpeed*lnDistance +BoatType	7	330.72	2.4	0.1	0.75
lnHmax ~ BoatType +lnBoatSpeed +lnDistance	6	330.98	2.65	0.09	0.83
lnHmax ~ BoatType*lnBoatSpeed +lnBoatSpeed*lnDistance	9	332.57	4.24	0.04	0.87
lnHmax ~ BoatType*lnBoatSpeed +lnDistance	8	332.75	4.42	0.04	0.91
lnHmax ~ BoatType*lnDistance +lnBoatSpeed*lnDistance	9	333.11	4.78	0.03	0.94
lnHmax ~ BoatType*lnDistance +lnBoatSpeed	8	333.8	5.48	0.02	0.96
lnHmax ~ lnDistance	3	335.13	6.81	0.01	0.97
lnHmax ~ BoatType*lnBoatSpeed*lnDistance -BoatType:lnDistance:lnBoatSpeed	11	335.34	7.02	0.01	0.98
lnHmax ~ BoatType*lnBoatSpeed +BoatType*lnDistance	10	335.87	7.54	0.01	0.99
lnHmax ~ BoatType +lnDistance	5	336.5	8.18	0.01	1
lnHmax ~ BoatType*lnBoatSpeed*lnDistance	13	339.34	11.01	0	1
lnHmax ~ BoatType*lnDistance	7	339.78	11.45	0	1
lnHmax ~ lnBoatSpeed	3	348.63	20.31	0	1
lnHmax ~ BoatType +lnBoatSpeed	5	351.29	22.97	0	1
lnHmax ~ BoatType*lnBoatSpeed	7	353.49	25.16	0	1
lnHmax ~ BoatType	4	356.39	28.07	0	1

AppendixTable 3: AIC Table for Probability of an Oyster/Cluster Moving Model Selection. Table was generated using AICmodavg package in R (version 3.1.0).

Model	K	AICc	Delta_AICc	AICcWt	Cum.Wt
DMP ~ ClusterSize*DepthBuried	5	93.98	0	0.25	0.25
DMP ~ ClusterSize*DepthBuried +WaveHeight	6	95.69	1.72	0.1	0.35
DMP ~ DepthBuried	2	95.97	1.99	0.09	0.44
DMP ~ ClusterSize*DepthBuried +NumberWaves	6	96.02	2.04	0.09	0.53
DMP ~ WaveHeight +DepthBuried	3	97.41	3.43	0.04	0.58
DMP ~ ClusterSize +DepthBuried	4	97.62	3.64	0.04	0.62
DMP ~ ClusterSize*DepthBuried +WaveHeight +NumberWaves	7	97.78	3.8	0.04	0.65
DMP ~ NumberWaves +DepthBuried	3	97.82	3.85	0.04	0.72
DMP ~ WaveHeight*DepthBuried +ClusterSize*DepthBuried	7	97.82	3.84	0.04	0.69
DMP ~ NumberWaves*DepthBuried +ClusterSize*DepthBuried	7	97.9	3.92	0.03	0.76
DMP ~ WaveHeight*ClusterSize +ClusterSize*DepthBuried	8	98.94	4.96	0.02	0.78
DMP ~ WaveHeight +ClusterSize +DepthBuried	5	99.11	5.13	0.02	0.8
DMP ~ NumberWaves*ClusterSize +ClusterSize*DepthBuried	8	99.26	5.28	0.02	0.82
DMP ~ WaveHeight +NumberWaves +DepthBuried	4	99.29	5.31	0.02	0.83
DMP ~ WaveHeight*DepthBuried	4	99.32	5.35	0.02	0.85
DMP ~ NumberWaves +ClusterSize +DepthBuried	5	99.61	5.63	0.01	0.87
DMP ~ NumberWaves*DepthBuried +ClusterSize*DepthBuried +WaveHeight	8	99.66	5.68	0.01	0.88
DMP ~ NumberWaves*DepthBuried	4	99.78	5.81	0.01	0.89
DMP ~ WaveHeight*DepthBuried +ClusterSize*DepthBuried +NumberWaves	8	99.93	5.95	0.01	0.91
DMP ~ WaveHeight*NumberWaves +ClusterSize*DepthBuried	8	100.17	6.2	0.01	0.92
DMP ~ WaveHeight*DepthBuried +ClusterSize	6	101.11	7.13	0.01	0.92
DMP ~ WaveHeight +NumberWaves +ClusterSize +DepthBuried	6	101.13	7.15	0.01	0.93
DMP ~ NumberWaves*ClusterSize +ClusterSize*DepthBuried +WaveHeight	9	101.16	7.18	0.01	0.94
DMP ~ WaveHeight*ClusterSize +ClusterSize*DepthBuried +NumberWaves	9	101.17	7.19	0.01	0.94
DMP ~ WaveHeight*DepthBuried +NumberWaves	5	101.22	7.24	0.01	0.95
DMP ~ NumberWaves*DepthBuried +WaveHeight	5	101.25	7.27	0.01	0.96
DMP ~ WaveHeight*NumberWaves +DepthBuried	5	101.49	7.51	0.01	0.96
DMP ~ NumberWaves*DepthBuried +ClusterSize	6	101.62	7.64	0.01	0.97
DMP ~ WaveHeight*ClusterSize +DepthBuried	7	102.44	8.46	0	0.97
DMP ~ NumberWaves*ClusterSize +DepthBuried	7	102.55	8.57	0	0.98
DMP ~ NumberWaves*DepthBuried +WaveHeight +ClusterSize	7	103.13	9.15	0	0.98
DMP ~ WaveHeight*DepthBuried +NumberWaves +ClusterSize	7	103.14	9.16	0	0.98
DMP ~ WaveHeight*DepthBuried +NumberWaves*DepthBuried	6	103.26	9.28	0	0.98
DMP ~ WaveHeight*NumberWaves +ClusterSize +DepthBuried	7	103.42	9.44	0	0.99
DMP ~ WaveHeight*NumberWaves +WaveHeight*DepthBuried	6	103.5	9.52	0	0.99
DMP ~ WaveHeight*NumberWaves +NumberWaves*DepthBuried	6	103.51	9.53	0	0.99
DMP ~ NumberWaves*ClusterSize +WaveHeight +DepthBuried	8	104.21	10.23	0	0.99
DMP ~ WaveHeight*ClusterSize +NumberWaves +DepthBuried	8	104.59	10.61	0	0.99
DMP ~ WaveHeight*ClusterSize +WaveHeight*DepthBuried	8	104.62	10.64	0	0.99
DMP ~ NumberWaves*ClusterSize +NumberWaves*DepthBuried	8	104.81	10.83	0	0.99
DMP ~ WaveHeight*DepthBuried +NumberWaves*DepthBuried +ClusterSize	8	105.23	11.26	0	1
DMP ~ WaveHeight*NumberWaves +NumberWaves*DepthBuried +ClusterSize	8	105.49	11.51	0	1
DMP ~ WaveHeight*NumberWaves +WaveHeight*DepthBuried +ClusterSize	8	105.53	11.55	0	1
DMP ~ WaveHeight*DepthBuried +NumberWaves*ClusterSize	9	106.36	12.39	0	1
DMP ~ NumberWaves*ClusterSize +NumberWaves*DepthBuried +WaveHeight	9	106.48	12.51	0	1
DMP ~ WaveHeight*NumberWaves +NumberWaves*ClusterSize +DepthBuried	9	106.63	12.66	0	1
DMP ~ WaveHeight*ClusterSize +NumberWaves*DepthBuried	9	106.74	12.76	0	1
DMP ~ WaveHeight*ClusterSize +WaveHeight*DepthBuried +NumberWaves	9	106.78	12.8	0	1
DMP ~ WaveHeight*NumberWaves +WaveHeight*ClusterSize +DepthBuried	9	106.99	13.01	0	1
DMP ~ WaveHeight*ClusterSize +NumberWaves*ClusterSize +DepthBuried	10	107.73	13.75	0	1
DMP ~ ClusterSize	3	112.7	18.72	0	1
DMP ~ WaveHeight +ClusterSize	4	113.79	19.81	0	1
DMP ~ NumberWaves +ClusterSize	4	114.84	20.86	0	1
DMP ~ WaveHeight +NumberWaves +ClusterSize	5	115.97	21.99	0	1
DMP ~ WaveHeight*ClusterSize	6	117.39	23.41	0	1
DMP ~ NumberWaves*ClusterSize	6	117.76	23.79	0	1
DMP ~ WaveHeight*NumberWaves +ClusterSize	6	118.04	24.06	0	1
DMP ~ NumberWaves*ClusterSize +WaveHeight	7	119.03	25.05	0	1
DMP ~ WaveHeight*ClusterSize +NumberWaves	7	119.69	25.71	0	1
DMP ~ WaveHeight*NumberWaves +NumberWaves*ClusterSize	8	121.24	27.26	0	1
DMP ~ WaveHeight	2	121.31	27.34	0	1
DMP ~ WaveHeight*NumberWaves +WaveHeight*ClusterSize	8	121.83	27.85	0	1
DMP ~ NumberWaves	2	122.38	28.4	0	1
DMP ~ WaveHeight*ClusterSize +NumberWaves*ClusterSize	9	122.81	28.83	0	1
DMP ~ WaveHeight +NumberWaves	3	123.4	29.42	0	1
DMP ~ WaveHeight*NumberWaves	4	125.34	31.36	0	1

AppendixTable 4: AIC Table for Distance Moved Model Selection. Table was generated using AICmodavg package in R (version 3.1.0)

Model	K	AICc	Delta_AICc	AICcWt	Cum.Wt
Log10DM ~ WaveHeight +NumberWaves +ClusterSize	6	99.43	0	0.07	0.07
Log10DM ~ WaveHeight +ClusterSize	5	99.89	0.46	0.05	0.12
Log10DM ~ NumberWaves +ClusterSize	5	100.08	0.64	0.05	0.21
Log10DM ~ WaveHeight*ClusterSize +NumberWaves	8	100.08	0.64	0.05	0.16
Log10DM ~ ClusterSize*DepthBuried +NumberWaves	7	100.08	0.65	0.05	0.26
Log10DM ~ NumberWave *ClusterSize +WaveHeight	8	100.27	0.84	0.04	0.3
Log10DM ~ ClusterSize*DepthBuried +WaveHeight +NumberWaves	8	100.35	0.92	0.04	0.34
Log10DM ~ NumberWaves*ClusterSize +ClusterSize*DepthBuried	9	100.6	1.16	0.04	0.38
Log10DM ~ ClusterSize*DepthBuried +WaveHeight	7	100.69	1.26	0.03	0.42
Log10DM ~ NumberWaves*ClusterSize	7	100.72	1.29	0.03	0.45
Log10DM ~ ClusterSize*DepthBuried	6	100.79	1.35	0.03	0.48
Log10DM ~ WaveHeight*ClusterSize	7	100.8	1.36	0.03	0.52
Log10DM ~ ClusterSize	4	100.91	1.47	0.03	0.55
Log10DM ~ WaveHeight*DepthBuried +ClusterSize*DepthBuried	8	100.96	1.53	0.03	0.58
Log10DM ~ WaveHeight*ClusterSize +NumberWaves*ClusterSize	10	101.09	1.66	0.03	0.61
Log10DM ~ NumberWaves*ClusterSize +ClusterSize*DepthBuried +WaveHeight	10	101.12	1.69	0.03	0.63
Log10DM ~ WaveHeight*DepthBuried +ClusterSize*DepthBuried +NumberWaves	9	101.2	1.77	0.03	0.66
Log10DM ~ WaveHeight*NumberWaves +ClusterSize	7	101.41	1.98	0.02	0.69
Log10DM ~ WaveHeight*ClusterSize +ClusterSize*DepthBuried +NumberWaves	10	101.49	2.06	0.02	0.71
Log10DM ~ WaveHeight*NumberWaves +WaveHeight*ClusterSize	9	101.82	2.39	0.02	0.73
Log10DM ~ WaveHeight +NumberWaves +ClusterSize +DepthBuried	7	101.93	2.5	0.02	0.75
Log10DM ~ WaveHeight*ClusterSize +ClusterSize*DepthBuried	9	102.04	2.61	0.02	0.77
Log10DM ~ WaveHeight +ClusterSize +DepthBuried	6	102.32	2.89	0.02	0.78
Log10DM ~ WaveHeight*NumberWaves +NumberWaves*ClusterSize	9	102.36	2.93	0.02	0.8
Log10DM ~ NumberWaves +ClusterSize +DepthBuried	6	102.41	2.97	0.01	0.81
Log10DM ~ WaveHeight*NumberWaves +ClusterSize*DepthBuried	9	102.45	3.02	0.01	0.82
Log10DM ~ NumberWaves*DepthBuried +ClusterSize*DepthBuried	8	102.57	3.14	0.01	0.84
Log10DM ~ WaveHeight*ClusterSize +NumberWaves +DepthBuried	9	102.88	3.45	0.01	0.85
Log10DM ~ NumberWaves*ClusterSize +WaveHeight +DepthBuried	9	102.97	3.54	0.01	0.86
Log10DM ~ NumberWaves*DepthBuried +ClusterSize*DepthBuried +WaveHeight	9	103.08	3.64	0.01	0.87
Log10DM ~ ClusterSize +DepthBuried	5	103.18	3.75	0.01	0.88
Log10DM ~ NumberWaves*ClusterSize +DepthBuried	8	103.23	3.79	0.01	0.89
Log10DM ~ WaveHeight*ClusterSize +DepthBuried	8	103.5	4.06	0.01	0.9
Log10DM ~ WaveHeight*NumberWaves +ClusterSize +DepthBuried	8	103.95	4.52	0.01	0.91
Log10DM ~ WaveHeight*DepthBuried +NumberWaves +ClusterSize	8	104.06	4.63	0.01	0.91
Log10DM ~ WaveHeight*DepthBuried +ClusterSize	7	104.08	4.64	0.01	0.92
Log10DM ~ WaveHeight*ClusterSize +NumberWaves*ClusterSize +DepthBuried	11	104.14	4.71	0.01	0.93
Log10DM ~ WaveHeight	3	104.26	4.83	0.01	0.93
Log10DM ~ WaveHeight +NumberWaves	4	104.41	4.98	0.01	0.94
Log10DM ~ NumberWaves*DepthBuried +WaveHeight +ClusterSize	8	104.49	5.06	0.01	0.94
Log10DM ~ NumberWaves*DepthBuried +ClusterSize	7	104.69	5.26	0	0.95
Log10DM ~ WaveHeight*NumberWaves + WaveHeight*ClusterSize +DepthBuried	10	104.7	5.27	0	0.95
Log10DM ~ NumberWaves	3	104.85	5.41	0	0.96
Log10DM ~ WaveHeight*NumberWaves + NumberWaves*ClusterSize +DepthBuried	10	105.1	5.67	0	0.96
Log10DM ~ WaveHeight*DepthBuried +NumberWaves*ClusterSize	10	105.19	5.76	0	0.96
Log10DM ~ WaveHeight*ClusterSize +NumberWaves*DepthBuried	10	105.55	6.12	0	0.97
Log10DM ~ WaveHeight +DepthBuried	4	105.7	6.27	0	0.97
Log10DM ~ WaveHeight*ClusterSize +WaveHeight*DepthBuried +NumberWaves	10	105.83	6.4	0	0.97
Log10DM ~ WaveHeight +NumberWaves +DepthBuried	5	105.84	6.4	0	0.98
Log10DM ~ NumberWaves*ClusterSize +NumberWaves*DepthBuried +WaveHeight	10	105.92	6.49	0	0.98
Log10DM ~ NumberWaves*ClusterSize +NumberWaves*DepthBuried	9	105.98	6.55	0	0.98
Log10DM ~ NumberWaves +DepthBuried	4	106.09	6.66	0	0.98
Log10DM ~ WaveHeight*NumberWaves + WaveHeight*DepthBuried +ClusterSize	9	106.23	6.79	0	0.98
Log10DM ~ WaveHeight*ClusterSize +WaveHeight*DepthBuried	9	106.29	6.86	0	0.99
Log10DM ~ DepthBuried	3	106.3	6.87	0	0.99
Log10DM ~ WaveHeight*NumberWaves	5	106.41	6.97	0	0.99
Log10DM ~ WaveHeight*DepthBuried +NumberWaves*DepthBuried +ClusterSize	9	106.56	7.13	0	0.99
Log10DM ~ WaveHeight*NumberWaves + NumberWaves*DepthBuried +ClusterSize	9	106.59	7.15	0	0.99
Log10DM ~ WaveHeight*DepthBuried	5	107.67	8.24	0	1
Log10DM ~ WaveHeight*NumberWaves +DepthBuried	6	107.78	8.34	0	1
Log10DM ~ WaveHeight*DepthBuried +NumberWaves	6	108.08	8.65	0	1
Log10DM ~ NumberWaves*DepthBuried +WaveHeight	6	108.2	8.77	0	1
Log10DM ~ NumberWaves*DepthBuried	5	108.22	8.79	0	1
Log10DM ~ WaveHeight*NumberWaves +WaveHeight*DepthBuried	7	110.15	10.72	0	1
Log10DM ~ WaveHeight*NumberWaves +NumberWaves*DepthBuried	7	110.21	10.78	0	1
Log10DM ~ WaveHeight*DepthBuried +NumberWaves*DepthBuried	7	110.45	11.02	0	1

AppendixTable 5: AIC Table for Probability of Erosion Occuring Model Selection. Table was generated using AICmodavg package in R (version 3.1.0).

Model	K	AICc	Delta_AICc	AICcWt	Cum.Wt
EP ~WaveHeight*NumberWaves +WaveHeight*DepthBuried +ClusterSize	8	82.61	0	0.15	0.15
EP ~ClusterSize	3	83.08	0.47	0.12	0.27
EP ~NumberWaves +ClusterSize	4	83.89	1.28	0.08	0.34
EP ~WaveHeight*NumberWaves +ClusterSize	6	84.16	1.55	0.07	0.41
EP ~WaveHeight*DepthBuried +ClusterSize	6	84.66	2.04	0.05	0.47
EP ~NumberWaves*DepthBuried +ClusterSize	6	84.92	2.31	0.05	0.51
EP ~WaveHeight +ClusterSize	4	85.03	2.41	0.04	0.56
EP ~WaveHeight*DepthBuried +NumberWaves*DepthBuried +ClusterSize	8	85.06	2.45	0.04	0.6
EP ~ClusterSize +DepthBuried	4	85.27	2.66	0.04	0.64
EP ~WaveHeight*DepthBuried +NumberWaves +ClusterSize	7	85.32	2.7	0.04	0.68
EP ~WaveHeight +NumberWaves +ClusterSize	5	85.89	3.28	0.03	0.71
EP ~NumberWaves +ClusterSize +DepthBuried	5	86.13	3.52	0.03	0.73
EP ~WaveHeight*NumberWaves +NumberWaves*DepthBuried +ClusterSize	8	86.17	3.56	0.03	0.76
EP ~WaveHeight*NumberWaves +ClusterSize +DepthBuried	7	86.5	3.89	0.02	0.78
EP ~WaveHeight*DepthBuried +ClusterSize*DepthBuried	7	86.56	3.95	0.02	0.8
EP ~NumberWaves*DepthBuried +ClusterSize*DepthBuried	7	86.89	4.28	0.02	0.82
EP ~ClusterSize*DepthBuried	5	87.14	4.52	0.02	0.83
EP ~NumberWaves*DepthBuried +WaveHeight +ClusterSize	7	87.14	4.53	0.02	0.85
EP ~WaveHeight*DepthBuried +ClusterSize*DepthBuried +NumberWaves	8	87.25	4.63	0.01	0.86
EP ~WaveHeight +ClusterSize +DepthBuried	5	87.27	4.66	0.01	0.88
EP ~ClusterSize*DepthBuried +NumberWaves	6	88.03	5.41	0.01	0.89
EP ~WaveHeight*ClusterSize +WaveHeight*DepthBuried	8	88.05	5.44	0.01	0.9
EP ~NumberWaves*ClusterSize	6	88.06	5.45	0.01	0.91
EP ~WaveHeight +NumberWaves +ClusterSize +DepthBuried	6	88.19	5.57	0.01	0.91
EP ~WaveHeight*NumberWaves +WaveHeight*ClusterSize	8	88.34	5.72	0.01	0.92
EP ~WaveHeight*NumberWaves +NumberWaves*ClusterSize	8	88.53	5.91	0.01	0.93
EP ~WaveHeight*NumberWaves +ClusterSize*DepthBuried	8	88.61	6	0.01	0.94
EP ~NumberWaves*ClusterSize +NumberWaves*DepthBuried	8	88.87	6.26	0.01	0.94
EP ~WaveHeight*ClusterSize +WaveHeight*DepthBuried +NumberWaves	9	88.87	6.26	0.01	0.95
EP ~NumberWaves*DepthBuried +ClusterSize*DepthBuried +WaveHeight	8	89.17	6.56	0.01	0.96
EP ~WaveHeight*ClusterSize	6	89.19	6.58	0.01	0.96
EP ~ClusterSize*DepthBuried +WaveHeight	6	89.21	6.59	0.01	0.97
EP ~WaveHeight*DepthBuried +NumberWaves*ClusterSize	9	89.77	7.15	0	0.97
EP ~ClusterSize*DepthBuried +WaveHeight +NumberWaves	7	90.15	7.54	0	0.98
EP ~NumberWaves*ClusterSize +WaveHeight	7	90.19	7.58	0	0.98
EP ~WaveHeight*ClusterSize +NumberWaves	7	90.2	7.59	0	0.98
EP ~NumberWaves*ClusterSize +DepthBuried	7	90.41	7.8	0	0.99
EP ~WaveHeight*NumberWaves +WaveHeight*ClusterSize +DepthBuried	9	90.79	8.17	0	0.99
EP ~WaveHeight*NumberWaves +NumberWaves*ClusterSize +DepthBuried	9	90.99	8.37	0	0.99
EP ~NumberWaves*ClusterSize +NumberWaves*DepthBuried +WaveHeight	9	91.23	8.61	0	0.99
EP ~WaveHeight*ClusterSize +DepthBuried	7	91.54	8.93	0	0.99
EP ~WaveHeight*ClusterSize +NumberWaves*DepthBuried	9	91.69	9.07	0	1
EP ~NumberWaves*ClusterSize +ClusterSize*DepthBuried	8	92.45	9.84	0	1
EP ~WaveHeight*ClusterSize +NumberWaves +DepthBuried	8	92.61	10	0	1
EP ~NumberWaves*ClusterSize +WaveHeight +DepthBuried	8	92.61	9.99	0	1
EP ~WaveHeight*ClusterSize +ClusterSize*DepthBuried	8	93.65	11.03	0	1
EP ~NumberWaves*ClusterSize +ClusterSize*DepthBuried +WaveHeight	9	94.71	12.09	0	1
EP ~WaveHeight*ClusterSize +NumberWaves*ClusterSize	9	94.73	12.12	0	1
EP ~WaveHeight*ClusterSize +ClusterSize*DepthBuried +NumberWaves	9	94.73	12.12	0	1
EP ~WaveHeight*ClusterSize +NumberWaves*ClusterSize +DepthBuried	10	97.26	14.65	0	1
EP ~WaveHeight*DepthBuried	4	106.45	23.83	0	1
EP ~WaveHeight*NumberWaves +WaveHeight*DepthBuried	6	106.81	24.2	0	1
EP ~WaveHeight*DepthBuried +NumberWaves	5	107.5	24.88	0	1
EP ~DepthBuried	2	107.52	24.91	0	1
EP ~WaveHeight*DepthBuried +NumberWaves*DepthBuried	6	108.55	25.94	0	1
EP ~NumberWaves +DepthBuried	3	108.59	25.98	0	1
EP ~NumberWaves*DepthBuried	4	109.14	26.53	0	1
EP ~WaveHeight +DepthBuried	3	109.45	26.83	0	1
EP ~WaveHeight*NumberWaves +DepthBuried	5	110.18	27.56	0	1
EP ~WaveHeight +NumberWaves +DepthBuried	4	110.6	27.98	0	1
EP ~WaveHeight*NumberWaves +NumberWaves*DepthBuried	6	111.12	28.5	0	1
EP ~NumberWaves*DepthBuried +WaveHeight	5	111.24	28.63	0	1
EP ~NumberWaves	2	111.48	28.86	0	1
EP ~WaveHeight	2	112.24	29.63	0	1
EP ~WaveHeight*NumberWaves	4	113.5	30.88	0	1
EP ~WaveHeight +NumberWaves	3	113.52	30.91	0	1

AppendixTable 6: AIC Table for Erosion Model Selection. Table was generated using AICmodavg package in R (version 3.1.0).

Model	K	AICc	Delta_AICc	AICcWt	Cum.Wt
Log10E ~ClusterSize	4	109.38	0	0.18	0.18
Log10E ~WaveHeight +ClusterSize	5	109.81	0.42	0.14	0.32
Log10E ~NumberWaves +ClusterSize	5	110.27	0.88	0.11	0.43
Log10E ~WaveHeight +NumberWaves +ClusterSize	6	111.08	1.7	0.08	0.5
Log10E ~ClusterSize +DepthBuried	5	111.56	2.18	0.06	0.56
Log10E ~WaveHeight +ClusterSize +DepthBuried	6	112	2.62	0.05	0.61
Log10E ~NumberWaves +ClusterSize +DepthBuried	6	112.64	3.26	0.03	0.65
Log10E ~WaveHeight*ClusterSize	7	112.82	3.44	0.03	0.68
Log10E ~NumberWaves*ClusterSize	7	113.09	3.7	0.03	0.7
Log10E ~ClusterSize*DepthBuried	6	113.15	3.77	0.03	0.73
Log10E ~WaveHeight*NumberWaves +ClusterSize	7	113.47	4.08	0.02	0.75
Log10E ~WaveHeight +NumberWaves +ClusterSize +DepthBuried	7	113.5	4.11	0.02	0.78
Log10E ~ClusterSize*DepthBuried +WaveHeight	7	113.64	4.25	0.02	0.8
Log10E ~WaveHeight*DepthBuried +ClusterSize	7	114.06	4.67	0.02	0.81
Log10E ~NumberWaves*ClusterSize +WaveHeight	8	114.1	4.71	0.02	0.83
Log10E ~WaveHeight*ClusterSize +NumberWaves	8	114.29	4.91	0.02	0.85
Log10E ~ClusterSize*DepthBuried +NumberWaves	7	114.37	4.98	0.01	0.86
Log10E ~NumberWaves*DepthBuried +ClusterSize	7	114.77	5.38	0.01	0.87
Log10E ~WaveHeight*ClusterSize +DepthBuried	8	115.18	5.8	0.01	0.88
Log10E ~ClusterSize*DepthBuried +WaveHeight +NumberWaves	8	115.27	5.88	0.01	0.89
Log10E ~WaveHeight*DepthBuried +ClusterSize*DepthBuried	8	115.59	6.21	0.01	0.9
Log10E ~NumberWaves*ClusterSize +DepthBuried	8	115.68	6.3	0.01	0.91
Log10E ~WaveHeight*DepthBuried +NumberWaves +ClusterSize	8	115.78	6.4	0.01	0.91
Log10E ~NumberWaves*DepthBuried +WaveHeight +ClusterSize	8	115.86	6.48	0.01	0.92
Log10E ~WaveHeight*NumberWaves +ClusterSize +DepthBuried	8	115.94	6.55	0.01	0.93
Log10E ~NumberWaves*DepthBuried +ClusterSize*DepthBuried	8	116.48	7.1	0.01	0.93
Log10E ~WaveHeight*NumberWaves +NumberWaves*ClusterSize	9	116.73	7.34	0	0.94
Log10E ~NumberWaves*ClusterSize +WaveHeight +DepthBuried	9	116.76	7.38	0	0.94
Log10E ~WaveHeight*ClusterSize +NumberWaves +DepthBuried	9	116.89	7.5	0	0.95
Log10E ~WaveHeight*NumberWaves +WaveHeight*ClusterSize	9	116.98	7.6	0	0.95
Log10E ~WaveHeight*ClusterSize +ClusterSize*DepthBuried	9	116.98	7.6	0	0.95
Log10E ~WaveHeight*ClusterSize +WaveHeight*DepthBuried	9	117.03	7.64	0	0.96
Log10E ~NumberWaves*ClusterSize +NumberWaves*DepthBuried	9	117.42	8.04	0	0.96
Log10E ~WaveHeight*DepthBuried +ClusterSize*DepthBuried +NumberWaves	9	117.49	8.1	0	0.96
Log10E ~WaveHeight*ClusterSize +NumberWaves*ClusterSize	10	117.57	8.19	0	0.97
Log10E ~NumberWaves*DepthBuried +ClusterSize*DepthBuried +WaveHeight	9	117.65	8.26	0	0.97
Log10E ~WaveHeight*NumberWaves +ClusterSize*DepthBuried	9	117.82	8.44	0	0.97
Log10E ~NumberWaves*ClusterSize +ClusterSize*DepthBuried	9	117.89	8.51	0	0.97
Log10E ~WaveHeight*NumberWaves +WaveHeight*DepthBuried +ClusterSize	9	118.16	8.78	0	0.98
Log10E ~WaveHeight*DepthBuried +NumberWaves*DepthBuried +ClusterSize	9	118.27	8.89	0	0.98
Log10E ~WaveHeight	3	118.32	8.94	0	0.98
Log10E ~WaveHeight*NumberWaves +NumberWaves*DepthBuried +ClusterSize	9	118.42	9.04	0	0.98
Log10E ~NumberWaves	3	118.49	9.11	0	0.98
Log10E ~WaveHeight*ClusterSize +ClusterSize*DepthBuried +NumberWaves	10	118.83	9.45	0	0.99
Log10E ~NumberWaves*ClusterSize +NumberWaves*DepthBuried +WaveHeight	10	118.86	9.48	0	0.99
Log10E ~NumberWaves*ClusterSize +ClusterSize*DepthBuried +WaveHeight	10	119.03	9.65	0	0.99
Log10E ~WaveHeight*ClusterSize +WaveHeight*DepthBuried +NumberWaves	10	119.04	9.66	0	0.99
Log10E ~WaveHeight*DepthBuried +NumberWaves*ClusterSize	10	119.23	9.85	0	0.99
Log10E ~DepthBuried	3	119.29	9.91	0	0.99
Log10E ~WaveHeight*ClusterSize +NumberWaves*DepthBuried	10	119.47	10.09	0	0.99
Log10E ~WaveHeight*NumberWaves +NumberWaves*ClusterSize +DepthBuried	10	119.47	10.09	0	0.99
Log10E ~WaveHeight*NumberWaves +WaveHeight*ClusterSize +DepthBuried	10	119.65	10.27	0	1
Log10E ~WaveHeight +NumberWaves	4	119.85	10.47	0	1
Log10E ~WaveHeight*ClusterSize +NumberWaves*ClusterSize +DepthBuried	11	120.44	11.06	0	1
Log10E ~NumberWaves +DepthBuried	4	120.46	11.08	0	1
Log10E ~WaveHeight +DepthBuried	4	120.47	11.09	0	1
Log10E ~WaveHeight +NumberWaves +DepthBuried	5	121.95	12.56	0	1
Log10E ~WaveHeight*NumberWaves	5	122.14	12.76	0	1
Log10E ~NumberWaves*DepthBuried	5	122.42	13.04	0	1
Log10E ~WaveHeight*DepthBuried	5	122.58	13.2	0	1
Log10E ~NumberWaves*DepthBuried +WaveHeight	6	124.1	14.72	0	1
Log10E ~WaveHeight*DepthBuried +NumberWaves	6	124.23	14.85	0	1
Log10E ~WaveHeight*NumberWaves +DepthBuried	6	124.35	14.96	0	1
Log10E ~WaveHeight*DepthBuried +NumberWaves*DepthBuried	7	126.49	17.11	0	1
Log10E ~WaveHeight*NumberWaves +NumberWaves*DepthBuried	7	126.6	17.22	0	1
Log10E ~WaveHeight*NumberWaves +WaveHeight*DepthBuried	7	126.67	17.28	0	1

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