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# Monterey Bay giant kelp forests and their potential to mitigate the impacts of climate change on local marine ecosystems

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## ABSTRACT

Unsustainable human activity poses a threat to oceanic health. Climate change, ocean acidification, ocean warming, and pollution interfere with aquatic communities and endanger marine life. Understanding the consequences of these threats will inform future endeavors in preservation and regeneration. While substantial research addresses seagrass' impacts on aquatic ecosystems, little is known about how kelp responds to these anthropogenic impacts. This study sought to assess the contributions of giant kelp forests (Macrocystis pyrifera) in Monterey Bay to the stability and health of the surrounding ecosystem. To achieve this, we conducted a longitudinal study measuring temperature, pH, dissolved oxygen (DO), and nutrient levels at multiple depths at sites along the kelp forest axis in two kelp forests. There was an observable trend across the surface samples, with higher pH and DO levels and lower nutrient levels in the center of the forest than on the edge and outside. Additionally, the pH and DO levels were elevated at the surface compared to those at depth, regardless of location along the kelp axis. The improved water quality within the kelp forests indicates a crucial role for kelp in regulating ocean chemistry and ecosystem balance, specifically in the bay in which the kelp forests reside.

**Keywords:** Kelp forest; Macrocystis pyrifera; climate change; ocean acidification; ecosystem; water physiochemistry

## INTRODUCTION

Climate change has several contributing factors, among the most pronounced being anthropogenic greenhouse gas emissions, which have been found to negatively impact the chemistry and habitability of the ocean (Doney *et al.* 2009). In recent decades, kelp forests and seagrasses have been proposed as a solution for the oceanic repercussions of climate change and pollution (Akinnawo, 2023;

Adelsman and Binder, 2012; Delille *et al.* 2009; Cooley *et al*. 2016). This results from their ability to absorb $CO_2$ and emit $O_2$ as a product during photosynthesis, which reduces ocean acidification (OA) and deoxygenation. In kelp forests, productivity is extremely high (Reed *et al*., 2008; Zimmerman and Kremer, 1986; Towle and Pearse, 1973), so this process occurs rapidly on a large scale, making it more fit to combat anthropogenic changes in oceanic biogeochemistry.

OA is associated with the continuously rising levels of atmospheric $CO_2$ observed since the industrial age. The ocean absorbs approximately 28% of anthropogenic greenhouse gases (Gattuso *et al*. 2015), among them $CO_2$, which is the primary contributor to global OA (Jiang *et al*. 2019; Doney *et al.* 2009). When $CO_2$ dissolves into the ocean, it reacts with water to form carbonic acid ($H_2CO_3$). $H_2CO_3$ subsequently dissociates by losing $H^+$ ions and becoming bicarbonate ($HCO_3^-$), increasing $H^+$ ion concentration and thus acidity within the ocean (Doney *et al.* 2009; Mostofa *et al*. 2016). In the past 250 years, atmospheric $CO_2$ content has increased by 50% (Jain, 2022). As a result, the average surface pH of the global ocean has decreased by a minimum of 0.1 in that same period, and it is expected to decrease by 0.33 more by the year 2100, diminishing the ocean's buffer capacity by an average of 34% (Jiang *et al.* 2019; Doney *et al.* 2012). One of the more urgent concerns associated with OA is its negative impact on calcifying organisms, such as starfish, sea urchins, corals, and shellfish. The lower oceanic pH decreases the saturation state of aragonite, inhibiting calcifying organisms from developing their shells and exoskeletons and impeding their growth and survival (Clark, 2020). The repercussions of the reduced biomass of calcifiers are not confined to the trophic levels they occupy; rather, the impact extends throughout the food web, disrupting the structure of entire communities and compromising ecosystem stability (Peck *et al.* 2015). While OA can occur as a consequence of natural events on a localized scale, the relatively significant decrease in average global oceanic pH in recent decades is linked to the anthropogenic increase in atmospheric $CO_2$. As such, in this paper, OA will refer to the anthropogenic decrease in average oceanic pH, both on a local and global scale.

Ocean deoxygenation is another product of climate change, driven by warming ocean temperatures, stratification, and altered circulation (Limburg *et al*. 2020; Oschlies *et al*. 2018). The ocean absorbs approximately 93% of the heat trapped by rising greenhouse gases (Gattuso *et al.* 2015). As water temperature increases, its capacity to hold dissolved gases decreases. In this paper, deoxygenation will refer to the broader phenomenon of decreased oceanic DO content on a global scale resulting from ocean warming and anthropogenically altered ocean dynamics. Hypoxia will refer to concentrated, localized events of oxygen depletion that result from nutrient pollution and upwelling, processes that will be explained in further detail below.

Eutrophication, the presence of excessive nutrients (namely nitrates and phosphates) in a body of water, has also proven to threaten the stability of marine ecosystems. Anthropogenic eutrophication can result from agricultural runoff and sewage disposal (Chislock *et al.* 2013). Increased nutrient content in bodies of water often leads to algal blooms as it provides the algae with sufficient resources to reproduce rapidly. When the algae die, they are decomposed by bacteria, a process that creates hypoxic, acidic conditions and, in extreme cases, dead zones (marine regions in which high oxygen depletion levels have created uninhabitable conditions; (Knight, 2021; Wassmann, 2005). The hypoxia that results from anthropogenic eutrophication can reduce the habitability of the ecosystem, disrupt the structure of communities, and decrease productivity and biodiversity (Steckbauer *et al.* 2011). While it should be noted that eutrophication to extreme extents has not been observed in Monterey Bay, countless ocean regions across the globe are negatively impacted by these extreme events.

Upwelling is a naturally occurring process observed along eastern ocean boundaries—including the Eastern Pacific Ocean, where Monterey Bay sits—in which currents pull water to the surface from the deep, where the water chemistry is inherently different due to atmospheric isolation. Upwelled water is characteristically colder, lower in pH and DO, and rich in nutrients (Feely *et al.* 2008). These traits allow upwelling to intensify OA, deoxygenation, and eutrophication (Lakhar, 2013; Levin, 2018) and potentially alter conditions within kelp forests.

The restoration and protection of macro aquatic vegetation have been proposed as a potential, localized solution to the aforementioned consequences of climate change within marine ecosystems (Akinnawo,

2023; Adelsman and Binder, 2012; Delille *et al.* 2009; Cooley *et al*. 2016). During photosynthesis, kelp absorbs carbon in the form of aqueous $CO_2$ and emits $O_2$ as a product. Because aqueous $CO_2$ is the primary contributor to ocean acidification as a key component of $H_2CO_3$, kelp's ability to absorb $CO_2$ decreases the free $H^+$ ion concentration of the surrounding water. If the rate at which the kelp absorbs the $CO_2$ is faster than the rate at which atmospheric $CO_2$ dissolves into the water, the kelp actively increases the pH of the water (Kapsenberg and Cyronak, 2019). Conversely, the output of $O_2$ during photosynthesis increases DO content, mitigating local deoxygenation and improving the habitability of the kelp forest ecosystem. Kelp also absorbs nutrients, including phosphates and nitrates, which are often the limiting factors in kelp productivity (Harrison and Hurd, 2001). As a result, aquatic vegetation is known to reduce the impacts of eutrophication, especially during upwelling events along the eastern Pacific Ocean (McGlathery *et al.* 2007). Consequently, *M. pyrifera* fronds experience extremely high growth rates, with productivity of 7 grams of carbon per square meter per day (Towle & Pearse, 1973) and frond elongation rates of up to 14 cm per day during upwelling season (Zimmerman and Kremer, 1986). Towle and Pearse (1973) also discovered that 98% of *M. pyrifera* productivity occurred in the upper 3 m of the water column because of the substantially higher biomass concentration in the canopy as well as self-shading produced by the concentrated fronds limiting light penetration to deeper waters. The denser canopy serves to store carbon and nutrients, making it an ideal mitigation tool for OA, deoxygenation, and eutrophication, especially in surface ocean communities.

The *M. pyrifera* forests that cover much of Monterey Bay are among the most productive ecosystems in the world. Understanding their significance to the health of local marine ecosystems is crucial as we continue to make efforts to preserve the bay and counteract the impact of climate change. The extent of the ecological threats described above and the potential for kelp to mitigate those threats call for further research on the subject. It is evident that we must obtain a better scientific understanding of the extent to which the presence of kelp forests mitigates the impacts of anthropogenic threats to marine ecosystems in Monterey Bay. By comparing the temperatures and levels of dissolved oxygen, pH, phosphates, and nitrates within and outside of kelp forests, we can quantify the contributions of giant kelp to the mitigation of the impacts of OA and pollution. This study employs these methods in two kelp forests of Monterey Bay–McAbee and the Breakwater at San Carlos–and sheds further light on the ability of Monterey Bay kelp forests to buffer the local marine ecosystem from the devastating impacts of anthropogenic climate change.

## MATERIALS AND METHODS

### *Site Description*

Monterey Bay, located on the California central coast, is home to several kelp forests, most reaching maximum depths of approximately 18 meters. The region experiences coastal upwelling from April to September (Checkley and Barth, 2009; Hauri *et al.* 2009) as a result of the strong equatorward winds that transport deep water to the bay's surface. Additionally, the region's offshore winds and internal bores, subsurface waves produced by tides, have been characterized as uniquely energetic, resulting in more effective mixing than other marine regions (Walter *et al.* 2012). This constant underwater movement provides crucial protection against eutrophication and some pollution.

All field sampling was conducted manually in two separate kelp forests (Figure 1A) located off of McAbee Beach (Figure 1B) and The Breakwater at San Carlos Beach (Figure 1C) in Monterey, California, USA. The latter kelp forest is located approximately 0.8 km south of the former.

### *Discrete Water Sampling Procedure*

A total of 9 samples were collected at each kelp forest with identical procedures in order to produce similar data sets. The 3 sampling sites were located at the center of the kelp forest (site C), on the edge (site E), and 10 m outside of the kelp forest (site O). Samples collected at these sites shall from hereon be referred to as center, edge, and outside samples. Dissolved oxygen, pH, nitrate, and phosphate tests were all conducted on shore after sample collection in watertight, 118 mL polyethylene containers.

On 10 July 2024 at 4:00 pm local time, utilizing standard SCUBA equipment, we collected a sample at each site at depths 0 mbsl, 4.6 mbsl, and 9.2 mbsl and recorded the water temperature as measured by an Aqualung i200c Dive Computer.

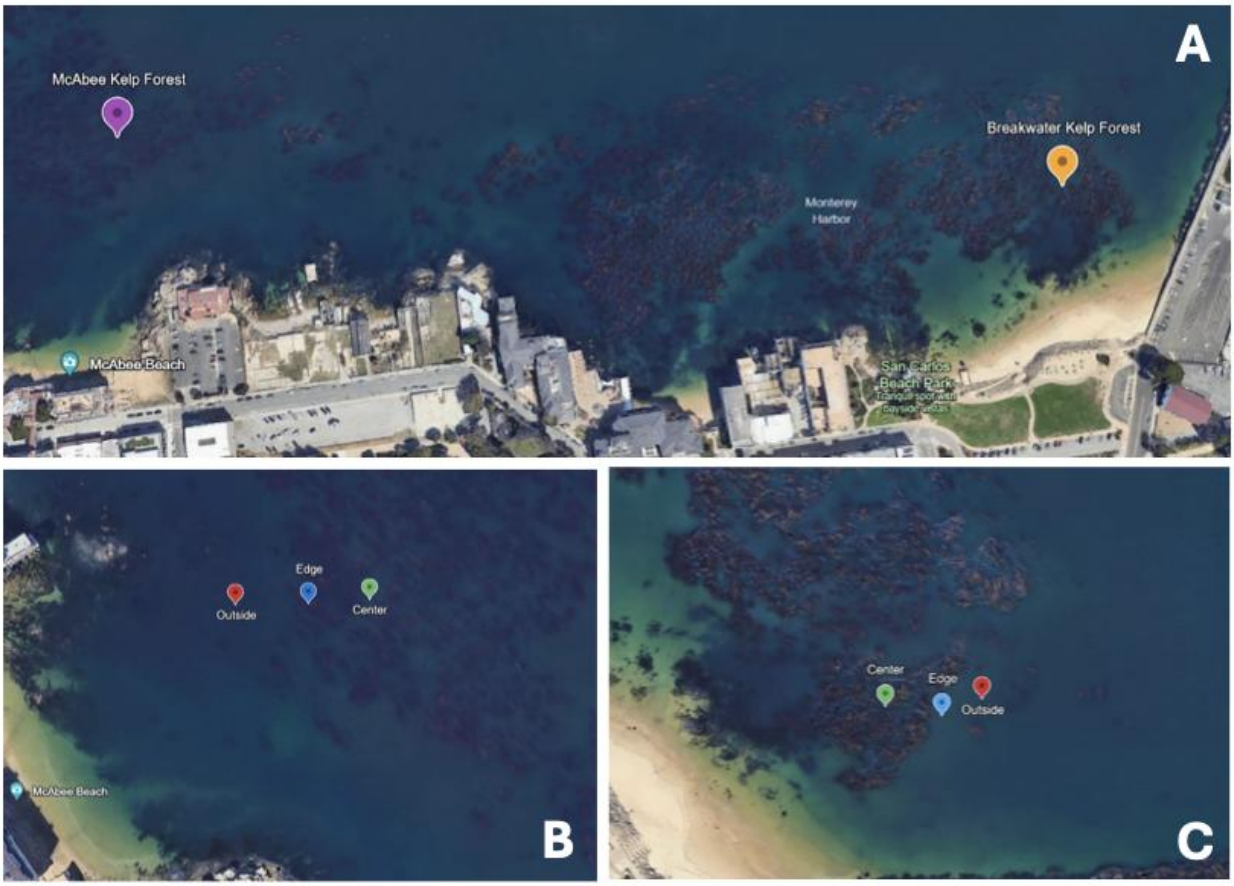


**Figure 1.** Maps of Monterey Bay showing the location of McAbee and Breakwater Kelp Forests relative to each other (A), and the approximate sampling sites at McAbee (B) and Breakwater Kelp Forests (C).

Immediately after returning to shore, we measured the dissolved oxygen content (see Materials and Methods: *Sample Testing and Data Collection*) of each sample before resealing them for later testing. DO is subject to change based on various environmental and physical factors, including pressure, temperature, and microbial activity (Kulkarni, 2016), so DO was assessed immediately after collection to ensure accuracy and mitigate the potential alteration of results by the aforementioned influences. We then proceeded to the kelp forest off of The Breakwater at San Carlos Beach to repeat the same sample collection process. After visiting both kelp forests, we returned to shore to test the pH, nitrate, and phosphate levels (see Materials and Methods: *Sample Testing and Data Collection*).

To assess these factors over time, we returned to both kelp forests and repeated the previously described procedures on 26 July 2024 and 5 August 2024, making sure to commence the first surface swim within 2 hours of the 10 July established start time of 4:00 pm.

***Sample Testing and Data Collection***

Samples were routinely tested in the following order of measurements: DO, pH, nitrates, and phosphates. Each of the aforementioned was tested in triplicate in all water samples, including DO, which was tested immediately after each dive.

To collect data for DO levels, we used the GISNPA Dissolved Oxygen meter with ATC, 0-40.00 mg/L Measurement Range. We calibrated the meter once for every sample at 100% calibration in air according to the manufacturer's protocol. To collect data for pH levels, we used the APERA Instruments AI209 Value Series PH20 Waterproof pH Meter. We conducted a 3-point calibration initially, and consistently checked the calibration before testing, recalibrating when necessary. For nitrate levels, we used Anniple 9 in 1 Aquarium Test Strips, and for phosphate levels, we used Advatec Phosphate Test Strips for Freshwater and Saltwater Fish Tank - Lab Grade Water Tester Kit. The nitrate test strips detect nitrate levels beginning at 10 mg/L, and the phosphate test strips detect phosphate levels beginning at 100 ppm. Based on

these limitations, we decided to record the nutrient data as either positive or negative for the respective nutrient levels (see Results: *Nutrient Measurements*).

### *CUTI Upwelling Data and Conditions*

To quantify the intensity of upwelling in the two kelp forests, we used the Coastal Upwelling Transport Index (CUTI), which approximates vertical transport into the surface mixed layer by integrating *in situ* and satellite data of surface wind stress, sea surface height, and mixed layer depth (Mihailov, 2024). The CUTI was calculated by averaging the values for 36°N and 37°N on each sampling day because the two sample sites were located at approximately 36.61°N.

## RESULTS AND DISCUSSION

### *Dissolved Oxygen Measurements*

DO values varied between 5.9 and 9.2 mg/L at McAbee Kelp Forest and 6.1 and 10.0 mg/L at Breakwater Kelp Forest (Figure 2; Supplementary Table S1). The minimum DO values were only measured in samples collected at depth, with the minimum DO value at Breakwater only occurring outside of the kelp forest at 9.2 mbsl. For both dive sites, the maximum DO values only occurred at the center of the kelp forest at the surface (Tables 1 and 2). Given the variability of the DO meter's measurements after prolonged periods of disuse, we decided not to comparatively analyze the mean of all corresponding values but rather to separate the 6 datasets for statistical analysis (Figures 2 and 3). In the case of DO, given the means of analysis, precision was more consequential than accuracy for the purposes of comparison in this study.

### *DO Analysis Across Location*

DO exhibited substantial variation between sites at the surface, but the values did not vary in a significant or consistent manner between sites at depth. Across the 6 datasets, we observed a noticeable trend for the

**Table 1.** Summary of pH and DO (mg/L) data at the center and outside of the McAbee Kelp Forest at depths 0, 4.6, and 9.2 meters below sea level (mbsl).

| **Depth (mbsl)** | **DO (mg/L)** | | **pH** | | |
|---|---|---|---|---|---|
| Center | Max | Min | Max | Min | Mean |
| 0 | 9.2 | 7.9 | 8.4 | 8.0 | 8.2±0.14 |
| 4.6 | 8.5 | 6.5 | 8.0 | 7.8 | 7.9±0.08 |
| 9.2 | 7.4 | 5.9 | 7.8 | 7.6 | 7.7±0.07 |
| Outside | Max | Min | Max | Min | Mean |
| 0 | 8.8 | 7.4 | 8.1 | 7.8 | 8.0±0.12 |
| 4.6 | 8.0 | 6.2 | 8.0 | 7.8 | 7.8±0.10 |
| 9.2 | 7.8 | 6.2 | 7.8 | 7.6 | 7.8±0.09 |

**Table 2.** Summary of pH and DO (mg/L) data at the center and outside of the Breakwater at San Carlos kelp forest at depths 0, 4.6, and 9.2 meters below sea level (mbsl).

| **Depth (mbsl)** | **DO (mg/L)** | | **pH** | | |
|---|---|---|---|---|---|
| Center | Max | Min | Max | Min | Mean |
| 0 | 10.0 | 7.9 | 8.3 | 8.0 | 8.2±0.11 |
| 4.6 | 8.6 | 7.3 | 8.2 | 7.9 | 8.0±0.12 |
| 9.2 | 8.3 | 6.8 | 8.0 | 7.6 | 7.8±0.19 |
| Outside | Max | Min | Max | Min | Mean |
| 0 | 9.4 | 7.7 | 8.2 | 7.8 | 8.0±0.12 |
| 4.6 | 8.7 | 7.3 | 8.0 | 7.9 | 7.9±0.05 |
| 9.2 | 8.7 | 6.1 | 8.0 | 7.8 | 7.9±0.08 |

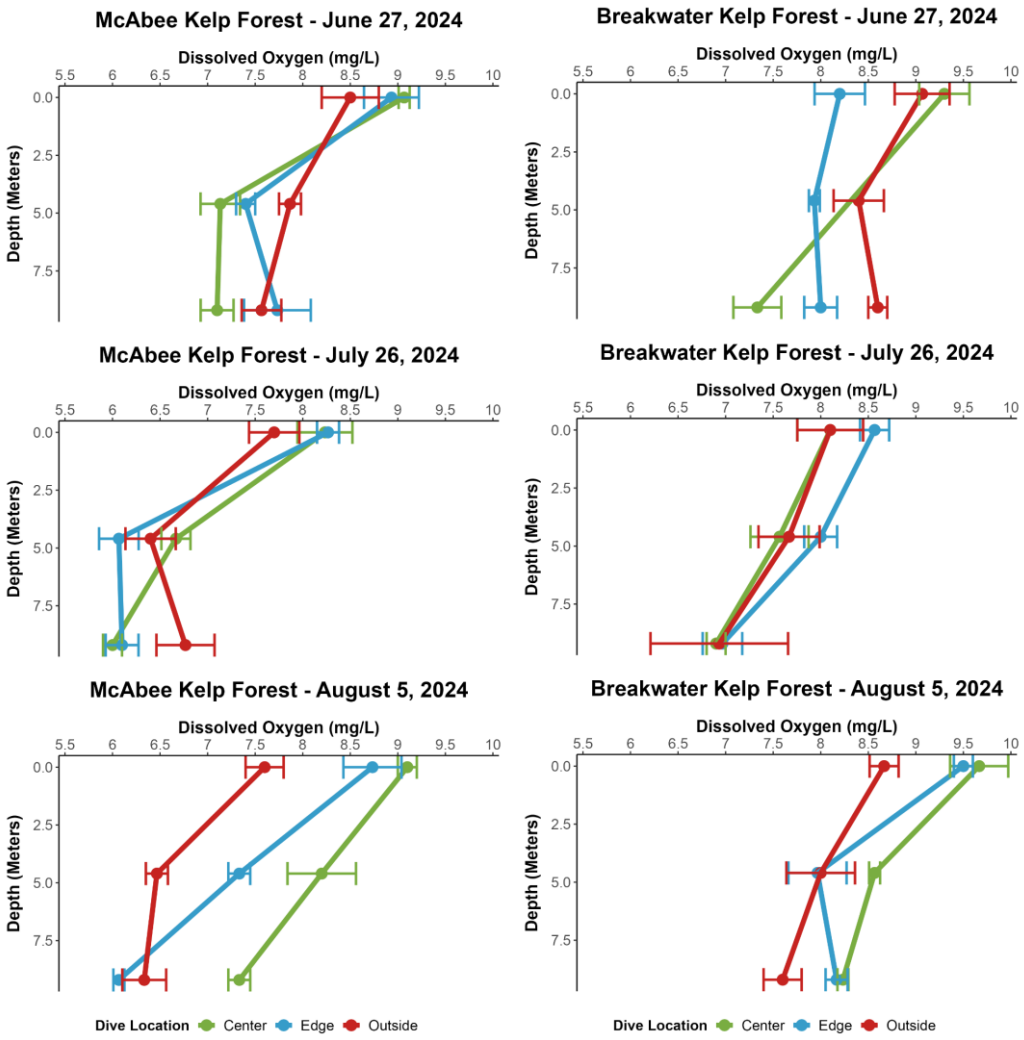


**Figure 2.** Dissolved oxygen (DO; mg/L) at the center, edge, and outside sampling locations for McAbee and Breakwater Kelp Forests across all three sampling dives.

surface values: the DO was consistently highest at the center of the kelp forest, and decreased as we moved away from the center of the kelp forest toward the edge and outside sites. Specifically, at McAbee Kelp Forest, the DO at the center of the kelp forest at the surface was, on average, 0.9±0.16 mg/L higher than the DO outside of the kelp forest at the surface. At Breakwater Kelp Forest, center DO at the surface was higher than outside DO at the surface by an average of 0.4±0.42 mg/L (Figure 2).

***DO Analysis Across Depth***

There was also a substantial variation in DO between surface and depth samples, and that variation was considerably more pronounced at the center of the kelp forest. Generally, there was a noticeable trend of greater difference in DO levels between the surface and 9.2 mbsl at the center and outside of the kelp forest (Supplementary Tables S1 and S2). At Breakwater Kelp Forest, DO levels at the center surface were, on average, 1.6±0.35 mg/L higher than at 9.2 mbsl. At the edge, they were an average of 1.0±0.24 mg/L higher, and outside of the kelp forest, they were an average of 0.9±0.45 mg/L higher. At McAbee kelp forest, the average difference between DO at the surface and 9.2 mbsl was 2.0±0.35 at the center, 2.0±0.33 at the edge, and 1.0±0.36 outside of the forest.

It is important to acknowledge that water at depth is subject to higher pressures than water at the surface (up to 1 atm higher). As a result of the higher pressure, its capacity to hold dissolved gases increases. When we brought samples from depth to the surface, they became subject to slightly lower pressures, so some DO is presumed to have dissipated into the atmosphere as a result of the water's suddenly decreased capacity to hold dissolved gases. However,

based on Henry's law, which can be employed to understand DO concentration as it relates to pressure (McNeil and Farmer, 1994; Markfort and Hondzo, 2009), as well as the fact that we minimized the amount of time exposed to air by testing DO immediately after opening the container, the amount of dissipated DO should be negligible to the results of the study.

***DO and Temperature***

*In situ* measurement of temperature followed a similar pattern to the pH and DO measurements in that the surface temperatures were significantly higher than the temperatures at depth. Because higher water temperature reduces the solubility of gases such as oxygen, the varying temperatures of the water samples had the potential to skew DO data (Tromans, 1998). Based on *in situ* measurements of water temperature, the temperature of the samples varied between 11.7°C and 16.7°C, but the design of the study allowed the samples to warm to similar temperatures (within 1.1°C of each other) during the rest of the dive and at the surface before measurements were conducted. We concluded that DO measurements are not affected by temperature because DO and temperature exhibited a weak correlation ($R^2$= 0.047; Supplementary Figure S1).

***pH Measurements***

In general, pH exhibited a similar pattern to the DO values across both location and depth. Values varied between 7.5 and 8.4 at McAbee and between 7.6 and 8.3 at Breakwater. For both dive sites, the minimum pH value was only observed in samples collected from 9.2 mbsl, and the maximum pH value was solely observed in samples collected from the center of the kelp forest at the surface (Tables 1 and 2). The pH data was analyzed together because the means of measurement was not variable, so most analysis was based on the average pH values over the course of 6 dives.

***pH Analysis Across Location***

We consistently observed a pronounced increase in pH at the center as compared to outside of the kelp forest (Figure 3). At both McAbee and Breakwater Kelp Forests, the pH at the center of the kelp forest at the surface was, on average, 0.2 higher than the pH outside of the kelp forest at the surface. At depth, the pH values exhibited no meaningful pattern across locations.

Because pH is a factor associated with photosynthesis and primary productivity (similar to DO), the surface measurements most accurately reflect the kelp's mitigating potential (see Discussion). As such, we placed more emphasis on the surface samples when analyzing the data across locations. Similar to the DO values, the edge samples had a lower pH than the center and a higher pH than the outside.

***pH Analysis Across Depth***

Similar to the DO values, there was a noticeable trend that the difference between the surface samples and the samples at 9.2 mbsl was substantially and consistently higher in the center than at the edge and outside (Supplementary Table S3). At McAbee Kelp Forest, the surface pH was higher than the pH at 9.2 mbsl by an average of 0.5±0.16 at the center, 0.4± 0.18 at the edge, and 0.4±0.15 outside of the kelp forest. At Breakwater Kelp Forest, the surface pH was higher than the pH at 9.2 mbsl by an average of 0.4±0.22 at the center, 0.1±0.12 at the edge, and 0.1±0.14 outside of the forest. The more pronounced difference in pH between the surface and depth samples parallels the trend observed with DO (see Results: *DO Analysis Across Depth*).

***pH and Temperature***

pH has the potential to be skewed by varying sample temperatures because higher temperatures increase the availability of $H^+$ ions (Ashton and Geary 2011), but because the samples warmed to similar temperatures during the course of the experiment, we concluded that pH was not affected by water temperature because there was no correlation between the pH and temperature at the time of measurement ($R^2$=-0.032; Supplementary Figure S2).

The nitrate and phosphate data was collected to assess the impact of kelp forests on the nutrient content of surrounding waters. Macroalgae, specifically kelp, absorb nutrients from their surroundings, especially during upwelling seasons, and extract nitrates and phosphates from the nutrient-rich upwelled waters (McGlathery *et al.* 2007). Saltwater aquarium test strips were used to measure both nitrates and phosphates, which posed some limitations for nutrient detection. As such, nutrient data was not recorded as a numerical value, but rather as a positive or negative detection (see *Sample Testing and Data Collection*).

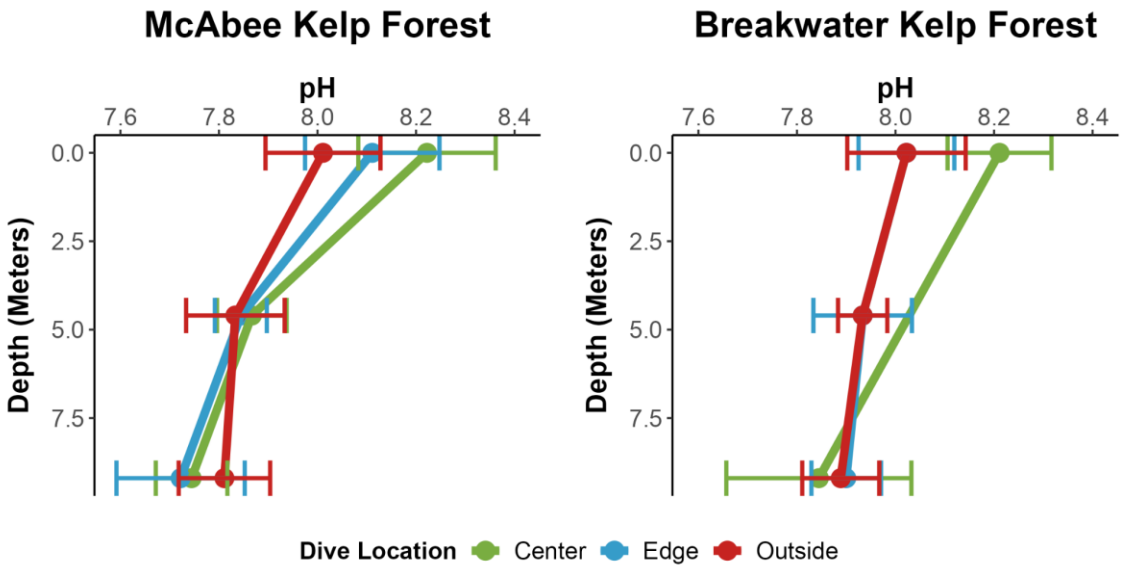


**Figure 3.** pH at the center, edge, and outside sampling locations for McAbee and Breakwater Kelp Forests, averaged across all three sampling dives.

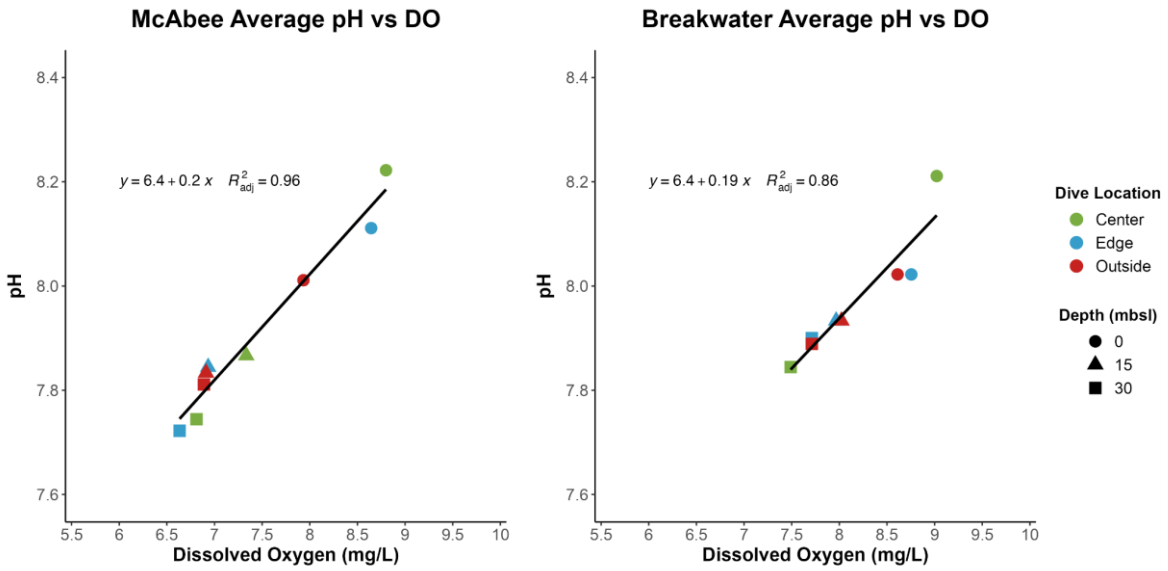


**Figure 4.** Average pH vs. average dissolved oxygen (DO; mg/L) at McAbee and Breakwater.

***Nutrient Measurements***

Due to complications with the test strips, most of the meaningful phosphate data was collected during the third sample collection, and our analysis focuses on this data (Supplementary Table S4). Within that data set, phosphates were consistently detected in concentrations no greater than 100 ppm outside of the kelp forest at depth. Some phosphates appeared at the edge of the kelp forest at depth at McAbee and Breakwater and at the surface of the edge and bottom of the center at Breakwater. Phosphates never appeared at the center of the kelp forest at the surface. If phosphates were present in concentrations significantly lower than 100 ppm, they were not detected.

Throughout the study, no nitrates were detected, and while these results were likely partially the product of the obstacles posed by limited resources to collect nutrient data, as discussed in Section 4, lower nitrate levels should be expected in Monterey Bay due to the unique subsurface dynamics of the bay (see Materials and Methods: *Site Description*), which dilute the nutrients.

## DISCUSSION

This study presents spatial data from manual seawater sample collection at the center, edge, and outside of two kelp forests and at depths 0, 4.6, and 9.2 meters, producing an in-depth analysis of the regulating potential of kelp forests between sites and over depth.

Overall, we found that the presence of the kelp forests in Monterey Bay increases DO and pH levels and decreases nutrient levels within a certain proximity of the forest ecosystem, specifically at the surface. In the center as compared to outside of the forest, we saw a significantly more pronounced difference between the pH and DO at the surface than at depth. DO and pH levels were highly correlated and generally decreased with increasing depth and distance from the center of the kelp forest. Conversely, phosphates were detected only on the edge and outside of the kelp forests at depth.

### *Comparison of Conditions Inside and Outside of the Kelp Forest Ecosystem*

The vast majority of the biomass of kelp forests is located in the canopy, which prevents a significant amount of sunlight from reaching deeper parts of the forest. As a result of the biomass distribution and self-shading, the vast majority of the productivity of kelp forests occurs at the surface, especially in Monterey, where upwelling conditions result in substantially higher blade concentrations higher in the water column (Hirsh *et al.* 2020). Because 98% of kelp productivity occurs within the first 3 m of the water column (Towle & Pearse, 1973), we expected the kelp's mitigation of OA and deoxygenation to be more apparent in shallower depths, where the most significant changes in water chemistry occur.

Analyzing the data between locations relative to the kelp forest is crucial because it provides an indication of whether the kelp forest's rate of oxygen output is substantially affecting the chemistry of the surrounding water. The measurements outside of the kelp forest provide a control group that gives us an idea of the chemistry of unaffected water.

The notable trend of decreasing DO with increasing distance from the kelp forest allows us to assess the extent of the primary productivity of the kelp forests as it impacts local deoxygenation. During photosynthesis, kelp emits a substantial amount of oxygen into the water, which should counteract the effects of deoxygenation associated with climate change. The significant increase observed in the DO values at the center of the kelp as opposed to outside indicates localized mitigation of ocean deoxygenation. Furthermore, the pronounced difference in pH consistently observed between locations relative to the center of the kelp forest is a key indication of the kelp's absorption of $CO_2$. Atmospheric $CO_2$, a significant amount of which is absorbed by kelp during photosynthesis, is crucial to the formation of carbonic acid, so the higher pH of the water around the kelp forest, compared to water without kelp, is directly indicative of the extent of their ability to locally mitigate OA.

Higher DO and pH levels inside of the kelp forest than outside of the kelp forest indicate that the kelp's rate of photosynthesis and primary productivity makes a significant and lasting impact on the DO content of the water that passes through it.

### *Comparison of Conditions Over Depth*

Because of the disproportional distribution of biomass in the water column, measuring the difference in DO and pH levels between depths is an alternative means of determining the mitigating potential of kelp, specifically the canopy, on water chemistry.

The more pronounced difference between surface and depth DO at the center suggests substantial physiochemical influence by the kelp canopy. Generally, DO is higher at the surface because of increased access to atmospheric $O_2$, but the higher observed difference between depths at the center of the kelp forests compared to outside the kelp forest indicates the influence of the kelp's photosynthetic output of oxygen. pH, for which the difference between the surface and depth measurements was higher at the center than at the edge or outside, similarly reflects a lasting, substantial influence of the kelp on the acidity of the water with which it comes in contact. The data specifically demonstrates small-scale mitigation of OA by the kelp forest through the absorption of $CO_2$.

The considerably higher pH and DO near the surface, which has also been observed in prior studies (Hirsh *et al.* 2020; Hoshijima and Hofmann, 2019; Koweek *et al.* 2017; Frieder *et al.* 2012), indicate the high

primary productivity and mitigating potential of the kelp's canopy. Because no consistent trend was observed between locations in samples at depth, the fact that the center values were less similar across depths provides support for the conclusion that the kelp forests, which exist primarily in the upper water column, provide significant protection against OA and deoxygenation.

***Metabolic System***

Taken together, the pH and DO values provide a more comprehensive insight into the metabolic systems of the kelp forests as they relate to the mitigation of climate change impacts on local oceanic chemistry.

We observed a strong correlation between the DO and pH values across all data points ($R^2$=0.9229; Figure 5), which has been previously observed in similar studies, most notably Hirsh *et al.* (2020) and Hoshijima and Hofman (2019). This correlation confirms the influence of the photosynthetic processes on water chemistry and suggests that ecosystems affected by low pH were simultaneously affected by low DO, which implies considerably healthier conditions within the kelp forest, where both DO and pH were observed to be higher.

The DO and pH values at the edge of the McAbee Kelp Forest were closer to the values at the center than the values outside of the kelp forest, an observation that differed from the values at Breakwater, where the DO and pH values at the edge more closely resembled those outside of the kelp forest than at the center. We do not have sufficient evidence to indicate the impacts of the McAbee Kelp Forest extended farther than that of Breakwater Kelp Forest, so we instead dismissed it as a result of the fact that the edge sampling location was further away from the kelp at Breakwater than at McAbee. That said, the variability does provide clearer insight as to the extent of the kelp forest's influence on water chemistry. When the samples were tested directly outside of the forest as opposed to 1 or 2 meters away from the edge, significantly different values were recorded. This observation being an unintended result of the data collection, any similar experiments seeking to quantify the extent of the kelp signal outside of the forest should more accurately measure the distance outside of the kelp forest and incorporate more sample sites at the edge.

***High Energy Mixing and Nutrients***

Monterey Bay's uniquely energetic internal bores contribute to constant high-energy mixing in subsurface ecosystems throughout the bay. While this does impact the distribution of factors like carbonic acid and dissolved oxygen, it has a greater effect on components such as nutrients, which generally originate from point-source pollution or upwelling as opposed to more widespread sources such as the atmosphere.

The mixing immediately dilutes the nutrients being introduced to the system, which prevents any significant changes to ecosystemic health, such as those produced by eutrophication. This is opposed to ecosystems such as that of San Francisco Bay, in which the nutrients are allowed by the subsurface water stillness to concentrate in a singular area, creating eutrophication (Cloern 2001; Walter *et al.* 2012). Where the kelp forest's structure attenuates the high energy mixing produced by internal bores, the increased residence time of the water within the kelp forest reduces the nutrient content as the kelp absorbs the phosphates and nitrates.

Taking into consideration the possibility of false negatives, the data aligns with the hypothesized pattern of nutrients around the kelp forests. Phosphates would not be absorbed as quickly outside of the kelp forest because biological processes that contribute to nutrient absorption are not as prevalent in those regions. Inside the forest, however, nutrients would be absorbed at a quicker rate by the productive, fast-growing kelp, the growth of which is generally impeded in Monterey by the limiting factor of nutrients (Strong-Wright 2022).

**CONCLUSION**

This study presents a comprehensive record and analysis of spatial physiochemical variability in relation to two kelp forests within Monterey Bay. The findings confirm the significance of kelp forests as an effective management tool for anthropogenic climate change in local marine ecosystems. We have demonstrated that the biological processes of the kelp forests in Monterey Bay have a consequential impact on the chemistry of proximate water, most substantially reducing OA and deoxygenation. As such, giant kelp forests in Monterey Bay contribute to the mitigation of the coastal impacts of anthropogenic

climate change, making it an indispensable component of local oceanic health. pH and DO were tightly correlated, and the patterns observed across locations and over depth suggested a highly influential metabolic system, specifically at the surface. Elevated pH and DO were observed inside of the kelp forest as compared to the edge and outside at the surface, and variation between surface and depth pH and DO values was consistently greater at the center than at the edge or outside. Nutrients, while not as extensively impacted, were never detected in the kelp canopy and consistently detected at depth and outside of the kelp forest. Based on these patterns, it is clear that the kelp forest regulates pH and DO in local ecosystems, but that mitigating potential may be limited to the kelp canopy in the upper few meters of the water column. The ecosystem services provided to Monterey Bay coastal systems, which include the aforementioned physiochemical regulation and habitat formation, make it imperative for local communities and governments to make conservation and restoration efforts to preserve these essential structures. Understanding gaps in our knowledge regarding potential tools for the mitigation of the consequences of climate change on marine ecosystems is a crucial first step in protecting our coastal communities. Action occurs most efficiently when those gaps in knowledge are minimized and legislators and the public are driven to improve kelp health. As such, it is essential that we improve education and outreach with actions such as the dedication of resources to the creation of climate change-related education programs and the inclusion of kelp forest education in local curricula. As outlined by Cuvelier *et al.* (2018), higher-investment, higher-impact actions include supporting industry and managing for resilience. This ranges from adjusting permitting requirements for relevant industries to actively funding the control of growing sea urchin populations within the forest, but it is important to consider the longevity of these measures when implementing them. As for non-legislative actions, focusing on community-oriented grassroots campaigns is the most conducive to the formulation of more enduring solutions. Strengthening public support for restoration movements, especially in Monterey Bay, is crucial to legislatively achieving and maintaining the actions outlined above.

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**Conflict of Interest**: The authors declare no conflict of interest in relation to this research.

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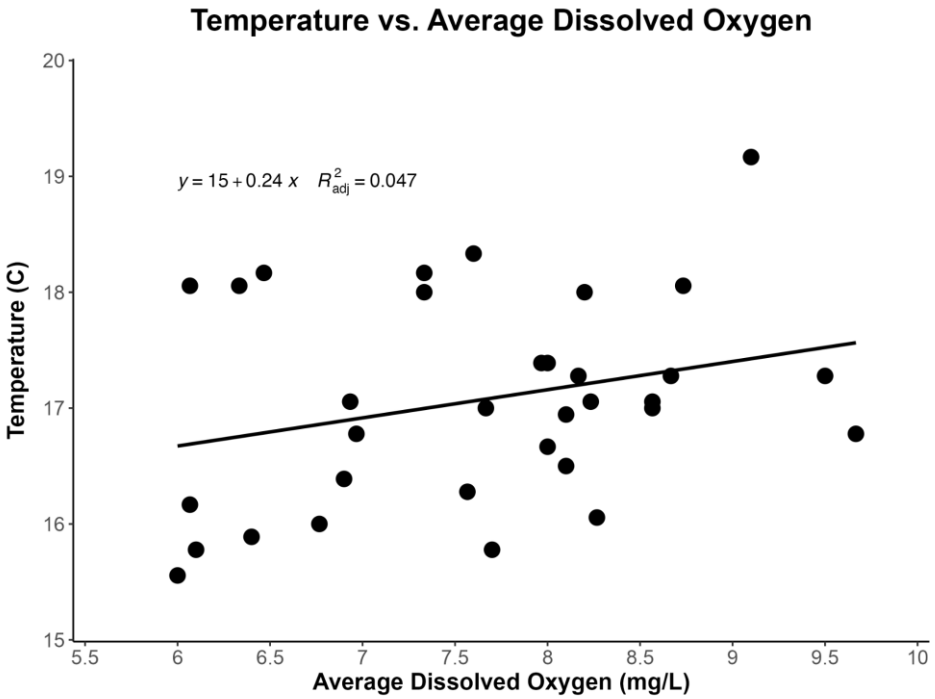
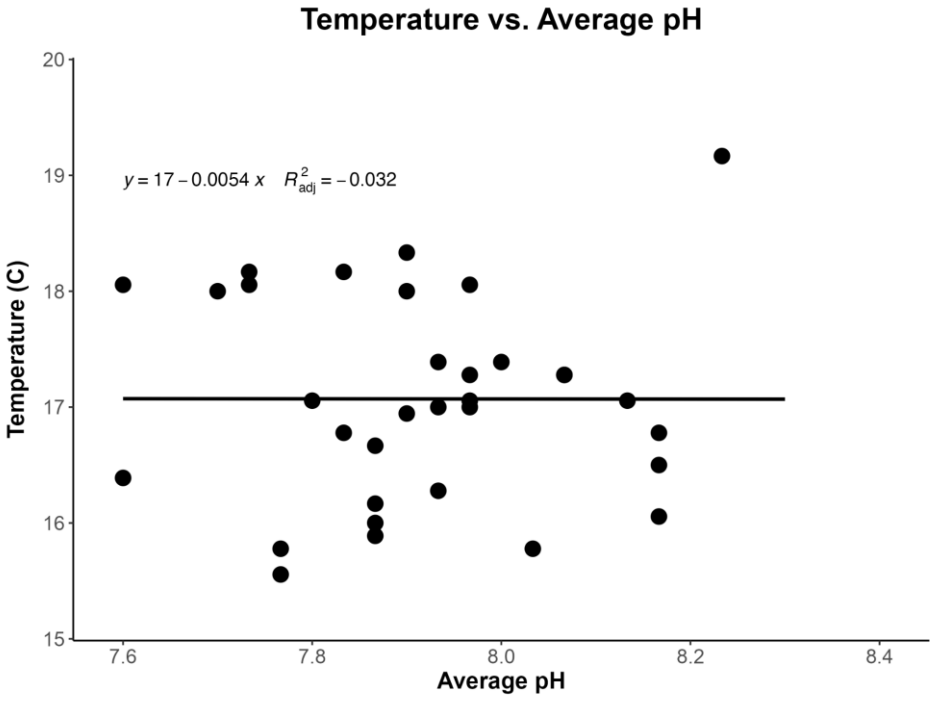
**Supplementary Figures**




**Supplementary Figure S1.** Trendline of temperature at measurement and average DO.




**Supplementary Figure S2.** Trendline of temperature at measurement and average pH.

**Supplementary Tables**

**Supplementary Table S1.** Difference in dissolved oxygen (DO; mg/L) between 0 and 9.2 mbsl at center, edge, and outside locations at McAbee Kelp Forest.

| | DO difference between 0 and 9.2 mbsl (mg/L) | | |
|---|---|---|---|
| | **Center** | **Edge** | **Outside** |
| **Dive 1** | 2.1 ± 0.22 | 1.2 ± 0.46 | 0.9 ± 0.37 |
| **Dive 2** | 2.2 ± 0.31 | 2.2 ± 0.21 | 0.9 ± 0.41 |
| **Dive 3** | 1.8 ± 0.16 | 2.6 ± 0.32 | 1.3 ± 0.31 |
| **Average** | 2.0 ± 0.35 | 2.0 ± 0.33 | 1.0 ± 0.36 |

**Supplementary Table S2.** Difference in dissolved oxygen (DO; mg/L) between 0 and 9.2 mbsl at center, edge, and outside locations at Breakwater Kelp Forest.

| | DO difference between 0 and 9.2 mbsl (mg/L) | | |
|---|---|---|---|
| | **Center** | **Edge** | **Outside** |
| **Dive 1** | 2.0 ± 0.36 | 0.2 ± 0.31 | 0.5 ± 0.31 |
| **Dive 2** | 1.2 ± 0.36 | 1.6 ± 0.26 | 1.2 ± 0.80 |
| **Dive 3** | 1.5 ± 0.32 | 1.3 ± 0.16 | 1.1 ± 0.25 |
| **Average** | 1.6 ± 0.35 | 1.0 ± 0.24 | 0.9 ± 0.45 |

**Supplementary Table S3.** Average difference in pH between 0 and 9.2 mbsl at center, edge, and outside locations at McAbee and Breakwater Kelp Forests.

| | pH difference between 0 and 9.2 mbsl | | |
|---|---|---|---|
| | **Center** | **Edge** | **Outside** |
| **McAbee** | 0.5 ± 0.16 | 0.4 ± 0.18 | 0.2 ± 0.15 |
| **Breakwater** | 0.4 ± 0.22 | 0.1 ± 0.12 | 0.1 ± 0.14 |

**Supplementary Table S4.** Nutrient detections at 0, 4.6, and 9.2 mbsl at center, edge, and outside locations at McAbee and Breakwater kelp forests.

| | Location | Depth (m) | Phosphates | Nitrates |
|---|---|---|---|---|
| **McAbee** | Center | 0.0 | – | – |
| | | 4.6 | – | – |
| | | 9.2 | – | – |
| | Edge | 0.0 | – | – |
| | | 4.6 | + | – |
| | | 9.2 | – | – |
| | Outside | 0.0 | – | – |
| | | 4.6 | + | – |
| | | 9.2 | + | – |
| **Breakwater** | Center | 0.0 | – | – |
| | | 4.6 | – | – |
| | | 9.2 | + | – |
| | Edge | 0.0 | + | – |
| | | 4.6 | – | – |
| | | 9.2 | + | – |
| | Outside | 0.0 | + | – |
| | | 4.6 | + | – |
| | | 9.2 | + | – |