Influence of River Proximity on Water Quality and Its Impact on Caribbean Mangrove Oyster Populations: A Case Study in Bowden Bay, St. Thomas, Jamaica

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Influence of River Proximity on Water Quality and Its Impact on Caribbean Mangrove Oyster Populations: A Case Study in Bowden Bay, St. Thomas, Jamaica

Leanne Morris Bennett

90 ECTS thesis submitted in partial fulfilment of a

Magister Scientiarum degree in Aquatic Biology

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Abstract

This study explored how distance from the open sea and abiotic factors affect the population abundance and shell dimensions of *Crassostrea rhizophorae* (CR) and *Isognomon alatus* (IA) in a mangrove estuary at Bowden Bay, St. Thomas, Jamaica. Results showed a higher *Crassostrea rhizophorae* population closer to the open sea, and more frequently found on mangrove roots than *Isognomon alatus* when both species are present. Both species exhibited variability in population size and shell dimensions across different sites, with IA generally having more prominent individuals at specific locations. Water quality parameters, including salinity, dissolved oxygen, and temperature, varied along the estuary, significantly influencing oyster populations. *Crassostrea rhizophorae* favoured slightly higher salinity levels and chlorophyll-a concentrations. The study's limitations included its short duration and narrow spatial focus, calling for extended monitoring and more comprehensive analysis. Findings highlight important considerations for oyster aquaculture, habitat restoration, and conservation efforts. Understanding these environmental and habitat factors can develop better strategies for sustainable oyster culture. Future research should examine long-term environmental changes, genetic variations, and their effects on oyster populations.

Útdráttur

Þessi rannsókn kannaði hvernig fjarlægð frá opnu hafi og ólífrænir þættir höfðu áhrif á þéttleika og útlit skelja Crassostrea rhizophorae (CR) og *Isognomon alatus* (IA) í leiruviðaskógi við Bowden Bay, St. Thomas, Jamaíka. Niðurstöðurnar sýndu hærri þéttleika *Crassostrea rhizophorae* nær opnu hafi. Sú tegund var einnig í hærri þéttleika á rótum leiruviðartrjáa en Isognomon alatus þegar báðar tegundirnar fundust á rótunum. Hjá báðum tegundunum sást breytileiki í stofnstærð og útliti skelja á milli sýnatökustöðva, og virtist IA vera stærri á ákveðnum stöðvum. Þættir er tengjast gæðum sjávar, þar með talin selta, uppleyst súrefni og hitastig voru breytileg með tilliti til staðsetningar í ósnum og hafði það áhrif á stofna ostranna. *Crassostrea rhizophorae* valdi lítillega hærri seltu og styrk blaðgrænu a. Það sem takmarkar þessa rannsókn er hversu stutt rannsóknin varði og hversu lítið svæði var skoðað. Mikilvægt er því að skoða rannsóknaspurningarnar á stærra svæði, með víðtækari vöktun. Niðurstöður rannsóknarinnar sýna mikilvæga þætti sem taka verður tillit til við ræktun á ostrum, endurheimt búsvæða og vernd náttúrunnar. Með því að skilja þessa umhverfis og búsvæðaþættir er hægt að þróa betri áherslur fyrir sjálfbæra ræktun á ostrum. Áframhaldandi rannsóknir ættu að skoða langtíma umhverfisbreytingar, erfðafjölbreytilika og hvernig þeir þættir hafa áhrif á ostrustofna.

Dedication

God is incredible to whom I owe my life, these new changes and completion of this degree- Romans 5:3-5 NIV

To my aunt, Gillian Angelic Channer, how I wish you were alive to see your impact on me. Believe it or not, your niece became a scientist! Your impact and influence will forever change my life, even if I am too stubborn to admit it. I love you always.

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Abbreviations

Crassostrea brasiliana: *CB*

Crassostrea gasar: CG

Crassostrea gigas: CG

Crassostrea rhizophorae: *CR*

Crassostrea virginica: *CV*

Isognomon alatus: *IA*

Isognomon bicolor: *IB*

Isognomon ephippium: *IE*

Mangrove Oyster: MO

Particulate organic matter: *POM*

Rhizophorae mangle: *Rhm*

Acknowledgement

My Faith in the Lord Jesus has kept me steadfast, and his role in my life is undeniable. He has started and continued to do a good work in me. ***Philippians 1:6***. Anyone reading this thesis, I want you to know that as Christians, we are everywhere and can do anything in his will. I want to acknowledge him first publicly and within the realm of academia.

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Everyone who has played a pivotal role in my success. There are so many more to mention but thank you.

1 Introduction

Mangrove refers to an evergreen halophilic forest, which includes woody trees and shrubs, with aerial roots for anchorage in a waterlogged, muddy coastal environment that interfaces between the coastal and estuarine environments (FAO, 2023; Villate Daza et al., 2020). They protect coastlines, especially during storm surges, cut wave action, reduce soil erosion, and stabilise coastlines (Miranda et al., 2021). They also aid in soil formation and primary production through photosynthesis, nutrient cycling, and water movement regulation. They assist in carbon storage at an average rate of 22 ± 6 Tg (Terra grams) per year (Anu et al., 2024; Villate Daza et al., 2020). This forest is also home to various other flora and fauna (FAO, 2023).

These dense coastal forests are habitats for a plethora of animals, including birds, marine mammals, amphibians, reptiles, fishes, and crustaceans (Villate Daza et al., 2020). Mangrove forests, a unique and vital ecosystem, are found in the coastal areas of 123 countries worldwide in tropical and subtropical regions (Sadeer et al., 2022). Up to the year 2000, it was estimated that the total area was 137,760 $km^{2,}$ with an estimated coverage of 152,000 km^2 of mangroves existing worldwide (Sadeer et al., 2022). However, recent global estimations are approximately 135,822 km^2. in 2016 (Spalding et al., 2021) and 147,256 km^2 in 2020 (leal et al., 2024), with the North and Central American region mangrove covering approximately 20,962 km^2 (Spalding et al., 2021) with a slight increase of 21,270 km^2 as reported by Leal et al. (2024). Mangroves also have financial and social significance, providing natural products such as tannins, timber, and medicinal plants (Hamilton, 2020; Ket al., 2024; Saoum & Sarkar, 2024).

While their importance cannot be overstated, these majestic and ecologically essential habitats are severely threatened by degradation in the form of dredging, deforestation and land use change (Aransiola et al., 2024). Finally, loss is also due to aquaculture activities. Aquaculture activities up to 2020 accounted for 26.7% of mangrove degradation (FAO, 2023). Worldwide aquaculture production in 2022 grew to 87.9 million tonnes from 43 million tonnes in 2000, increasing yearly by an average of 5.2%. In 2022, it was worth noting that production for bivalves, particularly for cupped oysters, *Crassostrea* spp., totalled 6.2 million tonnes (FAO, 2024). However, in countries like Ecuador, where shrimp culture ponds are located in the estuary, they often require the removal of mangroves to accommodate this activity (Hamilton, 2020). It means the destruction of this crucial ecosystem. Other activities contributing to degradation include Agricultural activities (8.4 % rice cultivation, 8.2% palm oil, 8.2% wood extraction, and direct and indirect settlement at 3.2%, 7.7%, and 5.6%, respectively). Natural disasters are at 2.0%, and other contributors are at 12.3% (FAO, 2023). Mangrove habitats usually attract a diverse range of marine species. This is due to its heterogeneity and complexity, which speaks to habitat structure and diversity, providing several classes of substrates and hiding places from predators for species, including mangrove crabs and bivalves such as oysters, other species such as sponges, coral ascidians, algae, and even corals (Aslam et al., 2020; Nauta et al., 2023; Sharifian et al., 2020).

Mangrove forests can be found within the tropical and subtropical coasts and estuaries (Rull, 2023; Spalding et al., 2021), with varying common plant species including *Rhizophora* (Rhizophoraceae), *Avicennia* (Acanthaceae), and *Laguncularia* (Combretaceae) within the Caribbean, of which *Rhizophora mangle* and *Rhizophora racemosa* are the most abundant (Rull, 2023). It is well known that the estuaries are an essential area that is home to several marine species, including bivalves (Antonio et al., 2021; Gilman et al., 2008) and endophytic fungi which live within mangroves roots or soil (Zeng et al., 2024) that aid in regulating nutrient cycles, phytohormones and salt tolerance (Zeng et al., 2024). The presence of oyster species may be due to several contributing water quality factors, including physiochemical parameters, wet or dry seasons, and soil composition, which is usually determined by a mixture of components, such as particulate organic matter (POM) made up of fresh and decomposing matter (Bearham et al., 2023), micro/macro minerals, especially in places like Malaysia (Al-Asif et al., 2023). Species richness seems dependent on temperature, among other factors (Sharifian et al., 2020). These accommodation factors and conditions may similarly occur in tropical and subtropical regions, including the Caribbean. However, they are poorly understood in the Caribbean context due to the limited research on these topics. These components for faunal residency, in this case oysters in mangrove forests, include parameters such as salinity, pH, temperature, soil composition, microbial, and macro-micro mineral components (Al-Asif et al., 2023), which may help to foster settlement. Through observation that coincides with the documentation of Nikolić et al. (1976), oysters, especially Mangrove oysters, usually attach themselves to the roots of the rhizophorae within the intertidal zone at 10-15 cm or 25-35 cm above low tide, hinting that there may or may not be some correlation with the parameters mentioned above. In species such as *Crassostrea virginica* (CV), a significant settlement indicator was temperature (Cunningham et al., 2025). These components above may also affect the population of bivalve species and where they settle. Further ecological research into mangrove habitat and species relationships is needed, as mangrove forests are intricately linked to the Caribbean way of life, providing access to fish and other species for consumption. Before further estuaries are used, it is crucial to understand the relationship between the species and their habitat.

Oysters' suitability to settle along coastal areas is an important consideration; equally important is how water quality affects the population of the oyster species present and the influences on the final location within the mangrove habitat. However, more research is needed on the species-specific diversity of oyster populations within the Caribbean context. Understanding the relationship between marine bivalves and their interaction with the Caribbean mangrove environment for a critical species like the mangrove oyster will help fill the research gap in identifying the factors that encourage settlement and population abundance. This study focuses on the two main oyster species, *Crassostrea rhizophorae* (CR) and *Isognomon alatus* (IA), as they are the most common species found within the Bowden Bay estuary and are widely consumed by Jamaicans (Siung, 1980a; Wright, 1992).

1.1 *Crassostrea rhizophorae*

1.1.1 Biology

The mangrove oyster is a euryhaline bivalve mollusc belonging to the *Ostreidae* family (Christo et al., 2010). Its shell comprises approximately 96 % calcium carbonate ($CaCO_3$) (called calcite in its mineral phase) and various trace elements (Christo et al., 2010). It is characterised by a distinctly leafy, deep cup-shaped (convex) left valve (Figure 1) and a small, flat upper right valve that fits into the cup of the left valve with an unpigmented muscle scar located near the dorsal edge of the shell margin (Amaral et al., 2014; Nascimento, 2019). The shape of the oyster also depends on the settling material used to collect the spat, with the cupped area being flat due to settling on items such as recycled car tyres used as cultches (Wade et al., 1981).

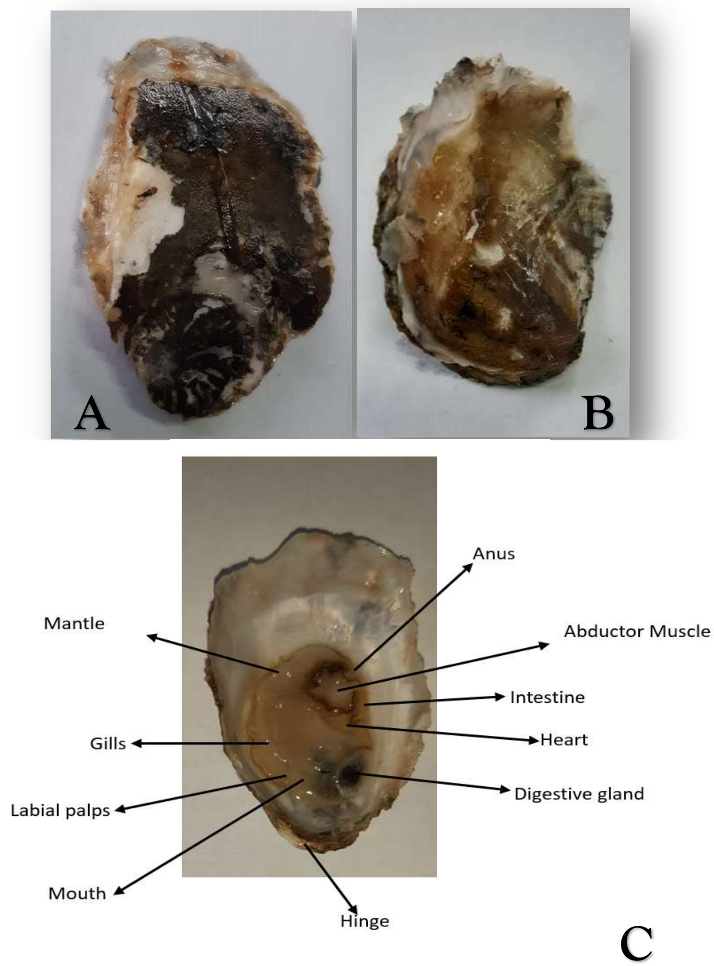

Figure 1 (A) Underside(cupped portion) view of *Crassostrea rhizophorae* its flat nature due to settlement on a rubber cultch (B) Top view of *Crassostrea rhizophorae (*C) Internal view of oyster's vital organs.

CR can average up to 10cm (100mm) in height (Nascimento, 2019). Its internal anatomy comprises the abductor muscle, responsible for the closing and opening of the shell, mouth, anus, mantle digestive gland, heart and other areas (Figure 1). These organs are responsible for the normal function of the oyster and for carrying out basic life processes: Ingestion, metabolism, etc. Suitable conditions for the survival of this oviparous dioecious hermaphrodite (Amaral & Simone, 2014; Antonio et al., 2021a) depend on a range of water parameters. Ideally, water salinity levels of 15 to 25 ppt, oxygen concentrations of 2-5 mg/l, and a temperature range between 22-28°C and a pH range of 7.7 to 8.3 (Neto et al., 2013; Nikolić et al., 1976) especially in estuary environments allow for the best survival of CR. Preferred habitats are tropical and temperate (except arctic waters), usually on the country's coast, either in the intertidal or shallow subtidal water level (Amaral & Simone, 2014; Antonio et al., 2021a; Guimaraes et al., 2008; Mancera & Mendo, 1996; Nascimento, 2019). Typical group behaviour is to find oysters in clusters either on the aerial support roots of the mangrove roots (*Rhizophorae mangle*) or on sedimentary or shelly bottoms (Amaral et al., 2014; Antonio et al., 2021; Bayne, 2017; Lapègue et al., 2002). CR are found throughout the Caribbean, Atlantic, and South America (Lapègue et al., 2002).

1.1.2 Reproduction

The reproductive mechanisms of *Crassostrea* species vary across different species and subspecies, including *Crassostrea gigas* (CG), a tropical species found in Florida, the Caribbean, Brazil, and as far as West Africa (Hannah et al., 2007; Lapègue et al., 2002b; Rampersad et al., 1992), which have similar climatic conditions; of these countries, Brazil is closest to the Caribbean and, like the Caribbean, has a consistent temperature range between 28°C-30°C (Paixão et al., 2013), making it suitable for the commercial culture of *Crassostrea* species of oysters. Mangrove cup oysters, CR, are known to occur from as far as the American Atlantic coast, within the Caribbean and to the Caribbean coasts of South America (Carranza et al., 2009; Lapègue et al., 2002), usually within a mangrove, bay or estuary, attaching themselves to the *Rhizophorae mangle* (Rhm) roots intertidally (Antonio et al., 2021a). *Crassostrea* species are oviparous dioecious i.e., gamete-releasing unisexual organisms (Gosling, 2015; Lopes et al., 2024) and sequentially hermaphroditic (starting as male and then converting to female). Their spawning mechanism is universal and functions by external release of their gametes (Antonio et al., 2021; Fakhrina et al., 2018). Fertilization begins within the first hour after the sperm meets the egg (Wallace et al., 2008; Vogeler et al., 2016). The fusion of these two haploid gametes produces a zygote with a polar body (circular bubble in egg), indicating successful fertilisation. Immediately thereafter, cell division begins until it becomes a larva. During development Figure 2 (between 14-17 days), larvae undergo a series of motile stages trochophore, D umbo-shaped larvae-eye, larvae-veliger, pediveliger-plantigrade (early spat), then become spat, then adults (Fakhrina et al., 2018; Wallace et al., 2008).

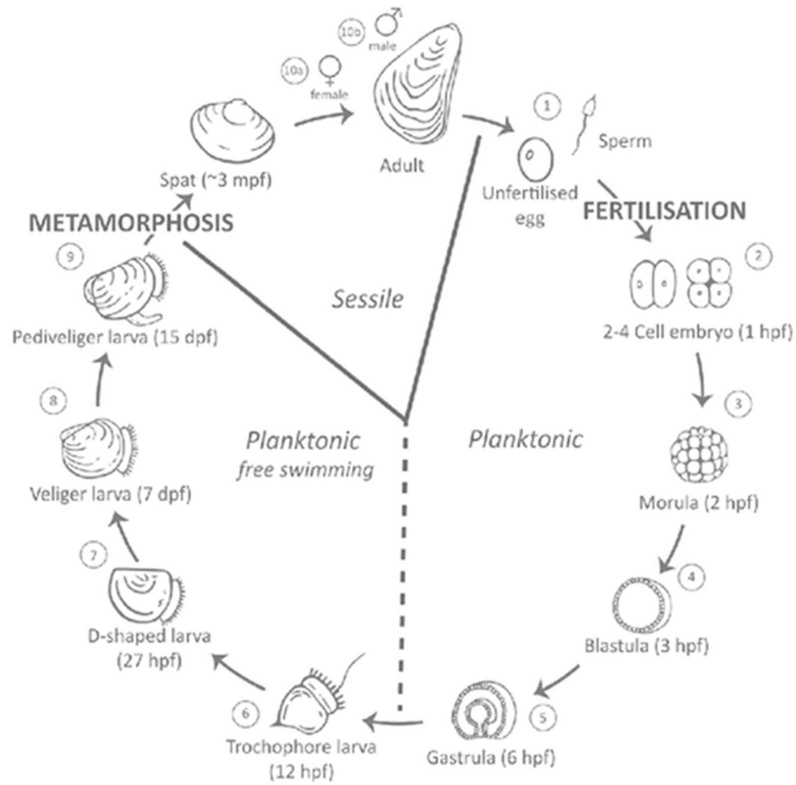

Figure 2 Lifecycle of *Crassostrea* species as demonstrated by (Vogeler et al., 2016)

The vital organs and nervous system continue to develop, while the Veliger and Pediveliger phases signify key stages in oyster shell growth, including the formation of new organs and the appearance of an eye spot. This is followed by the full development of the foot and eyespot, which signals its preparation to settle on the substrate. During the metamorphic phase, the internal organs of the *Crassostrea* species undergo significant changes. The velum is lost, and gills develop in its place. At the same time, the foot either partially or completely disappears. This process marks the transition to spat, miniature oysters with fully developed internal organs and external features resembling those of adult oysters (Fakhrina et al., 2018). They graduate to a sessile spat-juvenile phase, eventually maturing into adult (Fakhrina et al., 2018).

1.2 *Isognomon alatus*

1.2.1 Biology

The knowledge about *Isognomon alatus* is limited, so to better understand the species, information from other similar species in the Pteriidae family and the *Isognomon* genus, such as *Isognomon ephippium* (IE) and *Isognomon bicolor* (IB), will be used to bridge these gaps. IE belongs to the order *Ostreidae*, within the superfamily Pteriidae, and shares similarities with *Isognomon alatus* (Benthotage, 2022; Benthotage et al., 2020) Like most oyster species, IA is sessile and typically found in mangrove environments near streams (Romero-Murillo, Campos-Campos, et al., 2023), attaching to Rhm via byssus threads formed at the base of the foot (Siung, 1980a). IA is distributed throughout the Caribbean from Colombia through to South America, the Antilles, and the Gulf of the United States (Shah, 2016; Suarez-Ulloa et al., 2019). Morphologically, its outer shell is irregular, flat, and plate-like, with an encrusted surface, while the interior is pearly white. Younger specimens have reddish-brown shells, which change to yellow-brown or even black in older specimens (Benthotage et al., 2020; Holmes et al., 2015; Siung, 1980a). *Isognomon* can grow to a height of 3.6-14cm (36-140 mm) and tends to cluster (Benthotage et al., 2020; Shah Amena, 2016). The optimal environmental conditions for its survival include temperatures averaging 22.5°C to a maximum of 31.8°C, salinity levels from 32.5 to 38 ppt, a pH of 6.9, and dissolved oxygen levels between 47-103% (Benthotage et al., 2022; Leal et al., 2019; Suarez-Ulloa et al., 2019)

1.2.2 Reproduction

Isognomon species are strictly dioecious, meaning they have distinct male and female individuals (Queiroz et al., 2022). Their reproductive process involves the release of sperm and eggs into the water column (Figure 5), which typically occurs when salinity levels decrease at the onset of the rainy season. This environmental trigger also appears to stimulate other individuals to spawn (Siung, 1980a). *Isognomon* species such as IA are categorised as continuous reproducers, with little to no rest in between spawning events, implicating a high recovery rate after each period (Morton, 1983; Queiroz et al., 2022).The species becomes sexually mature after a year (Benthotage et al., 2020). The settlement process includes a planktonic stage where larvae undergo several developmental stages before settling. During the final phase, they undergo metamorphosis, lose their foot, and search for a suitable substrate (Figure 3). Once found, they attach themselves to mangrove roots using byssus threads (Leal et al., 2019; Siung, 1980b). It is worth noting that while the developmental stages of *Crassostrea* species are well documented, the precise stages of larval development in IA are not as well understood, presenting an opportunity for further research.

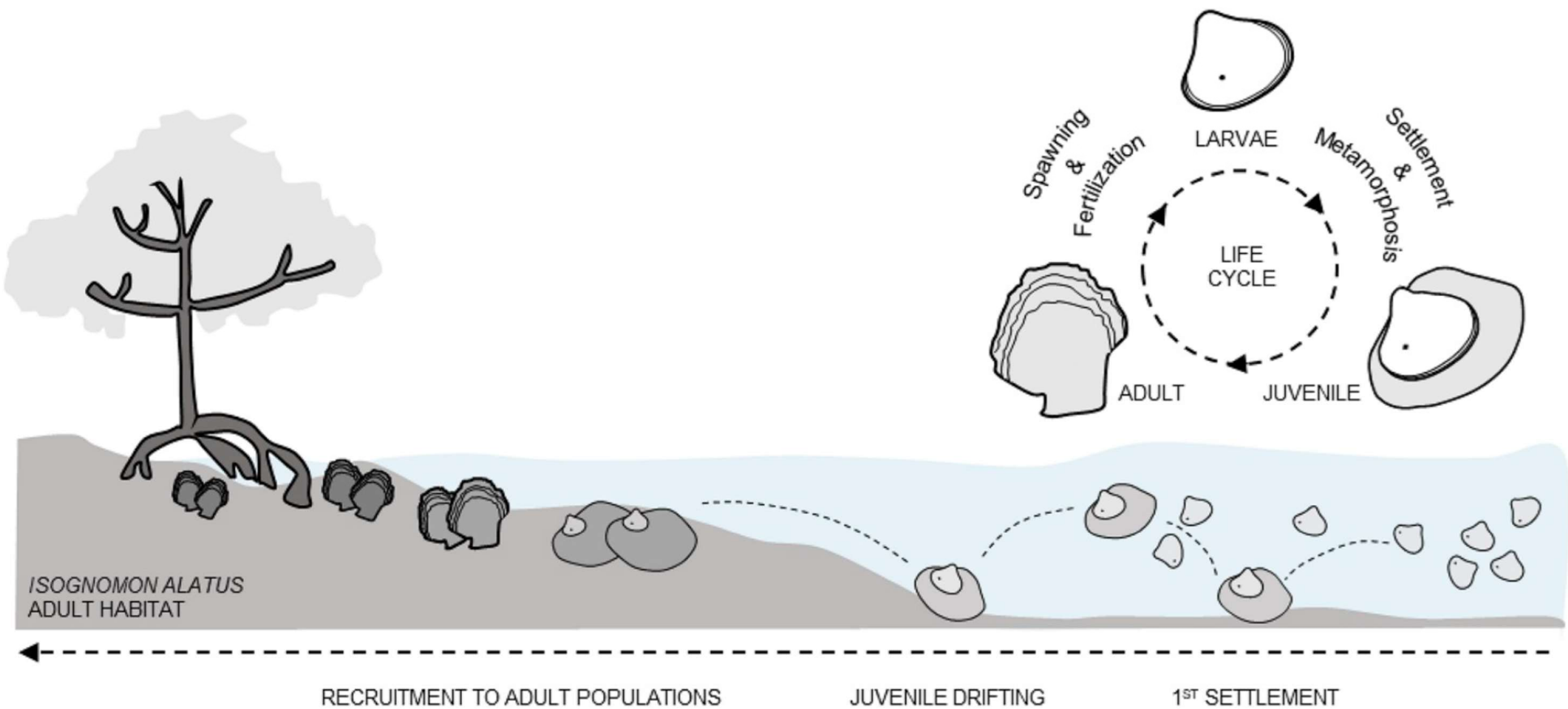

Figure 3 Lifecycle of the *Isognomon alatus* as demonstrated by (Leal et al., 2019). This displays the unique pattern of a phase: spawning, metamorphosis, first settlement, and final settlement.

2 General Feeding Behaviour of Oysters

Oysters' feeding mechanism involves the uptake of particles, preferably between 2 and 20 µm, but they can select sizes up to 100 µm (Bayne, 2017; Bougrier & Hawkins, 1997). Sea water passes over the gills, where particles are captured, filtered, and sorted using the finger-like protrusions called cilia, the extended parts of the labial palps. Particles deemed suitable for ingestion are retained, while unsuitable ones are rejected. The accepted particles are directed to the mouth, ingested, and nutrients are absorbed in the gut (Bayne, 2017). This process occurs when the oyster's shell is slightly open. Cilia on the gills beat rhythmically, creating a current that circulates water and transports filtered particles toward the mouth. Once ingested, the food moves to the stomach and is processed and absorbed in the digestive tract. Chlorophyll-a levels are often used as an indicator of food availability for oysters (Murray et al., 1986; Snyder et al., 2017).

3 Water Parameters in Oyster Development

Dissolved oxygen and salinity are two key factors that may influence oyster populations (Table 1) (Amaral & Simone, 2014; Antonio et al., 2021a). Additionally, there could be a connection between water parameters, oyster populations and the surrounding environment. However, further data analysis is needed to confirm these potential relationships.

Table 1 Water quality requirements for the survival of both mangrove oyster species CR and IA to survive in an estuary environment.

Species	*Crassostrea rhizophorae* 	*Isognomon alatus* 	
Common Name	Mangrove oyster/Cup oyster	Flat tree oyster	*(Benthotage et al., 2022; Menzel Winston, 2018).*
Environmental Conditions			
Temperature	22°C-28°C	26°C-30°C	*(Benthotage et al., 2022; Martinelli et al., 2024; Lailah et al., 2021; Nascimento, 2019; Suarez-Ulloa et al., 2019; Nikolić et al., 1976; Richard K. Wallace et al., 2008; Siung, 1980)*
Salinity	15 ppt-25 ppt	10.9 ppt-40 ppt	
pH	7	7.1-8.0	
Dissolved Oxygen	2mg/l-5mg/l	5.30 mg/l-7.9 mg/l	
Total Dissolved Soluble (TDS)	Ideal TDS -Unknown	Ideal TDS -Unknown	
Shape	Cup shape underside, flat top	Irregular shape, flat valves, rough outer shell	*Benthotage et al., 2020; Nascimento, 2019; Quamina Charnele, 2016)*
Attachment	Cementing by left valve (eventually losing the foot)	Byssus thread	*(Brian Leicester Bayne, 2017; Wilk & Bieler, 2009)*
Spawning Period	Continuous spawning (Peak – March and October)	Year-round peaks occur (drop in salinity-September and November	*(Benthotage et al., 2020; Nascimento, 2019)*
Spawning size (starting range)	11 mm-21mm	5.30 mm-11 mm	*(Antonio et al., 2021; Lailah et al., 2021)*
Reproductive category	Protandric hermaphrodite (Male then Female)	Dioecious (Single male and Female)	*(Anibal Vélez, 2018; Laing & Bopp, 2019 ;Queiroz et al., 2022)*
Settlement Size range and Settlement zone	≥ 300 µ Intertidal zone	≥ 210-280 µ Intertidal subtidal	*(Breese & Malouf, 1975; Siung, 1980; Wallace et al., 2008)*

4 Mangrove Oyster and Habitat

Oysters are part of the *Phylum Mollusca* and belong to the class Bivalvia, which includes around 9200 other species. Members of this group are characterised by having bodies compressed between two shell walls (Nascimento, 2019; Wullur et al., 2024). Other notable species in this class include Clams, scallops, and mussels (Gosling, 2015). Some oysters can display non-arboreal infaunal tendencies (living on any other substrate, e.g. tyres or stone burrowed in the substrate, e.g. sand) or arboreal (living attached to a substrate, e.g. red mangrove root, stem or leaves (Nikolić et al., 1976; Volety et al., 2014; Yahya et al., 2020). However, mangrove oysters of the *Crassostrea* and *Isognomonidae* varieties are found on the roots of the Rhm (Benthotage et al., 2020; Mancera & Mendo, 1996), some suggesting that conspecifics (previously existing oysters) within the habitat may also play a role in oyster settlement (Sussan et al., 2024). Oyster reefs, often classified as autogenic ecosystem engineers (Ramteke et al., 2023) i.e. organisms that build their habitat, play a crucial role in maintaining water quality by supporting denitrification and filtration, reducing water turbidity, and acting as carbon sinks (Ramteke et al., 2023). Oyster reefs also serve as a secondary habitat for finfish and are prey for many other species.

4.1 Distribution

Shallow brackish water estuaries within the intertidal and subtidal zones are usually the ideal areas in which mangrove oysters are found settling on rocks, shells and mangrove roots (Gosling, 2015; Morton, 1983). Distribution is known to occur across the globe from the Gulf of St Lawrence, Canada, to the Gulf of Mexico *(CV*), the West coast of Africa to the Philippines *Saccostrea cucullate* (Gosling, 2015). Some *Ostreidae* species native to the Caribbean and South American coastal waters include *CR, Crassostrea brasiliana (CB) an*d CG (Carranza et al., 2009). IA can be found in tropical and subtropical regions within the intertidal zone attached to mangrove roots from Malaysia to Panama, Florida to Tobago as well as Belize (Siung, 1980b; Wullur et al., 2024; Yap et al., 2011).

4.2 Economic importance of Bivalve

Marine bivalve production was valued at 28.9 billion USD globally (FAO, 2024). They are prized for their health benefits and taste. They provide essential minerals such as selenium, iodine, and calcium, nutrients such as protein, and a rich source of vitamins D and A and omega-3 fatty acids (Smaal et al., 2019). Hence the demand. Aquaculture accounts for 14% of global seafood production, and 89% of marine bivalves are produced from aquaculture sources. Overall, average production between 2010 and 2015 was 15 million tons per year (Smaal et al., 2019). It is clear to what extent the magnitude of bivalve production is and how important it is to ensure sustainability. We must, therefore, protect our resources, which can only be done by understanding how oysters interact in their natural environment. Based on their ability to provide food for these organisms, oyster reefs within a fifty-year lifespan are valued at approximately USD $40,000, which is additional value for finfish and crustacean fisheries (Volety et al., 2014). There is yet to be a cost associated with the production of *IA*.

5 Objective

This research aims to better understand the influence of distance from a river and water quality parameters on the mangrove oyster population and how oysters interact with other existing organisms, especially those within the estuary. This phenomenon is common within mangrove areas worldwide; however, to focus on the Caribbean perspective, it was ideal to use a small area, Bowden Bay, Jamaica, to test the following hypotheses.

1. Does distance from the river impact the mangrove oyster population's prevalence and size (length and height)?
2. Is there is a link between water parameters, mangrove oyster population prevalence and size (length and height)?

6 Material and Methodology

6.1 Sampling

6.1.1 Study Area Description

Bowden Harbour (17°53'20.2"N 76°19'03.0" W), often called Bowden Bay by Jamaicans, is located in the district of Pera on the Eastern side of the Island of Jamaica in the parish of St Thomas. The Harbour is divided into two sections (Figure 4), separated by a mud pit. The larger outer bay is approximately 2.96 km long followed by a smaller inner bay, at 0.58 km long. The Bay is fed by two rivers: Ginger River and Beating River (Wright, 1992). Generally, within an estuary environment, IA is found on the mangrove roots (Wullur et al., 2024). Within the inner bay (the area of study), the RM (red mangroves) are located along the outer edges. On the roots of the Rhm, *CR* settle and call home. A majority of the CR adults are found within the inner bay (Littlewood, 1988; Wade et al., 1981; Wright, 1992). This area is also where the National Fisheries Authority Oyster obtains spat for grow-out, which is why it was chosen for the study—the total mangrove expanse of the inner bay measures 2,078 m.

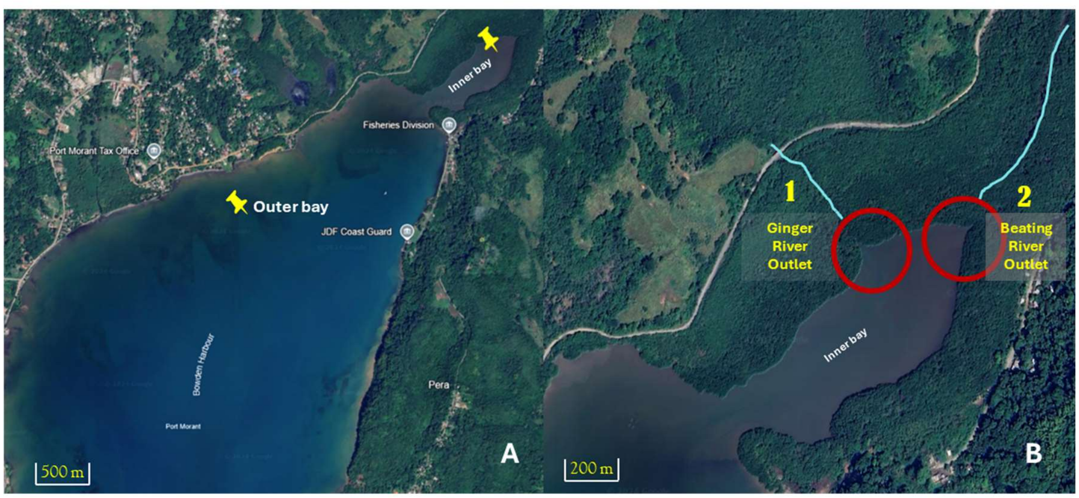

Figure 4 (A) Bowden Bay, St Thomas, Jamaica showing the location of the inner and outer Bay, (B) Inner Bay where two rivers (1) Ginger River and (2) Beating River empties within the bay . Google Earth (2024)

The study focused on two economically important bivalve species found on the roots of the red mangrove (Figure 5) that can be submerged at high tide i.e., mangrove oyster (*CR)* and flat tree oyster (*IA)*.

Figure 5 *Crassostrea rhizophorae* (A) and *Isognomon alatus* (B) attached to the *Rhizophorae mangle* roots in Bowden Bay St Thomas.

Three periods (January, February and March 2023) were chosen at the end of the 2022 spawning season to ensure proper weather conditions for accessing sampling sites. The focus of the study was not on spat recruitment. Using a measuring tape, a 396 m line transect was established along the edge of the inner Bay's northwestern area. An area 154 m from the river was chosen as the starting point for the transect (top) and labelled BMSS1. Subsequently, following the first point of establishment, two more areas (stations), BMSS2 and BMSS3, were established at the 198m mark and 369 m mark.

Figure 6 Layout of study area within the inner bay of Bowden Bay St Thomas Jamaica

A 10 m line transect at each station was placed parallel to the mangrove, using a measuring tape to create as straight a line as possible. The line started from the beginning point of each station and moved towards the left from 0m to 5m until the 10 m mark was reached (categorized as segments, Figure 6). Preliminary observations in the field revealed that it was impossible to go deeper into the mangrove; therefore, only the oysters located at the edge of the mangroves were sampled.

To keep track of sampled areas, each station was marked using a Garmin GPS max 60-CSx handheld device (Schmidt et al., 2008) and each segment was marked using a surveyor's tape. Yellow was used to identify the 0-meter and 10-meter areas, and red was used to identify the 5-meter mark of each station´s segment. A belt transect method was used to sample the oyster population (Frederick et al., 2016; Kimani et al., 2002) from each segment at each station. 10 root specimens were randomly selected using a 1m^2 quadrat frame made of plastic at each segment of each station along the mangrove root during low tide. After each root was removed, masking tape and a marker was used to label the root with the station, segment and a random number one to ten was assigned (BMSS1-0-1).

Each root was then placed in a designated section of the boat according to the station it was collected from and transported to the dock of the NFA's research post. Samples were then offloaded and placed in the saltwater, grouped according to their stations. Each period involved collecting 10 root specimens per quadrat at each of the three segments (0m, 5m, and 10m) totalling 30 per station (BMSS1, BMSS2, BMSS3) along the transect. A total of 270 roots were collected over the entire duration of the study.

6.1.2 Oyster Parameters

Firstly, two species of oysters were noted on some of the roots: *CR* and *IA.* Each mangrove root followed the protocol of having its length measured (in meters) using measuring tape. A final tally was conducted to ascertain the total oyster count per species on each root collected. Then, 30 oyster specimens from each species were selected through stratified randomisation based on habitat within the mangrove. their height (from the umbo to the top of the shell, in mm) and length (the widest portions of the oyster, in mm) were then collected using an electronic digital vernier calliper. Where there were less than 30 specimens per species, all specimen information was collected and logged.

Each root was then placed in a designated section of the boat according to the station it was collected from and transported to the dock of the NFA's research post. Samples were then off loaded and placed in the saltwater, grouped according to their stations. Each period involved collecting 10 root specimens per quadrat at each of the three segments (0m, 5m, and 10m) totalling 30 per station (BMSS1, BMSS2, BMSS3) along the transect. A total of 270 roots were collected over the entire duration of the study.

6.1.3 Environmental Variables

Surface water samples (0.25m deep) were collected at each segment of each sample station. Surface water is ideal due to the tidal range in which MO is found, 10-15 cm, and at low tide, 25-35 cm Nikolić et al., (1976). Water Parameters such as temperature, salinity, dissolved oxygen, pH, and total dissolved solids were measured *in situ* at every station's segment, using a YSI handheld digital meter with a probe (Guimaraes et al., 2008). A Hannah Instrument pocket pH/temperature meter was used for pH readings. Beginning at period one through to three Chlorophyll *a* assessment was done following the protocol described by previous authors (Liu et al., 2014).Water samples (1000ml) were collected and kept cool in a covered igloo away from light and processed the following day at the Port Royal Marine Lab in Kingston. Filtration was done through a Whatman GF (Glass fibre) filter paper (sizes 2.7µm, 0.7 µm and 20 µm) in a Nalgene size fractionating filter 24 hrs after collection. Filters were then frozen for 48 hrs. Lab analysis of chlorophyll *a* was done at the University of the West Indies lab (Hardikar et al., 2022; Webber & Webber, 1998). A 90% acetone solution was used to extract the chlorophyll *a*, and final readings was done using a Sequoia-Turner fluorometer (Hardikar et al., 2022; Webber & Webber, 1998) and measured in mg/L.

6.2 Statistical Analysis

All statistical analyses were performed with R v.4.3.3 (R Core Team 2022). Data were checked for normality and tested for homoscedasticity assumptions using the R package DHARMa (Hartig, 2022). Two types of R-squared values were computed to evaluate the explanatory power of the fitted mixed-effects models: the marginal R^2M and the conditional R^2C. R^2M quantifies the proportion of variance explained by the fixed effects alone, while R^2C represents the proportion of variance explained by both the fixed and random effects combined. The Nakagawa and Schielzeth (2013), approach using the MuMIn package (version 1.48.4) was used to calculate the metrics of the combined effects. Using both R^2M and R^2C allows for assessing the relative contributions of fixed and random effects to the overall model performance. R^2R, representing the difference between R^2C and R^2M, was employed to estimate the variance of random factors.

6.2.1 Oyster Count

To examine the influence of the distance from the river of both *CR* and IA, a negative binomial zero-inflated model using the glmmTMB package (Brooks et al., 2024) was performed. The statistical model employed was as follows:

NI-STA*SPC+RTLNGTH+(1|PRD:STA:SEGM)

Oyster count (NI) as a response variable. Station (STA) and species (SPC) were fitted as fixed effects, and root length (RTLNGTH) as a covariable. Finally, the segment (SEGM) was nested in the station, and the period (PRD) was fitted as a random effect (PRD:STA:SEGM) . A type III analysis of Variance (ANOVA) (car package, Fox & Weisberg, 2019) was employed to specify the relationships and interactions, followed by a post hoc test pairwise comparison to determine the significant relationships regarding the interaction using the glht function (Bretz et al., 2011).

6.2.2 Oyster Measurements

To examine whether there were length or height differences between species and stations, we applied a linear mixed model using the lme4 package (Bates et al., 2015). The statistical model was as follows:

LSQRT-SPC*STA+(1|PRD:STA:SEGM:RT)

WSQRT-SPC*STA+(1|PRD:STA:SEGM:RT)

Oysters' length (LSQRT) and height (WSQRT) were square root transformed to comply with the normality. Length or height was fitted as response variables, species (SPC) interacting with the station (STA) as fixed effects, and root (RT) nested in the segment (SEG), station (STA) and period (PRD) as the random effect. Type III analysis of variance tests ANOVA was done to specify the significant relationships and interactions, followed by a post hoc test pairwise comparison to determine the significant relationships regarding the interaction.

6.3 Competition

To investigate what species was more prevalent among stations, I subset the dataset to include only the roots where both species occurred. A quasi-binomial linear model using the MASS package (Venables et. al., 2002) was employed as follows:

Y-STA + (1|PRD:STA:SEGM)

The model used the proportion of species CR (Y) as the response variable, with the station (STA) as a fixed effect, the segment (SEGM) nested within the station (STA), and the period (PRD) as a random effect. Then, a type II ANOVA was performed to assess the station's effect.

6.4 Water Parameters

To examine whether there was any difference regarding the water parameters among stations i.e., distance from the river the following statistical model was employed

Water parameter-STA+(1|PRD:STA)

Each water parameter (pH, Temperature, DO, TDS, Salinity, Chlorophyll *a*) was fitted as the response variable in a linear model using the lme4 package (Bates et al., 2015). The station (STA) was fitted as a fixed effect, and the station was nested in the period (PRD) as a random effect. A type II ANOVA was employed to evaluate the effect of the station, followed by a pairwise comparison to see precisely which stations were statistically significant.

7 Results

All three stations were examined to see if the distance from the river affected the oyster population of both CR and IA. Two hundred seventy rhizophorae root samples were collected in total. Different categories of roots were identified throughout the study: those with both oyster species, those with only CR or IA, or those without oysters.

7.1 Oyster Count

Overall, for total oyster count, there was a significant interaction between station and species and a significant effect of root length (Table 2). The larger the root length, the more oyster specimens were present. Interactions were examined using a pairwise comparison to determine which relationships were significant.

Table 2 Results of zero inflation model testing total oyster count based on the fixed factors: Station (BMSS1, BMSS2, BMSS3), species (*Crassostrea rhizophorae; Isognomon alatus)* and root length against the random factors of period, station and segment. Significant effects are indicated in bold.

Random effect					
AIC	BIC	Log lik	Deviance	Df residual	
3057.4	**3113.1**	**-1515,7**	**3031.4**	**525**	
Groups	Name	Variance	Std. Dev.		
PERIOD:STATION:SEGMENT	(Intercept)	0.29	0.53		
Conditional model					
	Estimate	Std. Error	Df	**X2**	P
Intercept	2.37	0.31	1	58.59	**< 0.001**
BMSS2	-1.13	0.32	2	18.19	**< 0.001**
BMSS3	0.06	0.30	2	18.19	**< 0.001**
IA	-0.13	0.23	1	0.34	0.56
Root Length	0.45	0.15	1	8.70	**< 0.001**
BMSS2: IA	-0.93	0.34	2	9.42	**< 0.001**
BMSS3: IA	-0.76	0.28	2	9.42	**< 0.001**
Response: Total Oyster Count					
	Estimate	Std. Error	z value	Pr(>|z|)	
(Intercept)	-1.46	0.33	-4.38	**<0.001**	
IA	0.98	0.44	2.22	0.026	
BMSS2	-21.38	52639.38	0.00	1.00	
BMSS3	-16.77	2690.91	-0.01	1.00	

A significant effect was seen where *CR* numbers were higher in BMSS1 than in BMSS2 and higher in BMSS3 than in BMSS2 (Figure 7). Analysis of IA species interactions also yielded significant results. Both stations BMSS1 and BMSS3 contained higher quantities of IA than BMSS2, and both BMSS2 and BMSS3 contained significantly higher numbers of CR than IA. Fixed factors explained 27% of the variance in oyster count (R^2_M = 0.27), whereas random factors explained 11% of the variance (R^2_R = 0.11).

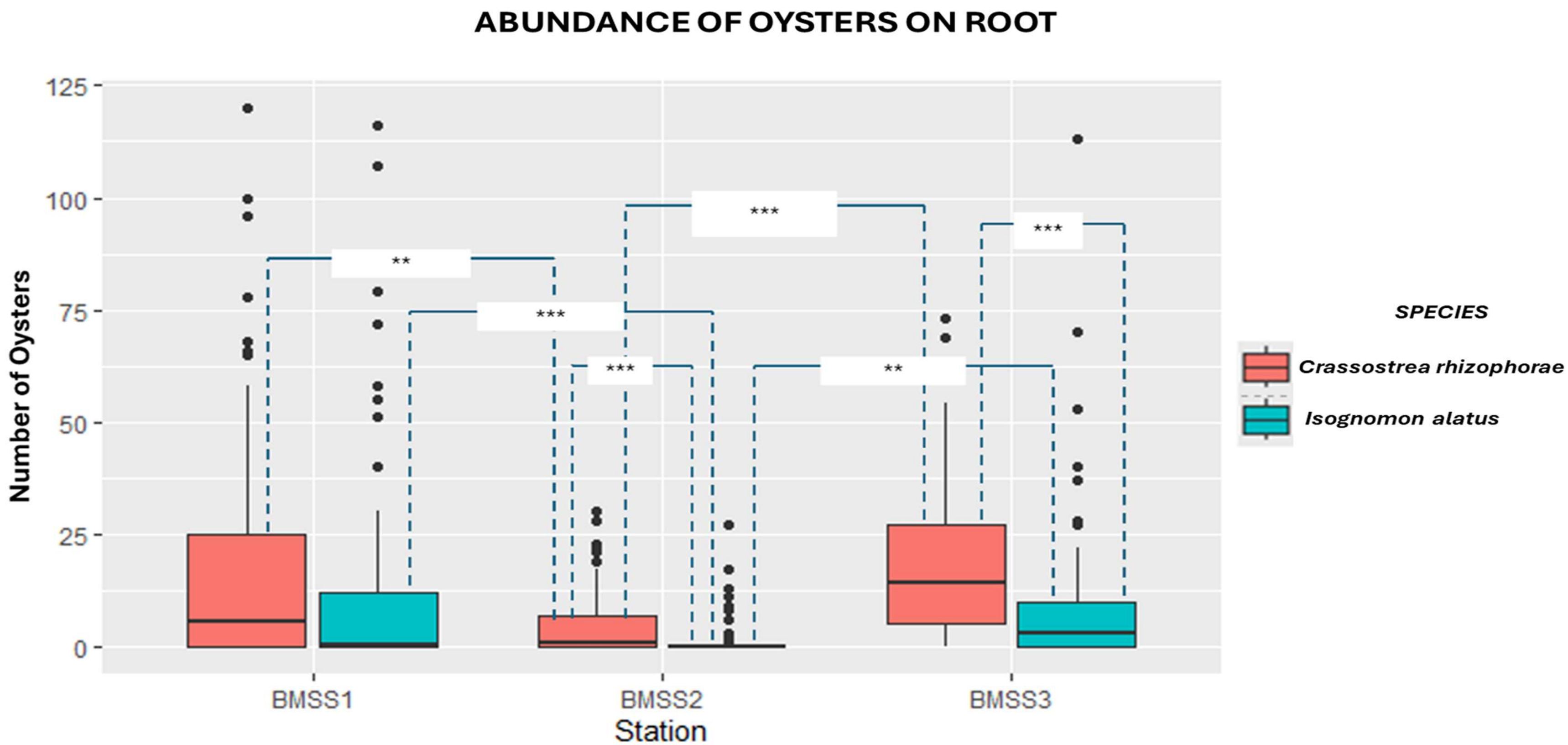

Figure 7 Box plots showing the median, first and third quartile of specimen abundance for *Crassostrea rhizophorae; Isognomon alatus* species between stations BMSS1, BMSS2, and BMMSS3. Asterisks (*p-value<0.05, ** p value<0.01, *** p value < 0.001) represent significance between species and station.

In this study, several RhM roots were without oysters. The bar graph (Figure 8) shows the number of roots without oysters for both species. IA had significantly higher zero counts than CR, regardless of the station.

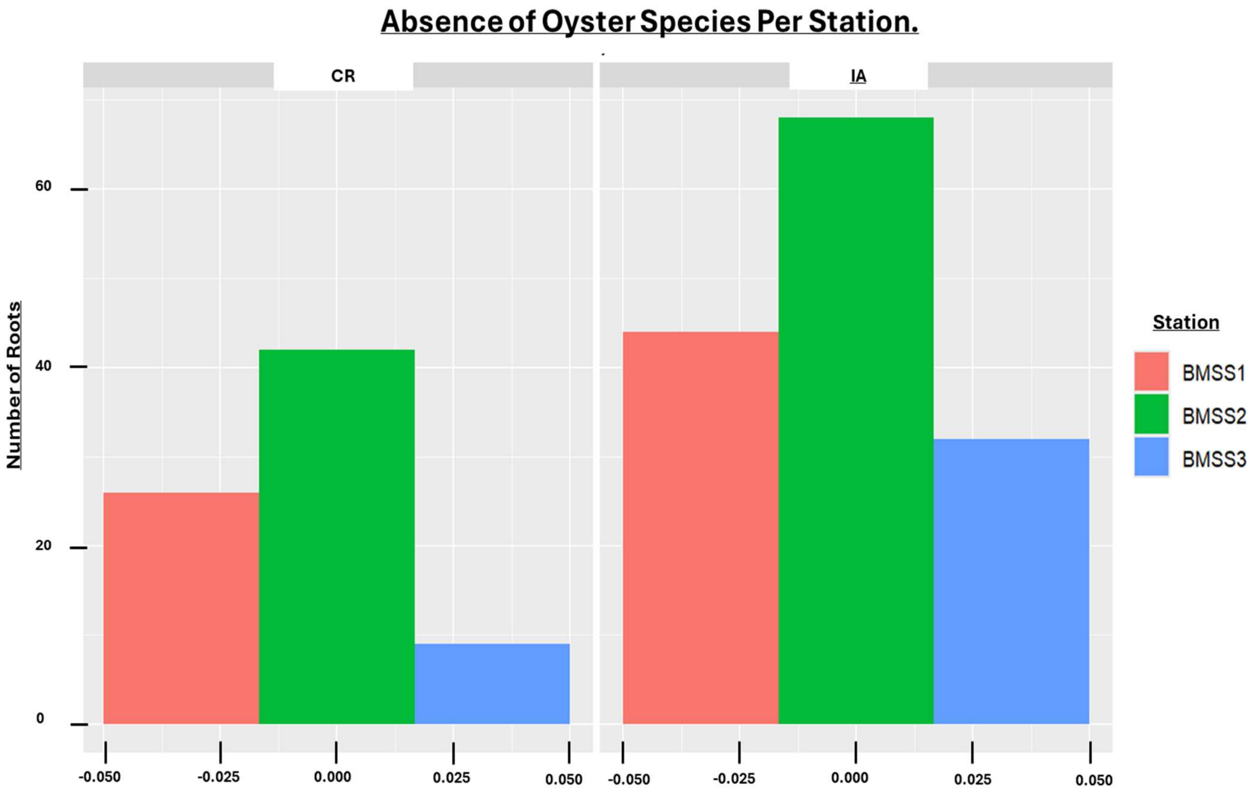

Figure 8 Analysis of Rhizophorae mangle roots containing no CR : *Crassostrea rhizophorae* or IA: *Isognomon alatus* oyster specimen present per station (BMSS1, BMSS2 and BMSS3) throughout the entire study.

7.2 Oyster Height

A significant difference was seen between station and species (Table 3) regarding oyster height. Specimens from BMSS1 had significantly larger heights than those from BMSS2 and BMSS3 for IA only (35.20±24.82 mm and 25.03±14.64 mm, 23.97±15.89 mm, respectively). Interspecies effects were observed only in BMSS1 and BMSS3 (Figure 9) respectively, with IA showing a larger height than CR (35.20±24,82 mm and 18.58±12.24 mm, respectively). There was no significant difference in height for *CR* among all three stations (18.58±12.24 mm, 16.24±9.52 mm, and 16.16±8,83 mm, respectively). 6.5% of the variance in oyster height (R^2_M = 0.065) was explained by the fixed factors, whereas random factors explained 44.5% of the variance (R^2_R = 0.445).

Table 3 Result of mixed-effects model, testing the effect of species (*Crassostrea rhizophorae; Isognomon alatus*) and station (three stations: BMSS1, BMSS2, BMSS3) on oyster shell height. Significant effects are in bold.

Oyster Height Analysis

Random effects:					
Groups	Name	Variance	Std. Dev.		
PERIOD:STATION:SEGMENT	(Intercept)	1.10	1.05		
Residuals		1.20	1.09		
Fixed Effects:					
	Estimate	Std. Error	Df	**X2**	p
Intercept	4.01	0.14	1	816.59	**< 0.001**
IA	0.96	0.06	1	252.16	**< 0.001**
BMSS2	-0.08	0.22	2	0.31	0.276
BMSS3	-0.10	0.19	2	0.31	0.276
IA:BMSS2	-0.80	0.16	2	49.09	**< 0.001**
IA:BMSS3	-0.58	0.10	2	49.09	**< 0.001**

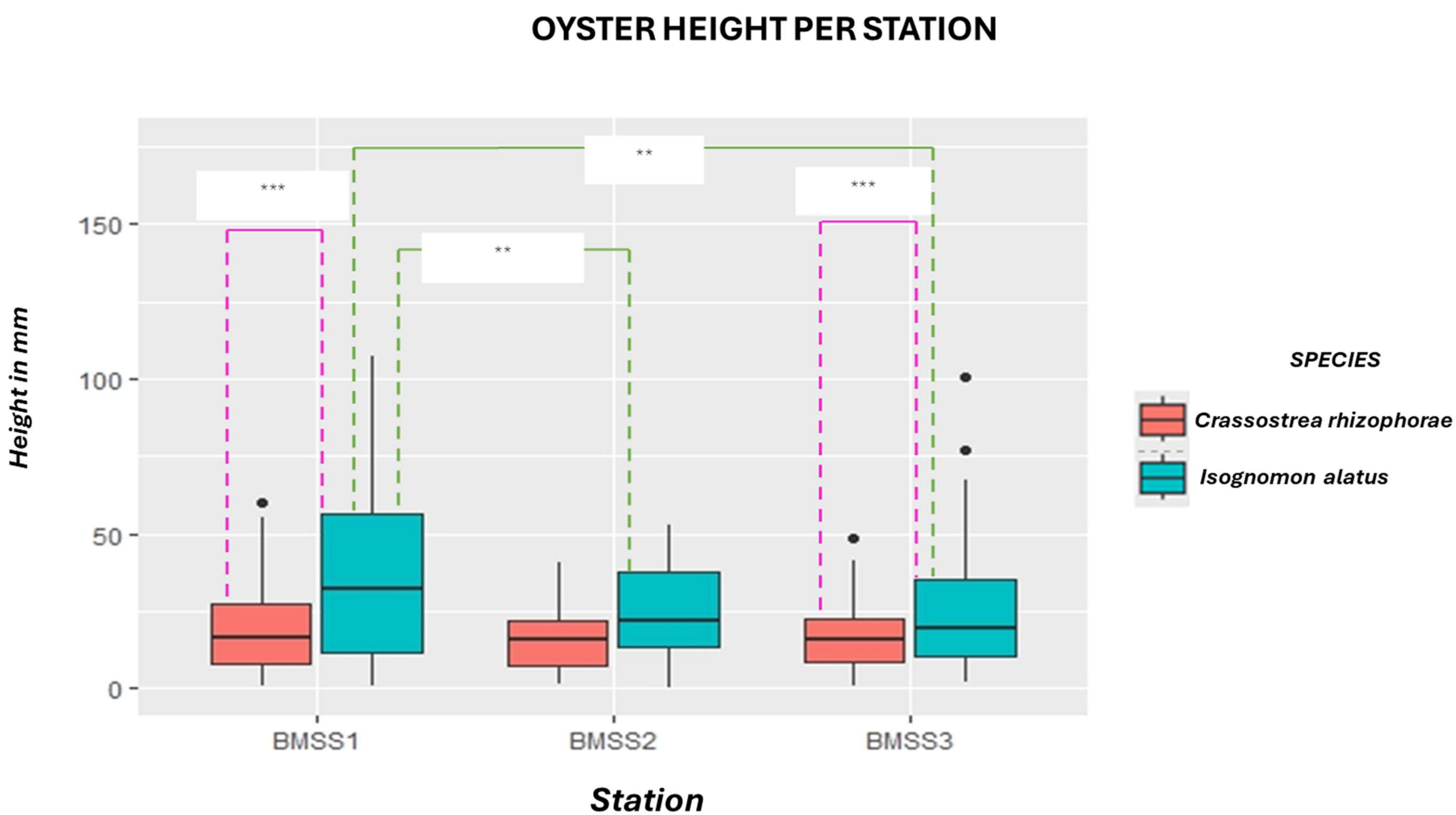

Figure 9 Box plots showing the median, first and third quartile of specimen height for *Crassostrea rhizophorae; Isognomon alatus* species between stations BMSS1, BMSS2, and BMMSS3. Asterisks (*p-value<0.05, ** p value<0.01, *** p value < 0.001) represent significant difference between species.

7.3 Oyster Length

The results for oyster length (Table 4) were similar to those for oyster height (Table 3). There was a significant interaction between species and stations.

Specimens from BMSS1 were significantly larger than those from BMSS2 and BMSS3 for IA only (Figure 10). Interspecies effects were observed only in BMSS1 and BMSS3, respectively, with IA being longer compared to *CR*. BMSS1 had the highest length for CR among all three stations at 14.67mm±11.92. Between stations BMSS2 and BMSS3, there was no significant difference in length, 11.50±6.62 and 11.63±6.08, respectively. Ten percent of the variance in oyster length (R^2_M = 0.10) was explained by fixed factors whereas random factors explained 41% of the variance (R^2_R = 0.41).

Table 4 Result of mixed-effects model testing the effect of Species (*Crassostrea rhizophorae; Isognomon alatus*) and Station (three stations: BMSS1, BMSS2, BMSS3) on oyster shell length. Significant effects are in

Oyster Length Analysis

Random effects:					
Groups	Name	Variance	Std. Dev.		
PERIOD:STATION:SEGMENT	(Intercept)	0.89	0.97		
Residuals		1.06	1.03		
Fixed effects					
	Estimate	Std. Error	Df	X2	p
Intercept	3.60	0.13	1	797.16	< **0.001**
IA	1.02	0.06	1	317.03	< **0.001**
BMSS2	-0.26	0.20	2	2.56	0.28
BMSS3	-0.25	0.17	2	2.56	0.28
IA:BMSS2	0.43	0.15	2	19.40	< **0.001**
IA:BMSS3	-0.36	0.09	2	19.40	< **0.001**

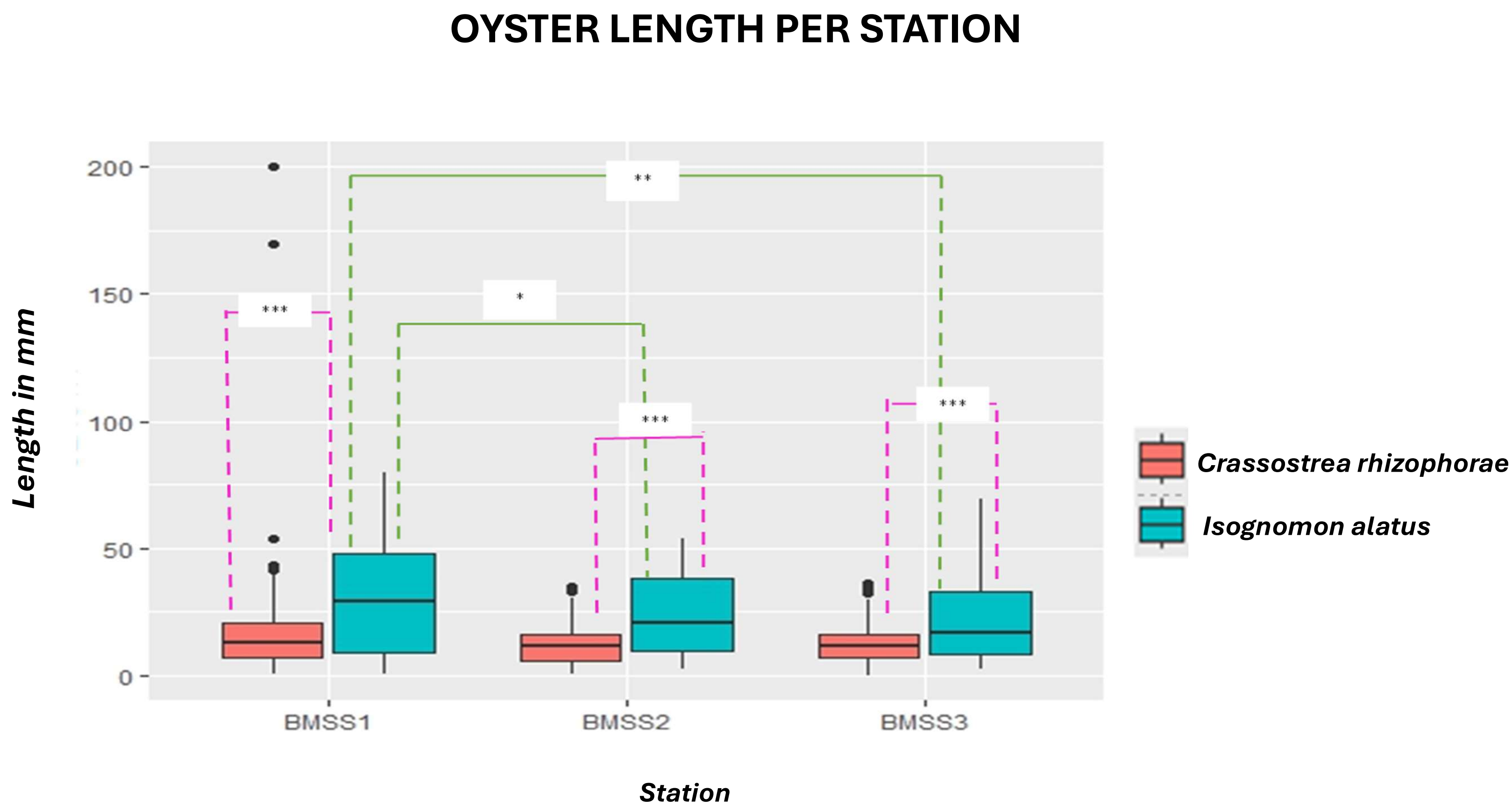

Figure 10 Box plots showing the median, first and third quartile of specimen length for *Crassostrea rhizophorae and Isognomon alatus* species between stations BMSS1, BMSS2, and BMMSS3. Asterisks (* p value <0.05, ** p-value <0.001, *** p-value < 0.0001) represent significance of interactions between species and stations.

7.4 Interspecies Competition

When looking specifically at the roots where both species were present, a significant difference was found between stations (Table 5) for the proportion of *CR* on the roots. As they move along the stations (Figure 11), the number of CR present increases, with BMSS1 at 50%, BMSS2 at 60%, and BMSS3 at 70%, respectively. The proportion of CR tended to increase from BMSS1 to BMSS3 but only significantly differed between BMSS1 and BMSS3. The fixed factors explained 45% of the variance in the CR proportion (R^2_M = 0.45), while the random factors explained 36% of the variance (R^2_R = 0.36).

Table 5 Results of a quasi-binomial model testing the proportion of *Crassostrea rhizophorae* in comparison with *Isognomon alatus* when both species are present on the root of the mangrove.

Oyster Competition Analysis

Random effect					
Groups	**Name**	**Variance**	**Std. Dev.**		
Period:Station:Segment	(Intercept)	0.2916	0.54		
	Residuals	8.0656	2.84		
Fixed effects					
	Estimate	**Std. Error**	**Df**	**X2**	**P**
Intercept	-0.41	0.23			
Station-BMSS2	0.85	0.44	2	14.12	**<0.001**
Station-BMSS3	1.19	0.32	2	14.12	**<0.001**

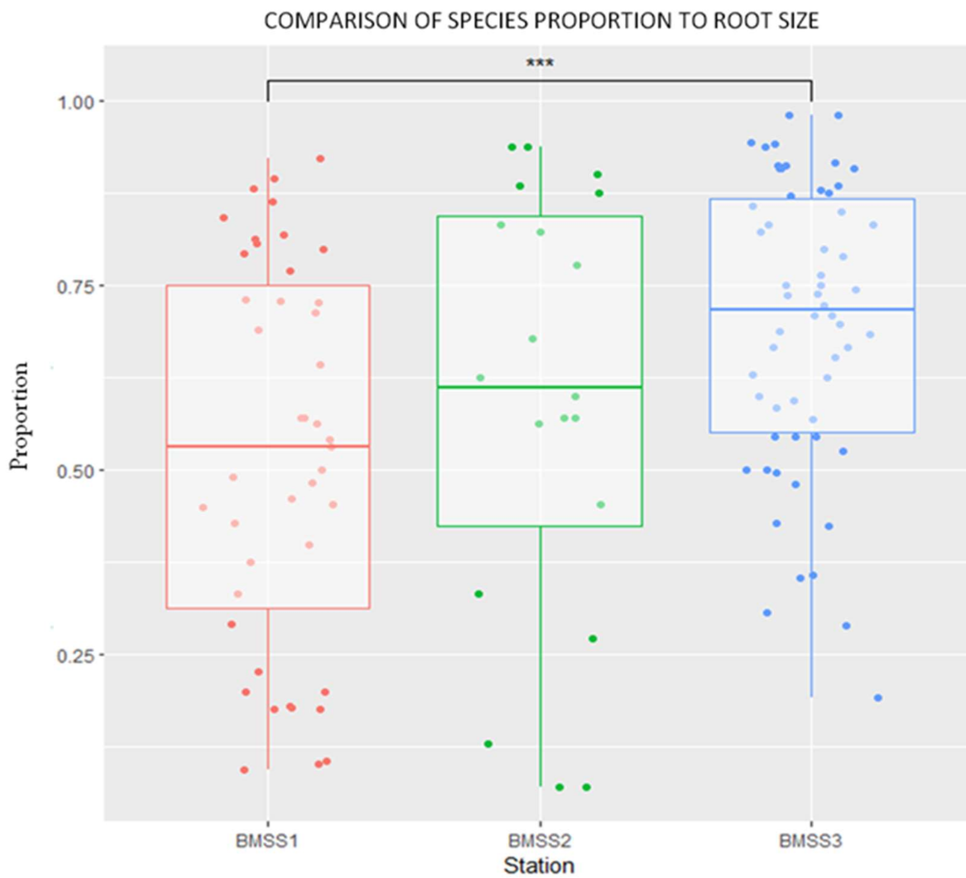

Figure 11 Proportion of *Crassostrea rhizophorae* on the root in comparison with *Isognomon alatus* in three different stations samples in the study site, Bowden Bay, St-Thomas. Box plots show medians, first and third quartiles (middle, upper and lower hinge, respectively). Asterisks (* p value <0.05, ** p-value <0.001, *** p-value < 0.0001) represent significance of interactions between species and stations.

7.5 Water Parameters

The results of water parameters among the stations (Table 7) shows the significant difference between the stations. All water parameters tended to increase from BMSS1 to BMSS3 (Figure 12). Analysis shows a tendency for higher temperature for station BMSS 3 than BMSS1 (27.91°C ±0.42 and 25.90 ±1.06 °C, respectively). Salinity ranges tended to be higher in BMS3 at (36.57 ± 0.67 ppt) than in BMSS1 at 30.94 ± 4.13 ppt. Dissolved oxygen was significantly higher in BMSS3 (82.43±5.86%) compared to BMSS1 (43.00±13.64%) and BMSS2 was significantly higher than BMSS 1 (68.04±8.75% and 43.00 ±13.64 %, respectively). TDS increased gradually from 31464.33 mg/l ± 3334.17 at BMSS1, 34516.44 mg/l±1168.26 at BMSS2 and 35924.89 mg/l ± 587.67 at BMSS3 but differed significantly only between BMSS3 and BMSS1 Chlorophyll *a* only showed a slight increase from stations 1,2 and 3 at (2.28 µg/l ± 1.43, 3.18 µg/l ± 1.71and 4.25 µg/l ± 2.37, respectively but no significant difference between stations could be shown. Finally, pH gradually increased from 5.27±2.23 at BMSS1 to 6.07±2.21 at BMSS2 and 6.58±2.27 at BMSS3, but no significant difference. The average ranges in this study for stations 1, 2, and 3 are listed in (Table 6). It shows that all parameters were within range compared to the ideal readings mentioned in (Table 1) The station explained 12 to 73% of the variance according to the water parameter, whereas random factors explained 14 to 50% of the variance (Table 5).

Table 6 Mean and standard deviation of water quality parameters for BMSS1, BMSS2 and BMSS3 located within the estuary of Bowden Bay, St Thomas., Jamaica

Mean and SD Water Parameter Readings Per Station						
STATION	TEMPERATURE °C	SALINITY µg L^{-1}	DISSOLVED OXYGEN mg L-1	CHLA µg/L	TDS µg/L	pH
BMSS1	26.00 ± 1.12	30.9 ± 4.37	3.05 ± 0.91	2.29 ± 1.52	31464 ± 3527	6.98 ± 0.49
BMSS2	27.40 ± 0.83	35.00 ± 1.40	4.69 ± 0.28	3.39 ± 1.82	34516 ± 1236	7.98 ± 0.29
BMSS3	28.00 ± 0.44	36.60 ± 0.71	5.65 ± 0.36	4.25 ± 2.51	35925 ± 622	8.10 ± 0.34

Table 7 Water quality analysis between stations BMSS1, BMSS2, and BMMSS3 with . (p- value <0.1,* p-value <0.05, ** p-value <0.01, *** p-value < 0.001). Significant effects are in bold.

Water Parameter	Fixed Effects	Estimate	Standar Error	Df	X2	P	R^2_M	R^2_C
Temperature	Intercept	26.02	0.51					
	Station-BMSS2	1.36	0.72	2	7.34	**0.025**	**0.45**	**0.95**
	Station-BMSS3	1.90	0.72	2	7.34	**0.025**		
Salinity	Intercept	31.46	1.17					
	Station-BMSS2	3.53	1.67	2	9.87	**0.007**	**0.37**	**0.55**
	Station-BMSS3	5.71	1.67	2	9.87	**0.007**		
Dissolved Oxygen	Intercept	45.55	3.93					
	Station-BMSS2	22.50	5.68	2	43.12	**<0.001**	**0.73**	**0.73**
	Station-BMSS3	36.89	5.68	2	43.12	**<0.001**		
TDS	Intercept	31826.68	849.47					
	Station-BMSS2	2689.76	1282.40	2	10.59	**0.005**	**0.37**	**0.51**
	Station-BMSS3	4098.21	1282.40	2	10.59	**0.005**		
Chlorophyll *a*	Intercept	2.29	1.14					
	Station-BMSS2	0.89	1.62	2	1.47	0.47	**0.12**	**0.77**
	Station-BMSS3	1.96	1.62	2	1.47	0.47		
Ph	Intercept	7.12	0.22					
	Station-BMSS2	0.85	0.31	2	11.53	**0.003**	**0.56**	**0.72**
	Station-BMSS3	0.96	0.31	2	11.53	**0.003**		

Random effect

Groups	Name	Variance	Std. Dev.
PERIOD:STATION	(Intercept)	0.75	0.87
Residuals		0.08	0.29

Random effect

Groups	Name	Variance	Std. Dev.
PERIOD:STATION	(Intercept)	2.32	1.52
Residuals		5.87	2.42

Random effect

Groups	Name	Variance	Std. Dev.
PERIOD:STATION	(Intercept)	9.10	3.02
Residuals		123.82	11.13

Random effect

Groups	Name	Variance	Std. Dev.
PERIOD:STATION	(Intercept)	118853	1090
Residuals		4018568	2005

Random effect

Groups	Name	Variance	Std. Dev.
PERIOD:STATION	(Intercept)	3.53	1.88
Residuals		1.27	1.13

Random effect

Groups	Name	Variance	Std. Dev.
PERIOD:STATION	(Intercept)	0.06	0.24
Residuals		0.10	0.31

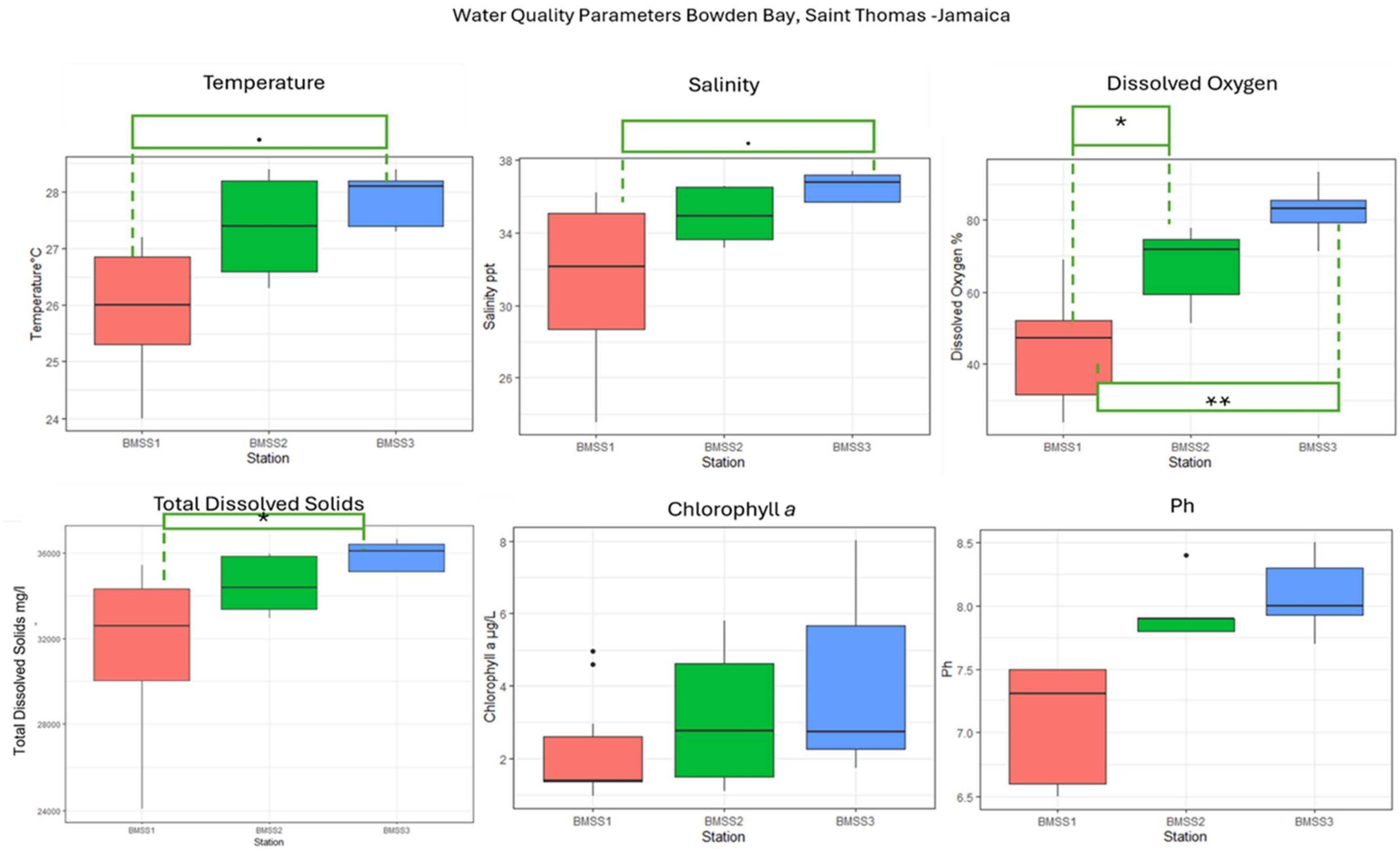

Figure 12 Box plots showing the median, first and third quartile of water parameters for stations BMSS1, BMSS2, and BMMSS3. (p- value <0.1,* p-value <0.05, ** p-value <0.01, ***) represent significance readings.

8 Discussion

The primary objective of this study was to examine the influence of distance from the open sea and associated abiotic factors on the population abundance and shell dimensions (length and height) of the two oyster species, CR and IA, within a mangrove estuary environment. The findings showed an increase in the Mangrove Oyster CR population versus the Flat Tree Oyster IA population as we move towards the open sea. Factors contributing to the settlement and development of oyster populations are vast and inexhaustible. However, we could identify conditions that could potentially explain the results regarding the population abundance establishment and shell dimensions of the two targeted species within the estuary. The results from this study on CR and IA represent a comprehensive first attempt to understand better the population structure of prominent oyster species within an estuary environment, i.e., Bowden Bay, St Thomas Jamaica

8.1 Population prevalence, dimension and Zero count roots

Our first research question, i.e., Does distance from the river impact the prevalence and size of the mangrove oyster population, can be validated. Distance impacts the oyster population; a higher abundance of CR was noticed closer to the open sea. Both CR and IA demonstrated variability in population prevalence and oyster dimension, which was higher at the first and third sites and lower at the second site. When considering mangrove roots, more roots without individuals were identified for the IA population, regardless of the station. However, most roots without both individuals were seen in the second station. Oyster dimensions (length and height) showed variation between the species among the three sites, with larger individual IA than CR between the first and third sites but less pronounced between the second and third sites. Overall, the first site had the largest oyster dimensions for IA. The proportion of CR was consistently higher on the roots compared with IA, and this difference increased as we proceeded towards the sea. Observations during the study showed IA featuring lower on roots and CR within the intertidal zone.

8.2 Water Quality Parameters and Mangrove Root

Our second research question, i.e., Is there a link between water parameters and mangrove oyster population prevalence and size, was also confirmed. The freshwater influx causes the station closest to the river to have a lower temperature, DO, salinity, TDS, and pH values along the gradient of the study sites. The last station, closest to the open sea, had the highest readings for the abovementioned parameters. Chlorophyll-a also showed a tendency to increase, although not significantly. Oysters usually establish themselves where water parameters are optimal. Though CR and IA differ slightly when considering water quality parameters as demonstrated in Table 1 both species would be able to survive in similar ranges with subtle differentiation, as shown in Table 6. DO requirement for both species range above 5mg/l (Brandão et al., 2013); temperature ranges are similar for CR and IA between 25°C to 30°C; (Akita et al., 2021; Amaral et al., 2014; Gardunho et al., 1983; Romero-Murillo, et al., 2023); ideal pH levels for both CR and IA is 7.5-8.5 (Akita et al., 2021; Antonio et al., 2021); Chlorophyll-a concentration for IA is ideal at over 5 µg/L (Leal et al., 2022), while for CR, ranges are suggested to be between 5-20 µg/L (Lenz et al., 2011). TDS ideal ranges for CR and IA are not well documented but are tied to the salinity range (Antonio et al., 2021; Romero-Murillo, et al., 2023). Regarding salinity, both species survive when the salinity range is between 20-36 ‰ (Antonio et al., 2021; Polo-Osorio & Campos, 2016). However, there is a slight difference in this parameter's optimal conditions per species. In IA, optimal salinity conditions are at 30 ‰ (Polo-Osorio, et al., 2016), while CR optimal growth will occur between 27-37‰ (Amaral et al., 2014; Antonio et al., 2021).

These parameters play a critical role in regulating essential processes in oysters. Dissolved oxygen (DO) levels, for instance, directly support oyster populations (Benthotage, 2022). Higher DO concentrations lead to improved growth rates and lower mortality in CR (Pinho Brandão et al., 2013), while reduced DO negatively impacts physiological functions and increases mortality in IA (Antonio et al., 2021a; Manuel et al., 2014). Temperature also influences vital activities like metabolic rate, with decreased ciliary activity observed at extremes—32°C and 20.5°C (Hasan et al., 2021; McAfee et al., 2017). Low pH levels can weaken shell hardness and stiffness and impair shell formation and composition under acidic conditions (Meng et al., 2018; Welladsen et al., 2010). Total dissolved solids (TDS) indicate sediment load, affecting edible oysters' filtration rate (Hasan et al., 2021). Determining the optimal TDS range remains a promising area for further research, though it must account for other significant factors. Salinity is especially important: IA thrives at 30‰, while CR shows optimal growth between 27‰ and 37‰, with increased spawning activity within this range. (Amaral et al., 2014; Antonio et al., 2021) with CR larvae able to tolerate salinities as high as 40‰ (Amaral et al., 2014).

Salinity stands out as one of the most crucial of all these parameters (Mancera & Mendo, 1996; Nascimento, 2019). It plays a significant role in shaping oyster populations, as their reproduction and growth rely on stable salinity levels. Extreme fluctuations can adversely affect the oyster condition index (Batchelor et al., 2023). Examples are seen in areas such as Texas Bay, where environmental simulations for CV reveal that low salinity averages of 5.5 ‰, driven by freshwater influx, are detrimental to oyster populations due to dilution levels too low for survival. In contrast, higher salinities, averaging 18.7 ‰ resulting from increased seawater influx, create more favourable conditions for oyster populations by maintaining mesohaline levels- that support growth (Dekshenieks et al., 2000). Salinity data from Bowden Bay in this study showed readings between 31-37 ‰, aligning with conditions that promote healthy oyster populations. Optimal salinity for both species ranges between 15-38‰ (Benthotage, 2022; Martinelli et al., 2024; Nikolić et al., 1976). However, long-term analysis covering both wet and dry seasons would provide deeper insights, something this study could not achieve due to its limited duration.

Salinity alone cannot determine the prevalence and size of oyster populations and dimensions. A key factor is the availability of chlorophyll-a, which serves as an indicator of food supply within the oyster´s environment, influencing the health and growth of oyster populations (Theuerkauf et al., 2019). For species like CG, optimal feeding occurs within an average chlorophyll-a concentration range of 25-500 $\mu g\ l^{-1}$ (Theuerkauf et al., 2019). In this study, mean chlorophyll-a levels across the three sites ranged from 2.29 to 4.25 $\mu g\ l^{-1}$ (Table 6) which falls outside the optimal range stated by (Theuerkauf et al., 2019) . Despite this, there was a noticeable trend of increasing oyster populations, suggesting that more favourable conditions may occur more frequently than indicated by these measurements alone. Therefore, the data from this study should not be interpreted in isolation, and long-term, in-situ analysis is necessary to confirm the frequency and duration of optimal conditions throughout the year.

Oyster dimensions, including length and height, are closely linked to food availability, particularly phytoplankton, which is typically measured through chlorophyll-a concentrations (Dame et al., 2002). While water parameters like salinity are important, habitat quality also plays a critical role in determining oyster population dynamics and size.

Mangrove ecosystems, with their unique and crucial role, support coastal communities and provide habitat for diverse flora and fauna, including crabs, molluscs, and sessile species like bivalves, especially oysters. The extensive aerial root system of various mangrove plants, such as RM, *Avicennia germinans*, and *Laguncularia racemosa*, provides an ideal settlement medium, underscoring the unparalleled ecological importance of these ecosystems (Alleng, 1998; Cheng et al., 2023; Macnae, 1968; Ramteke et al., 2023; Zeng et al., 2024). Roots play a part in the presence of oysters as they are the habitat for these sessile organisms (Suheriyanto et al., 2024). Larger roots provide more surface area for oyster larvae to settle, especially when larvae reach a size of approximately 280 µm or more (Siung, 1980a; Wallace et al., 2008). A contributing factor to settlement is biofilm, composed of microorganisms such as diatoms, bacteria, fungi, and unicellular algae, which form on mangrove roots (Peng et al., 2020). The biofilm enhances adhesion for species like CV and CG (Bonar et al., 1990). Mangrove roots also offer vertical relief in intertidal zones, where oysters commonly settle (Benthotage et al., 2020; Nascimento, 2019), increasing spat survival and providing a stable, textured surface for attachment. In addition, larval settlement is influenced by both environmental and conspecific cues (Bonar et al., 1990; Sussan et al., 2024). Oysters often prefer to settle near older adults, likely due to the biofilm that forms on their shells (Bonar et al., 1990; Peng et al., 2020).

This influences settlement patterns, with oysters observed in varied shapes and positions, sometimes clustering atop one another. *Crassostrea* species, susceptible to environmental conditions, tend to settle in areas that optimise their survival, such as the intertidal zone of mangrove roots (Benthotage et al., 2020; Nascimento, 2019; Romero-Murillo et al., 2023; Suheriyanto et al., 2024; Wilket al., 2009). As conditions improve, oyster populations will likely grow and concentrate in these areas. These combined factors contribute to the size and distribution of oyster populations within estuaries.

8.3 Research Limitations

The findings of my study offer a restricted perspective on a single aspect of the primary oyster species within the estuary. Several strategies could have been employed to enhance the acquisition of knowledge about the species within the Bowden Bay estuary. Firstly, continuous in-situ collection and analysis of water parameter data readings using durable, permanently stationed equipment gives continuous quantitative data for analysis over seasonal periods with long-term advantages for further research, showing the advantage for documenting and investigating environmental effects on the species in the estuary. A larger sample size would facilitate a more accurate population count and prevalence analysis. Additional stations would enhance data analysis, providing a more nuanced understanding of the subject matter. The implementation of a continuous monitoring system for tagged specimens over extended periods, coupled with a comprehensive analysis of their flesh and a detailed assessment of their complete growth parameters in situ (i.e., length, height, and width), would facilitate a more profound understanding of the behavioural dynamics of the oyster population in relation to their surrounding environment. However, this presents a challenge in measuring the oysters without sampling the roots, given the presence of multiple layers of individuals that are partially or fully overlapped.

Expanding the study's collection area within the mangrove could provide insight into the population's prevalence in the estuary's inner areas. Such an approach could yield valuable insights into the comparative growth of prevalence at the edges versus the interior and the factors that may or may not encourage oyster settlement. However, this challenges accessibility to this particularly dense mangrove area.

Extending the study's period would produce a better outcome, charting seasonal changes, if any exist, and what characteristics are evident. This, alongside periodic physical count of the species using data software, would create a more strategic effort in understanding holistically IA and CR and their conditions for prevalence and growth in situ.

8.4 Research Findings- Impact on Aquaculture and Habitat Preservation

Several variables are involved in examining the findings of this research when considering oyster aquaculture and conservation within an estuary like the Bowden Bay Area. Regarding oyster culture, key factors include habitat selection and restoration. These sessile organisms live in the mangrove habitat (Lapègue et al., 2002). Understanding the estuary will guide our efforts to preserve and restore the habitat, encouraging more bivalve settlement and areas for bivalves to settle, leading to more spat production and spat collection. Understanding oyster preference, closer to river vs closer to open sea, provides insight into selecting ideal areas for the culture of the preferred species CR. Water quality information from this research emphasises the basic parameters and critical thresholds required to support generally healthy oyster populations while managing and monitoring water quality in aquaculture areas within the estuary, ensuring optimal conditions to encourage oyster growth and development, particularly with species-specific conditions; habitat preference, population dynamics and growth for CR and IA, the role of conditioning agents such as biofilm and its influence on oyster recruitment. However, more needs to be understood about area-specific biofilm constitution, e.g., the Jamaican estuary, which leads to settlement and, ultimately, an increase in the oyster population.

The farming of oysters also has an ecological effect on the balance between the two species, CR and IA. The implication of one species spawning before the other, particularly when CR is favoured over the two species for consumption. Finally, there is the need for continuous autonomous long-term in-situ environmental monitoring that will enable seasonal variation and climate change to impact understanding of the estuary and aquaculture areas and ensure the conservation and sustainability of these valuable resources. Applying these insights can improve habitat monitoring and management, protect oyster populations, and ensure sustainable aquaculture of the species using effective strategies. By extension, it can sustain marine ecosystems and enhance food security.

9 Conclusion

In conclusion, CR and IA currently exist within the estuary due to the favourable conditions for both oyster species; however, there may be more CR as conditions are likely favourable towards them. The study experienced limitations, including time constraints and assessment of flesh and flesh makeup, complete growth analysis and further estuary exploration, all deterred by limited financing and the natural makeup of the estuary. These, however, can be examined in further research along with spawning periods for both species, food preference and availability types of microalgae within the waters of Bowden Bay and consumption preference by each species, along with aquaculture area carrying capacity and analysis of water content as anthropogenic activities are located within the community in which the mangrove is situated.

As time progresses, there will be additional interest by persons to obtain spat resources and get into the business of grow-out operations; disease management and genetic analysis of oyster flesh must be considered to mitigate any issues over time to maintain quality and improve reproduction of the species for aquaculture. Finally, these findings are crucial to inform decision-making when developing policies and regulations for aquaculture zoning, marine spatial planning and permission regulations to safeguard the future of oyster culture operations in Jamaica.

10 Recommendations

Questions remain to be answered. While it is validated that capture of oyster spat is best at the location where the third station (BMSS3) was established, additional research is needed to investigate the following:

1. Changes that are likely to occur over the long term for oyster populations within Bowden Bay, considering climate change.

2. Implications of specific environmental factors on oyster survival and growth (chemical composition and sanitation of water within the estuary)

3. Impact of effective, efficient, climate-smart aquaculture production processes for the culture of oysters within the estuary.

4. Thoroughly assess both species' life cycles and spawning patterns for aquaculture, considering climate change and its impact on the natural environment.

5. A continued study is needed to determine the total oyster quantity, considering internal and external oyster location and numbers. This should be considered in developing a model that can be replicated in other Caribbean estuaries.

6. The relationship between the estuary and aquaculture activities regarding area carrying capacity should be considered for further investigation. This will enable the sustainable use of resources within the grow-out area.

7. Developing a model for oyster reaction over time due to climate change should be considered.

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