University of Ghana http://ugspace.ug.edu.gh

UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

SCHOOL OF BIOLOGICAL SCIENCES

HABITAT SUITABILITY MAPPING TOWARDS THE RESTORATION OF OYSTER POPULATION IN THE ANYANUI CREEK, GHANA.

MAURICE OTI EDUSEI

(11004437)

THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF **MPHIL IN MARINE SCIENCE DEGREE.**

DEPARTMENT OF MARINE AND FISHERIES SCIENCES

NOVEMBER 2024

University of Ghana http://ugspace.ug.edu.gh

DECLARATION

I, Maurice Oti Edusei hereby declare that this thesis is the result of my independent research conducted at the Department of Marine and Fisheries Sciences, School of Biological Sciences, University of Ghana, under the joint supervision of Prof. Edem Mahu and Dr. Benjamin Osei Botwe. I also declare that as far as I know, this thesis has neither in part or a whole been published nor presented to any other institution for an academic award.

Signature: 13th November 2024

Maurice Oti Edusei Date

(Student)

Signature: 13th November 2024

Prof. Edem Mahu Date

(Principal Supervisor)

Signature: 13th November 2024

Dr. Benjamin Osei Botwe Date

(Co-supervisor)

University of Ghana http://ugspace.ug.edu.gh

ABSTRACT

The rapid decline of oyster populations globally due to climate change, pollution, habitat and overexploitation poses significant ecological and socio-economic challenges. In Ghana, particularly at Anyanui Creek, ineffective conservation strategies and inadequate governmental support have intensified these impacts. This research aims to identify the factors contributing to the decline of *Crassostrea tulipa* populations in the Anyanui Creek and to determine sites with optimal conditions for restoration efforts. Utilizing the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS), the study evaluated habitat suitability across Anyanui Creek, facilitating the mapping of areas with the highest potential for oyster restoration based on environmental and ecological conditions conducive to oyster survival at pre- and post-larval settlement phases.

Findings indicated that the rainy season exhibits the highest habitat suitability for post-larval phases, as favorable temperature levels during this period enhance conditions for *C. tulipa* growth and survival. Stations with the highest consistency in suitability, particularly those midstream and closer to the ocean with a 33.33% consistency rate, were identified as prime candidates for restoration. On the other hand, several stations exhibited lower suitability, indicating a need for targeted interventions to address specific environmental stressors. The success rates of veliger development were significantly influenced by water temperature, alongside critical factors such as pH and salinity, underscoring their pivotal roles in oyster development and growth.

The study highlights the importance of seasonality in oyster restoration at Anyanui Creek, recommending specific times and locations for intervention to maximize restoration success. Emphasizing the necessity for comprehensive monitoring and tailored restoration strategies, the findings advocate for policy adjustments and the implementation of robust conservation measures that account for climate and environmental variabilities. Additionally, engaging local

University of Ghana http://ugspace.ug.edu.gh

communities and stakeholders is essential to ensure the sustainability of restoration projects and maximize socio-ecological benefits. By addressing these multifaceted challenges, the restoration of oyster reefs can significantly enhance ecosystem health, support local fisheries, and contribute to the socio-economic well-being of coastal communities in Ghana.

University of Ghana http://ugspace.ug.edu.gh

DEDICATION

Forever in my heart, Big brother loves you…

University of Ghana http://ugspace.ug.edu.gh

ACKNOWLEDGEMENT

I would like to extend my heartfelt gratitude to those whose contributions were invaluable to the success of my research and the presentation of this thesis.

Firstly, I am grateful to my Principal Supervisor, Dr. Edem Mahu, and Co-supervisor, Dr. Benjamin Osei Botwe, for their guidance, expertise, and support throughout this journey. Their encouragement and insights were instrumental in shaping the direction and depth of my research. I would also like to acknowledge the Department of Marine and Fisheries Sciences for providing an enriching environment that fostered my academic and research growth.

This work would not have been possible without the generous financial support of the National Geographic Society and the AAS-ARISE project. Their funding provided essential resources that enabled me to carry out this research, and I am appreciative of their commitment to advancing scientific inquiry and conservation efforts.

My sincere appreciation goes to the 'Mahu Lab' for the collaborative support and resources that were essential in carrying out this project. Special thanks to Samuel Tawiah for his assistance with laboratory analysis and to and Fatawo Abubakar for his diligent efforts during field sampling. Their commitment to precision and quality was crucial to the reliability of my findings.

I am also thankful to Emmanuel Brempong, Dr. Phillip-Neri Jayson-Quashigah, and Michael Kwame Biney for their GIS applications and statistical analysis expertise. Their contributions provided a solid foundation for the analytical components of this work.

I gratefully acknowledge the dedicated efforts and expertise of individuals and institutions whose collaboration made this research possible. Their unwavering support has been instrumental to the successful completion of this thesis.

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

TABLE OF CONTENTS

DECLARATION.....ii

ABSTRACT..... iii

DEDICATION.....v

ACKNOWLEDGEMENT.....vi

LIST OF FIGURES.....x

LIST OF TABLES.....xii

CHAPTER ONE.....1

INTRODUCTION.....1

1.1. Background.....1

1.2. Problem statement.....5

1.3. Justification.....6

1.4. Research questions......6

1.5. Aim.....7

1.6. Objectives.....7

CHAPTER TWO.....8

LITERATURE REVIEW.....8

2.1. Global context of Oyster decline.....8

2.2. Biology of *Crassostrea tulipa*.....9

2.3. Ecology and Functional Roles.....13

2.4. Restoration Science.....15

2.5 Site-Selection Science.....17

University of Ghana http://ugspace.ug.edu.gh

2.6 Local Context: Anyanui Creek.....20

2.7 Management and Policy Implications.....22

2.8 Knowledge Gaps & Future Directions.....24

CHAPTER THREE.....28

METHODOLOGY.....28

3.1. Study area.....28

3.2 Collection of datasets related to environmental variables......31

3.3. Analytical hierarchical process (AHP) for weight selection.....33

3.4. Suitability functions and Indices selection.....35

3.5. Comprehensive depiction of model, explanation of its design, components, and functionalities.....36

3.6 Map generation and validation......42

3.7 Field Validation of Oyster Population and Habitat Suitability......42

3.9 Estimating the Condition Index of *C. tulipa* in the Creek.....43

3.8 Statistical analysis.....43

CHAPTER FOUR.....45

RESULTS.....45

4.1. Spatial and Temporal Variation of Physical and Chemical Conditions.....45

4.2. Environmental Drivers of *C. tulipa* Population Decline.....46

4.3. Spatial and Temporal Dynamics of Habitat Suitability for *C. tulipa*.....48

4.4. Peak Conditions in Habitat suitability.....51

4.5. Identification of Consistently Suitable Areas for C. tulipa Culture.....52

University of Ghana http://ugspace.ug.edu.gh

4.6. Validation of Habitat Suitability Index model using Biometric Correlations ...53

CHAPTER FIVE 56

DISCUSSION 56

5.1. Spatial and Temporal Variation of Physical and Chemical Conditions....56

5.2. Environmental Factors Impacting *C. tulipa* Population 57

5.3. Habitat Suitability Assessment for *C. tulipa* ..... Error! Bookmark not defined.

5.4. Optimal timing and location for Restoration efforts.....**Error! Bookmark not defined.**

5.5. Model validation and methodological considerations. .....**Error! Bookmark not defined.**

CHAPTER SIX 72

CONCLUSION AND RECCOMENDATION 72

6.1. Conclusion 72

6.2. Recommendations for Future Research 74

REFERENCES....78

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

LIST OF FIGURES

Figure 1: The life cycle of Ostreidae. 12

Figure 2: Map of the study area (Anyanui creek). 29

Figure 3: Picture showing some of the factors affecting *C. tulipa* populations within ANC. a) Harvested mangrove ready to be sold and distributed. b) Areas very close to ANC used for waste disposal. 30

Figure 4: Hierarchy model for AHP process. 34

Figure 5: A tree diagram visually representing the interconnections among environmental variables, life stages, and habitat types utilized in establishing the Habitat Suitability Index (HSI) for the West African mangrove oyster, C. tulipa. 37

Figure 6: Connection between environmental variables and their corresponding habitat suitability values for the West African mangrove oyster *C. tulipa*. 39

Figure 7: Monthly box-and-whisker plots of Temperature (°C), Salinity (ppt), Dissolved O (mgL^{-1}), pH, and Chlorophyll-a (μgL^{-1}) recorded at Anyanui Creek from Mar-23 to Feb-24. Boxes represent the interquartile range with the median marked; whiskers extend to 1.5 × IQR and points denote outliers. Translucent green bands indicate reference 'optimal' ranges for Temperature (°C), Salinity (ppt), and pH. 46

Figure 8. The temporally estimated percentage of embryonic development (success rate) for each of the sample stations was estimated using the ANN model. (March 2023 – February 2024). 47

Figure 9: Spatial distribution of estimated HSI index model values for post settlement. (a = March 23, b = April 23, c = May 23, d = June 23, e = July 23, f = August 23, g =

University of Ghana http://ugspace.ug.edu.gh

September 23, h = October 23, i = November 23, j = December 23, k = January 24, l = February 24) 51

Figure 10: Monthly Average Habitat Suitability Index (HSI) from March to February, showing temporal variations in habitat suitability.....52

Figure 11: Percentage of Months Exceeding HSI Threshold by Station between March 2023 and February 2024. This map shows the percentage of months in which each station recorded HSI values exceeding the suitability threshold of 0.5, representing moderately suitable conditions for *C. tulipa* culture. 53

Figure 12: Correlation between Habitat Suitability Index (HSI) and Oyster Biometrics.....55

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

LIST OF TABLES

Table 1. The genus Crassostrea comprises 25 species that are distributed globally (WoRMS taxon details of Crassostrea., 2021; Kasmini & Batubara, 2022).....10

Table 2. Illustration of notable environmental fluctuations (mean ± standard deviation based on 12 observations) during the Dry and Rainy months at Anyanui Creek from March 2023 – February 2024. DO = Dissolved oxygen; Chla = Chlorophyll a; NO3 = Nitrates; PO4 = Phosphates; SiO3 = Silicates.....31

Table 3: Summary of Instruments, Variables, and Measurement Accuracy Used in Water Quality Monitoring.....32

Table 4. Selected Indices for C. tulipa reef restoration suitability assessment and assigned weights using the AHP approach adopted from Wang et al. (2023).....35

Table 5. Environmental variables, ranges, and data sources for oysters to be used in the indicator systems HSI model.....37

Table 5. Summary of linear regression models 48

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

CHAPTER ONE

INTRODUCTION

1.1. Background

There is a growing recognition of the extent to which marine habitats are being degraded, and the consequent loss of socio-economic and ecosystem services has led to heightened efforts to restore lost ecosystems and conserve existing ones (Duarte et al., 2020). Baggett et al. (2015) described an oyster reef as a three-dimensional, biogenic structure built as generations of oysters settle on (and cement to) one another, creating rock-like habitat that harbours a rich community of marine life. Oyster reefs worldwide face significant threats and are considered one of the most endangered marine habitats, with about 85% lost and the remaining in poor condition (Michael W Beck et al., 2011). Various environmental pressures have contributed to the drastic decline in oyster reef functionality, including over-exploitation, habitat degradation, pollution, and climate change (McAfee et al., 2020).

Over-exploitation through intensive harvesting has significantly reduced oyster populations, disrupting their ecological balance and diminishing their capacity to filter water and provide habitat for other marine species (Stechele, 2023). Habitat degradation resulting from coastal development and destructive fishing practices, such as dredging and bottom trawling, has led to the physical destruction of oyster reefs (Ibrahim et al., 2018). Moreover, pollution from agricultural runoff, industrial waste, and urbanization introduces harmful substances into marine environments, adversely affecting oyster health and reproduction (Islam & Tanaka, 2004; Freeman et al., 2019). Additionally, climate change contributes to ocean acidification and rising sea temperatures, which can impair shell formation and increase susceptibility to diseases in oyster populations (Okon et al., 2023).

University of Ghana http://ugspace.ug.edu.gh

Rapid urbanization, industrial and agricultural development along coastal cities over the past few decades has resulted in land-based nutrient enrichment, potentially leading to heightened cases of eutrophication (Kennish, 2002). These issues have shown evidence of their detrimental effects on marine ecosystems and water quality (Adeyemo, 2003; Taljaard et al., 2006; Häder et al., 2020). Being filter feeders, oysters can purify water, remove nutrients, and enhance water clarity (Rice, 2001; Li et al., 2010). Therefore, the restoration of damaged oyster habitats has become a vital solution for addressing eutrophication, biodiversity decline, and related issues (Council, 1995). Given the critical ecological role played by oyster reefs within coastal and estuarine ecosystems, extensive initiatives have been undertaken to revitalize indigenous oyster populations.

The current state of oyster restoration science is reviewed by Smith and Pruett (2024), who highlight the significant loss of oyster reefs and the resulting impact on essential ecosystem services such as habitat provision, water filtration, and shoreline protection. They note that since the 1990s, there has been a concerted global effort to rebuild oyster populations to recover these services, with practices now incorporating emerging technologies, emphasising community engagement, and committing to long-term monitoring. However, they also point out that climate change poses challenges to these efforts, because rising sea temperatures, ocean acidification that weakens shell formation, and more frequent severe storms can lower post-restoration survival and physically damage newly established reefs, necessitating adaptive management to maintain the effectiveness of restoration initiatives.

Efforts to revive oyster populations are currently under way across many regions and species. In 2012, despite limited funding, two acres of reefs were constructed adjacent to native oysters at the mouth of the Squamscott River, Newmarket, New Hampshire (Konisky et al., 2012). Restoration initiatives for the Eastern oyster (*Crassostrea virginica)* have been documented in Delaware's Inland Bays, USA (Rossi-Snook et al., 2010; Ozbay et al., 2014). Similarly, efforts

University of Ghana http://ugspace.ug.edu.gh

to re-establish the European flat oyster *Ostrea edulis* in the North Sea are reported by Pogoda et al. (2019), Merk et al. (2020) and Colsoul, Boudry, Pérez-Parallé, et al. (2021). In Ghana, work has focused on restoring the West African mangrove oyster *Crassostrea tulipa* (Lamarck, 1819) (Chuku, 2019), and comparative growth-and-survival studies by Osei et al. (2022) are improving the scientific basis for future restoration projects.

Crassostrea tulipa (Lamarck, 1819), plays a crucial role in Anyanui Creek. Each adult oyster filters up to 50 gallons (approximately 190 litres) of water daily (Newell, 2004), improving water clarity and nutrient balance. Their clustered shells stabilize muddy banks, dampen wave energy, and reduce shoreline erosion (Fisheries, 2025). Furthermore, the oysters' three-dimensional reef matrix provides a vital nursery refuge for juvenile fish, crabs, and shrimp, which in turn support local artisanal fisheries (Mumby, 2006).

Unfortunately, these benefits have diminished as the oyster stock has declined. A 2021 survey of shellfisheries in Anyanui revealed only about 10 active oyster harvesters, compared to the 170–300 reported in healthier Ghanaian systems like Whin, Kpomkpo, and Densu (Osei & Agyekumhene, 2021). This indicates a reduction of over 90% in local harvesting capacity. Given that natural oyster habitats have declined by more than 85% globally (M. W. Beck et al., 2011), restoring Anyanui's oyster population is an urgent priority.

The decline in oyster populations in the area has been attributed to several factors, the most immediate being the sand-bar that formed in front of the former coastal village of Fuveme, a low-lying settlement at the mouth of the Anloga–Anyanui channel that was wiped out by severe erosion and tidal-wave events in 2016–2021 (Bokpe, 2021). The new sand-bar now blocks direct exchange with the Gulf of Guinea and prevents tidal flushing, promoting nutrient build-up and altering ecological dynamics in the creek.

University of Ghana http://ugspace.ug.edu.gh

Within the wider Keta Lagoon complex, Anyanui Creek is the branch that reported to support the densest and most persistent beds of the West African mangrove oyster *Crassostrea tulipa* (present study) and is reiterated by a participatory shellfisheries survey that found only ~10 active oyster harvesters in Anyanui, compared with >170 in other Ghanaian creeks, indicating a >90 % reduction from past levels (Osei et al., 2021). Small remnant populations of *C. tulipa* are also known from the Densu, Narkwa, Amisano, Benya, Whin and Domunli lagoon systems (Mawusi et al., 2022).

At present, there exists a dearth of information regarding the state of the environment of oyster habitats and the criteria for identifying suitable locations for oyster reef restoration, while the establishment of a substantial artificial oyster reef in Ghana remains unrealised. To date, no comprehensive initiative or pilot project has been implemented to explore the feasibility of artificial oyster reef development in Ghana's coastal ecosystems. To address these knowledge gaps, the development of a Habitat Suitability Index (HSI) model is proposed, leveraging the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS). This model aims to provide scientifically grounded guidance for oyster restoration initiatives and serve as a decision-support tool for resource managers and policymakers. Despite its utility, the potential influence of seasonal variations on the accuracy and long-term relevance of such "one-time models" remains insufficiently addressed. Seasonal fluctuations, dynamic coastal processes, and anthropogenic impacts often present considerable environmental changes due to shifting conditions. These stressors influence the oyster population's survival, growth, and reproductive capabilities and, consequently, the appropriateness of a restoration-suitability index model.

University of Ghana http://ugspace.ug.edu.gh

1.2. Problem statement

The global decline of oyster populations presents an ecological and socio-economic challenge (Jamil et al., 2024). Factors such as climate change, pollution, and overexploitation have substantially reduced oyster numbers worldwide (Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al., 2022). This global issue is mirrored in Ghana, where a lack of effective governmental and non-governmental efforts for marine and freshwater conservation has exacerbated the decline of oyster populations. This insufficiency is evident in inadequate sustainable oyster farming practices and poor monitoring of wild oyster beds as reported by Colsoul, Boudry, Pérez-Parallé, et al. (2021). Without effective governance and conservation measures, reviving declining oyster populations becomes a formidable task, particularly in the face of climate-induced stressors that directly impact oyster growth and survival (Asare et al., 2019).

Ghana's limited resources directed towards marine and freshwater conservation have hindered the implementation of initiatives aimed at reviving dwindling oyster populations, both locally and regionally. Moreover, the dearth of research and understanding regarding how climate and human-induced stress affect shellfish and finfish in Ghana and West Africa further complicates conservation efforts (Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al., 2022). This knowledge gap impedes the development of targeted strategies to mitigate adverse impacts on these species.

Another significant barrier to restoring oyster populations in Ghana is the insufficient information available for selecting suitable sites for oyster reef restoration. This knowledge gap hinders the creation of oyster reefs and undermines regional conservation endeavours. Without a comprehensive understanding of site prioritization for oyster reef restoration, the potential for restoration to have a significantly positive impact on oyster populations and the marine and coastal ecosystem remains unrealized (Costa-Pierce, 2010).

University of Ghana http://ugspace.ug.edu.gh

1.3. Justification

The restoration of oyster reefs in Ghana holds significant promise for various ecological, socio-economic, and conservation reasons. Oyster reefs play a pivotal role in enhancing ecosystem health and supporting the recovery of fish populations (Coen et al., 1999). As oysters serve as natural water filters, their restoration can help offset the decline in water quality (Kellogg et al., 2014; Kreeger et al., 2018), potentially caused by the alarming rate of mangrove cultivation, harvesting, and creek blockage, especially within the Anyanui area (Adda, 2016; Kondra, 2019).

Healthy oyster reefs also increase coastal resilience against erosion and storms (Grabowski et al., 2012; Chowdhury et al., 2021). This benefit enhances the health of the immediate coastal environment. It provides crucial support to nearby communities and industries reliant on clean water and coastal protection, such as fisheries and tourism.

The socio-economic benefits of oyster reef restoration are equally compelling. Restoration efforts have the potential to contribute to sustainable fisheries and increased food security for local communities (Nix, 2011; Knoche et al., 2020). Additionally, the creation of eco-tourism opportunities and recreational activities can generate significant economic benefits. The conservation value of oyster reef restoration cannot be overlooked. By restoring oyster reefs, Ghana can make a valuable contribution to regional and international conservation goals and commitments, such as the Ramsar Convention and the Sustainable Development Goals (placeholder), while also protecting and conserving its coastal ecosystems.

1.4. Research questions.

- How do the physical and chemical conditions in the Anyanui Creek vary spatially and temporally?

University of Ghana http://ugspace.ug.edu.gh

- What are the potential environmental factors driving the decline of *C. tulipa* abundance in the Anyanui?
- How does the suitability of habitat for *C. tulipa* culture vary spatially and temporally?
- What month in a year has the highest recorded average suitability, what environmental and ecological conditions are observed, and how do they promote habitat suitability for *C. tulip*a culture?

1.5. Aim

To develop Habitat suitability maps for determining suitable sites for the restoration of *C. tulipa* reefs by integrating the Analytical Hierarchical Process (AHP) and Geographic Information System (GIS) applications within the Anyanui Creek, Ghana.

1.6. Objectives

- To assess the physicochemical conditions (temperature, Salinity, pH, dissolved oxygen, and chlorophyll-a concentrations) in the Anyanui Creek within a one-year period.
- To identify the potential influencing factors driving the decline of the *C. tulipa* population decline of in Anyanui Creek within the one-year study period.
- To predict and map out suitable sites for *C. tulipa growth* in the creek that should be targeted for restoration using a suitability index model for the one-year duration of the study.
- To identify the peak months and locations that show consistency in recording Suitability index values of >0.5 (moderate suitability) in the Anyanui creek.

University of Ghana http://ugspace.ug.edu.gh

CHAPTER TWO

LITERATURE REVIEW

2.1. Global context of Oyster decline

The global decline of oyster populations is a critical environmental issue with far-reaching implications for marine ecosystems and coastal communities worldwide. Oysters serve as essential ecosystem engineers by enhancing biodiversity, filtering seawater, and stabilizing coastal habitats (McAfee, 2018). Their capacity to improve water quality and provide habitat for various marine species underscores their ecological significance (Zhao & Wu, 2024). However, a multitude of factors, including habitat degradation from destructive fishing practices (Ibrahim et al., 2018), overharvesting, pollution, disease outbreaks, and climate change, have led to a substantial global decrease in oyster numbers. Notably, it is estimated that over 85% of oyster reefs have been lost globally since the late 19th century, making oyster reefs one of the most severely impacted marine habitats (Hemraj et al., 2022). Historical records further reveal that vast oyster reef ecosystems, once dominant along European coastlines, have been reduced to near-functional extinction in many regions, highlighting the scale of this ecological collapse (Thurstan et al., 2024).

Despite widespread recognition of their importance, current conservation and management strategies often prove insufficient, particularly in regions like Western Africa with only a few studies, such as Atindana et al. (2020), Solomon and Ahmed (2016) and Ajao (1994) being amongst the few to document this. This inadequacy highlights significant gaps in our approach to safeguarding oyster populations. The decline is an ecological concern and presents substantial socio-economic challenges. Many coastal communities depend on oyster fisheries for their livelihoods and sustenance, and the loss of these populations adversely affects local economies and threatens food security (Pogoda, 2019). This situation emphasizes the need for more effective interventions that address both environmental and human dimensions.

University of Ghana http://ugspace.ug.edu.gh

2.2. Biology of *Crassostrea tulipa*

The genus *Crassostrea*, which includes the species *Crassostrea tulipa*, plays a vital role as an ecosystem engineer within coastal and mangrove environments by creating shelter and breeding habitats for a wide range of marine organisms (Kasmini & Batubara, 2022). The biological processes of species within this genus, including their growth and reproductive cycles, are strongly shaped by environmental variables such as water temperature, dissolved oxygen levels, and water clarity (Neto et al., 2013). To date, approximately 25 species have been identified within the Crassostrea genus (Kasmini & Batubara, 2022). These species are characterized by soft bodies enclosed within hard, rough, irregularly shaped, and thick calcareous shells (see Table 1).

2.2.1. Taxonomy and Life Cycle

Crassostrea tulipa dominates many West African shorelines, thriving on mangrove roots and other firm surfaces in the intertidal zones of rivers and lower estuaries. Its abundance mirrors local salinity regimes, i.e. populations concentrate where moderate salinities buffer the oysters from both prolonged freshwater pulses and full-strength seawater (Kamara, 1982; Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al., 2022).

Shell form adapts to the settling surface. On mud or other soft substrates, shells show subdued ridging, whereas oysters cemented to rocks, mangrove pneumatophores, or wharf pilings grow flatter shells that mould to the irregular surface beneath them (Borges, 2002; Kasmini & Batubara, 2022). Despite this plasticity, most shells remain rough, concave, and deeply grooved. Typical individuals reach < 20 cm in length, but under favourable conditions some attain 40 cm and can survive for three decades (Schellekens et al., 2012; Zwerschke, Kochmann, et al., 2018; Kasmini & Batubara, 2022).

University of Ghana http://ugspace.ug.edu.gh

Table 1. The genus Crassostrea comprises 25 species that are distributed globally (WoRMS taxon details of Crassostrea., 2021; Kasmini & Batubara, 2022).

No	Species	Distribution
1	*Crassostrea aequatorialis* (d'Orbigny, 1846)	Pacific, America
2	*Crassostrea angulata* (Lamarck, 1819)	Spain, Belgium, North Sea
3	*Crassostrea ariakensis* (Fujita, 1913)	USA
4	*Crassostrea belcheri* (Sowerby II, 1871)	Myanmar
5	*Crassostrea bilineuta* (Roding, 1798)	India, Bangladesh, Vietnam
6	*Crassostrea brasiliana* (Lamarck. 1819)	Brazil
7	*Crassostrea columbiensis* (Hanley, 1846)	Colombia
8	*Crassostrea corteziensis* (Hertlein, 1951)	Panama
9	*Crassostrea dactylena* (Iredale. 1939)	Australia
10	*Crassostrea dianbaiensis* (Xia, Wu, Xiao & Yu, 2014)	China, Japan
11	*Crassostrea gigas* (Thunberg, 1793)	Widely distributed
12	*Crassostrea gryphoides* (Schlotheim, 1820)	India, Bangladesh
13	*Crassostrea hongkongensis* (Lam & Morton, 2003)	China
14	*Crassostrea mangle* (Amaral & Simone, 2014)	Brazil
15	*Crassostrea markashuberi* (Thach, 2018)	Vietnam Central
16	*Crassostrea nippona* (Seki, 1934)	Japan, South Korea
17	*Crassostrea praia* (lhering, 1907)	Brazil
18	*Crassostrea rhizophorae* (Guilding, 1828)	Caribbean Sea, Colombia, Gulf of Mexico, Jamaica, Panama, Venezuela
19	*Crassostrea rivularis* (Gould, 1861)	Bay of Biscay
20	*Crassostrea sikamea* (Amemiya, 1928)	Bay of Biscay
21	*Crassostrea talonata* (Li & Qi, 1994)	China, North Atlantic Ocean, South Atlantic Ocean, South Pacific Ocean
22	*Crassostrea tulipa* (Lamarck, 1819)	Ivory Coast, Nigeria
23	*Crassostrea valentichscotti* (Thach, 2018)	Vietnam
24	*Crassostrea virginica* (Gmelin, 1791)	European, USA
25	*Crassostrea zhanjiangensis* (Wu, Xiao & Yu, 2013)	China

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

Reproduction, consistent with other species within the genus is equally responsive to the environmental conditions. *C. tulipa* are protandric, initially functioning as males and later potentially transitioning to females in subsequent reproductive cycles, depending on prevailing environmental factors (Kasmini & Batubara, 2022).

Sexual reproduction in these oysters follows a sequence of gonadal development, spawning, and fertilization. During gonadal maturation, the follicular cavities become filled with gametes, preparing the oysters for spawning. Environmental cues such as changes in temperature, salinity, light availability, water pressure, currents, and other physical and chemical water parameters serve as natural triggers for spawning events (Chuku et al., 2023). In tropical environments, Crassostrea species typically exhibit continuous, year-round spawning cycles (Bae et al., 1978; Barber, 1996; Almeida et al., 1999).

2.2.2. Growth and Environmental tolerances

Early development in *C tulipa* hinges on a narrow envelope of temperature and salinity. Optimal ranges for successful development are between 25–30°C and salinity levels of 20–30‰ (Yankson, 1990). Following fertilization, the embryos develop into free-swimming larvae known as veligers. These larvae feed on phytoplankton and remain planktonic for approximately two weeks, undergoing several developmental stages (see Fig. 1). Although they can actively regulate their vertical position in the water column, their horizontal movement is primarily governed by currents (Borges, 2002). At the pediveliger stage, the larvae develop a foot that enables them to explore substrates for suitable settlement sites. Once an appropriate substrate is found, they attach themselves and undergo metamorphosis into juvenile oysters, initiating the secretion of calcium carbonate to build their shells.

Post-settlement growth responds strongly to salinity and overall water quality. On average, they grow approximately 2–3 cm per year, reaching sexual maturity within one to three years

University of Ghana http://ugspace.ug.edu.gh

(Kasmini & Batubara, 2022). Higher salinity environments generally promote faster growth in oysters (Rubio Zuazo, 2007). The lower shell of C. tulipa typically exhibits more defined and concentrated ridges, which are slightly larger and deeper than those found on the upper shell.

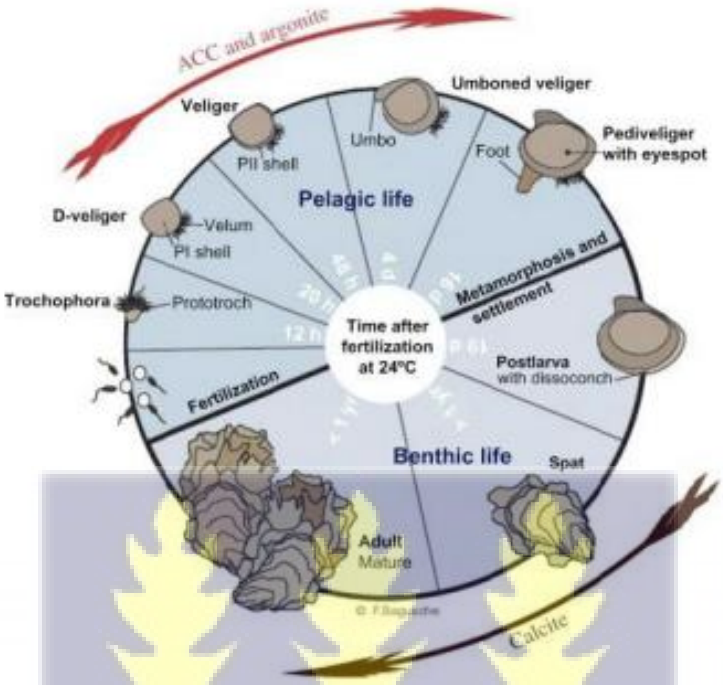


Figure 1: The life cycle of Ostreidae.

Human pressures compound natural stresses. Coastal development and dredging remove or smother reef habitat, shrinking the pool of suitable settlement sites. Agricultural runoff and industrial effluents load surrounding waters with nutrients, heavy metals and other contaminants. This potentially impairs larval survival and bioaccumulates in adult tissues (Webber et al., 2021). Unregulated harvesting, especially during spawning peaks, skews age structure and depletes brood stock, while invasive predators or competitors can introduce novel diseases and out-compete native oysters (Ruesink et al., 2005; Zwerschke, Hollyman, et al., 2018). Collectively, these impacts threaten the persistence of *C. tulipa* populations and the ecosystem services their reefs provide.

University of Ghana http://ugspace.ug.edu.gh

2.3. Ecology and Functional Roles

2.3.1. Keystone functions

Oysters are recognized as keystone species within marine and estuarine ecosystems due to the wide range of ecological functions they perform, which support both biodiversity and ecosystem stability (Dame & Kenneth, 2011; Ozbay et al., 2017). Beyond their own survival, oysters create complex reef structures that provide critical habitats and shelter for numerous marine species, including commercially and ecologically important fishes (Coen et al., 1999). These reefs not only support diverse aquatic communities but also play a pivotal role in maintaining water quality. As filter feeders, oysters actively remove suspended particles, algae, and contaminants from the water column, thereby enhancing water clarity and improving overall ecosystem health (Nelson et al., 2004; Gallardi, 2014; Kreeger et al., 2018).

In addition to habitat provision and water filtration, oyster reefs contribute significantly to nutrient cycling and sediment stabilization. Through their feeding and excretion processes, oysters facilitate the transfer of nutrients between the water column and the benthic environment, influencing coastal productivity and nutrient dynamics (Dame & Libes, 1993). The physical structure of oyster reefs also reduces wave energy, mitigates coastal erosion, and offers natural protection against storms and tidal surges (Chowdhury, Walles, et al., 2019). These ecosystem services are increasingly valuable in the face of rising sea levels and more frequent extreme weather events linked to climate change (Scholes, 2016).

Despite their ecological importance, significant knowledge gaps remain, particularly concerning the functions of natural reef systems and their complex food web interactions (Coen et al., 1999). The continued decline of oyster populations jeopardizes not only the species directly dependent on oyster reefs but also the broader ecological functions that sustain coastal resilience (Kennish, 2002). Closing these knowledge gaps and implementing effective

University of Ghana http://ugspace.ug.edu.gh

conservation and restoration strategies are therefore critical to safeguarding these keystone organisms and the ecosystems they support.

2.3.2. Physicochemical needs

Key environmental factors such as water quality, substrate availability, and habitat connectivity play vital roles in supporting oyster populations. Water quality is particularly critical, influencing essential physiological processes such as respiration, osmoregulation, and reproduction (Petes et al., 2012). Optimal conditions, including salinity levels between 20–30‰, temperatures of 25–30°C, adequate dissolved oxygen, and balanced nutrient availability, are essential for promoting oyster growth and resilience (Volety et al., 2014; Ledezma, 2024). Prolonged deviations from these optimal ranges can lead to physiological stress, stunted growth, and heightened vulnerability to disease outbreaks (La Peyre et al., 2013).

Substrate availability is another crucial determinant of oyster survival and reef sustainability. Oysters depend on hard surfaces, such as rocks or existing oyster shells, for larval settlement and growth (Coen et al., 2007). However, the widespread decline of oyster populations has reduced the abundance of natural shell material, limiting suitable settlement areas (Powell & Klinck, 2007). Overharvesting and destructive fishing practices further exacerbate the loss of these essential substrates, undermining reef formation and long-term population stability (Coen et al., 1999).

The spatial arrangement of surrounding habitats, including salt marshes and seagrass beds, also significantly influences oyster reef sustainability. These adjacent ecosystems enhance the abundance of juvenile fish and invertebrates on oyster reefs, reflecting the interconnectedness of coastal habitats and underscoring the importance of integrated ecosystem management (Grabowski et al., 2005).

University of Ghana http://ugspace.ug.edu.gh

Food availability is equally essential for oyster growth and reproduction, as oysters are filter feeders that rely on phytoplankton and other suspended particles for nutrition (Coen et al., 2007). However, environmental issues such as eutrophication can disrupt phytoplankton communities, affecting oyster feeding efficiency and negatively impacting oyster productivity. Restoration of oyster reefs contributes to mitigating these effects by enhancing water filtration and improving ecosystem health (Gottlieb & Schweighofer, 1996).

Temperature and predation also influence oyster population dynamics. Temperature affects metabolic processes and reproductive cycles, while predation by natural enemies can limit population growth (Kennedy et al., 1996; Lord, 2014) . Effective management of these factors is critical for successful conservation and restoration efforts.

Although oyster aquaculture can support population recovery, poorly managed practices may lead to habitat degradation and pollution (Solomon & Ahmed, 2016). Nevertheless, when appropriately designed, oyster restoration projects offer significant ecosystem services, including water filtration, habitat creation, and enhanced coastal resilience (Coen et al., 2007; Chowdhury et al., 2021). The success of these initiatives depends on careful site selection, consideration of local ecological dynamics, and long-term management strategies.

2.4. Restoration Science

Efforts to restore oyster populations focus on complementary strategies that revive degraded habitats and easing pressures on remaining wild stocks (Thackaberry, 2021). Central to these initiatives is reef rehabilitation, the placement of recycled shells, limestone, or purpose built concrete structures that offer firm settlement surfaces for larvae and recreate the three dimensional complexity of natural oyster reefs (Coen & Luckenbach, 2000; Reeves et al., 2020). Reestablished reefs enhance biodiversity and strengthen the water filtering services that sustain coastal ecosystems (Graham et al., 2017).

University of Ghana http://ugspace.ug.edu.gh

Equally important is sustainable aquaculture. When farmers use native or locally adapted stocks, maintain genetic diversity, and select for disease resistance, oyster culture can supply seafood, reseed wild beds, and reduce harvest pressure on natural reefs (Colsoul, Boudry, Pérez-Parallé, et al., 2021; Bishop et al., 2023). In combination, habitat restoration and responsible aquaculture provide a mutually reinforcing pathway to long term population recovery (Jiang et al., 2024).

2.4.1. Global restoration approaches

Across the world practitioners integrate reef construction, strict harvest controls, and routine monitoring to counteract oyster decline, though success varies with local stressors, funding levels, and governance capacity (McLeod et al., 2019; Wasson et al., 2020). Meaningful gains depend on close coordination among scientists, policy makers, and coastal communities. Current research is refining affordable reef materials and designs, linking water quality improvements to restoration targets, and testing adaptive farming practices that supplement rather than compete with wild stocks. Filling these knowledge gaps will strengthen evidence-based management and help oyster restoration bolster marine ecosystem resilience on a global scale.

2.4.2. Community and Stakeholder Engagement

Community engagement and close collaboration among stakeholders are now regarded as core pillars of effective oyster restoration. When local residents take part in planning and field work the objectives remain culturally relevant and more likely to endure over time (Goldstein & Butler, 2010). Their active involvement enlarges the collective knowledge base, improves teamwork and increases the social legitimacy of restoration projects, ultimately raising the chances of success (Favretto et al., 2022). Indigenous and local knowledge offers detailed insights into site history, seasonal variability and traditional resource management. Integrating this information through participatory decision making strengthens stakeholder ownership and

University of Ghana http://ugspace.ug.edu.gh

provides practical guidance that standard scientific surveys may overlook (Reyes-García et al., 2019; Hemmerling et al., 2020; Ortega-Álvarez et al., 2022).

Successful programmes also rely on adaptive management that combines clear objectives with continuous monitoring and periodic reassessment of progress (Gann et al., 2019). Long term datasets reveal emerging challenges such as disease outbreaks or climate driven shifts, allowing practitioners to revise methods before setbacks become irreversible. Learning from each intervention and adjusting techniques accordingly improves ecological resilience and helps secure sustainable oyster populations despite evolving environmental pressures (Pogoda et al., 2019). By embedding community leadership within an adaptive management framework restoration initiative can deliver lasting ecological gains alongside social and economic benefits.

2.5 Site-Selection Science

2.5.1. Environmental & structural criteria

Successful oyster reef restoration depends on the careful alignment of environmental conditions with sound structural design. Site selection remains the first decision because salinity, temperature, turbidity, dissolved oxygen and depth together determine oyster survival and growth (Gomes, 2019). Once a suitable location is chosen the reef must offer physical features that resist predation and promote continuous recruitment. Vertical relief and adequate live oyster density both signal a reef that can sustain itself and recover from disturbance (Walles et al., 2016; Reeves et al., 2020). Regular checks for disease are equally important because outbreaks can quickly undermine even the best prepared sites. Standardised monitoring of reef dimensions, oyster density and the key environmental variables noted above provides a consistent way to track progress and compare outcomes among projects (Sciences et al., 2017). Integrating these biological, physical and environmental criteria allows practitioners to match

University of Ghana http://ugspace.ug.edu.gh

local conditions with broader ecological goals and gives each restoration effort the best chance of long-term success.

2.5.2. GIS-based habitat models

Geographic Information Systems have become central to modern habitat suitability assessments for oysters because they bring together large spatial data sets and reveal patterns that are not obvious when variables are viewed in isolation (Barnes et al., 2007; Beseres Pollack et al., 2012). Layers that describe water temperature, salinity, dissolved oxygen and substrate can be combined to identify the precise ranges in which oysters thrive. The resulting suitability maps guide reef placement and aquaculture zoning and also highlight areas where restoration would face severe stress. By overlaying pollution sources, coastal infrastructure and records of invasive species GIS helps managers anticipate conflicts and direct resources to locations with the greatest probability of success (Theuerkauf & Lipcius, 2016a; Theuerkauf et al., 2019). Studies that merge water quality data with sediment type and shoreline form show how such integrated models refine site selection and reduce costly trial and error (Mahu, Danso, Edusei, & deGraft-Johnson, 2023; Wang et al., 2023). Progress is uneven, however, because many coastlines still lack fine scale environmental data. Continued collection of local measurements and the development of region-specific models will close these gaps and allow GIS tools to reach their full potential in oyster habitat management.

2.5.3. AHP and other multi criteria tools in habitat assessment

The Analytical Hierarchy Process is a well-established multi criteria decision method that breaks a complex problem into a clear hierarchy of objectives, criteria and alternatives. By combining pairwise comparisons with a consistency check it balances quantitative data and expert opinion and reduces bias in environmental planning (Ishizaka & Nemery, 2013). Its flexibility makes it valuable in assessments that involve several stakeholders and competing objectives, for example environmental impact studies, land use planning and the allocation of

University of Ghana http://ugspace.ug.edu.gh

limited funds (Ramanathan, 2001). Applications range from selecting reclamation methods for open pit mines to prioritising habitat conservation where trade-offs must be explicit and transparent (Bascetin, 2007; Calabrese et al., 2019; Sahoo & Goswami, 2023).

When coupled with Geographic Information Systems the method gains a spatial dimension that is essential for habitat suitability work. GIS provides layered maps of salinity, temperature, substrate, dissolved oxygen and anthropogenic stressors, while the Analytical Hierarchy Process supplies the weighting scheme that ranks these layers according to stakeholder goals. The combined approach has proven effective in oyster restoration. Satellite chlorophyll data, flow velocities and oxygen maps have been weighted to reveal locations that maximise water filtration services (Theuerkauf et al., 2019). Habitat suitability indices derived in this way show strong agreement with observed farm yields and natural reef performance, confirming their predictive strength (Cho et al., 2012; Theuerkauf & Lipcius, 2016a). Recent work extends the framework by adding Monte Carlo simulations and hydrodynamic models to account for uncertainty and tide driven transport, producing a quantitative suitability index for Crassostrea gigas reefs (Wang et al., 2023). Similar studies demonstrate how GIS combined with farm scale models can guide shellfish aquaculture even in data poor regions, thereby widening the geographic reach of restoration science (Silva et al., 2011; Mahu, Danso, Edusei, & deGraft-Johnson, 2023).

Despite these successes, two challenges remain. First, many coastlines still lack the high-resolution environmental layers that underpin reliable maps. Second, criteria weights often vary from one study to the next, which complicates comparisons across regions. Continued field monitoring, remote sensing and stakeholder workshops will help fill data gaps and move toward standardised weighting schemes. Refining the integration of the Analytical Hierarchy Process with GIS and related decision tools will therefore play a central role in future oyster conservation and habitat restoration planning.

University of Ghana http://ugspace.ug.edu.gh

2.5.4. Case-study evidence

Research on site prioritisation offers practical guidance for shellfish restoration. Swannack et al. (2014) produced a habitat suitability index for oyster reefs that links key environmental variables to restoration success, showing how quantitative screening can streamline field work. Pogoda et al. (2020) identified criteria for reviving native European oyster reefs and stressed the need to match historical distribution with present-day habitat quality and natural recruitment potential. Smaal et al. (2009) set out a management framework that blends aquaculture, conservation and restoration, aiming to rebuild stocks while safeguarding ecosystem services. Although Null and Lund (2012) focused on fish habitats, their optimisation model demonstrates how similar analytical tools can be adapted for shellfish by substituting species-specific habitat requirements.

Taken together, these studies highlight three consistent lessons. Rigorous environmental data and historical baselines improve the accuracy of site selection. Restoration outcomes are stronger when ecological goals are integrated with economic and social considerations. Decision support models work best when they remain flexible enough to incorporate local ecosystem dynamics and the habitat needs of the target species. A site-prioritisation strategy built on these principles can raise the efficiency of restoration projects and support the long-term recovery of shellfish populations.

2.6 Local Context: Anyanui Creek

Anyanui Creek is an approx. 26 km tidal channel that drains into the lower Volta River estuary on Ghana's south-eastern coast. The creek once supported dense shellfish beds yet now shows clear signs of habitat degradation, overharvesting and land-based pollution, all of which depress local oyster stocks. These pressures make the system an obvious candidate for place-specific restoration that blends ecological science with community priorities.

University of Ghana http://ugspace.ug.edu.gh

Active participation by residents can raise project success and strengthen long-term stewardship. Hands-on restoration and targeted education programmes give local fishers and youth a direct stake in reef recovery and improve public understanding of water-quality links to livelihoods (Gassett, 2022). Cultural assessments further ensure that restoration plans respect traditional resource use while maximising ecological and economic benefits (Paolisso & Dery, 2010).

Quantifying the monetary value of reef services also helps secure political and financial backing. A framework that converts filtration, shoreline protection and fish habitat into economic terms clarifies the tangible returns on investment in oyster restoration (Grabowski & Peterson, 2007). Site-specific substrate tests are equally important, because grain size, carbonate content and surface complexity strongly influence larval settlement and the associated fauna that drive ecosystem recovery (Graham et al., 2017).

Sustainable aquaculture can complement reef building by supplying seed oysters, reducing pressure on wild beds and creating alternative income streams. Farming practices that use locally adapted strains and limit environmental impacts align well with the broader restoration goals for the creek.

A strategy that unites these elements such as scientific assessment, cultural integration, economic valuation, careful substrate choice and responsible aquaculture, offers the best chance of rebuilding resilient oyster populations in Anyanui Creek. Success here would not only restore a key component of the local coastal ecosystem but also provide a model for similar tidal creeks facing parallel challenges in West Africa and beyond.

University of Ghana http://ugspace.ug.edu.gh

2.7 Management and Policy Implications

2.7.1 Local and National Conservation Policies for Oyster Restoration

Strong policy frameworks are essential because they turn site level science into sustained action. Decision support systems that weigh ecological data against financial and social considerations help managers set clear priorities and allocate limited funds where they will have the greatest impact (Smith & Pruett, 2024). In practice these systems perform best when they sit inside a wider policy environment that encourages open data flows and coordinated planning among projects. Shared monitoring standards reduce duplication and create the economies of scale noted by Blomberg (2022), allowing smaller initiatives to benefit from regional expertise.

Examples from Europe show how ecological and economic goals can be aligned. In the United Kingdom feasibility studies for the native European oyster paired sanctuary zones with commercial production to protect brood stock while sustaining livelihoods (Laing et al., 2006). The Native Oyster Restoration Alliance later refined this model by defining common baselines and methods that individual countries can adopt yet still compare across borders (Zu Ermgassen et al., 2020).

Ghana can draw on these lessons for Anyanui Creek and similar systems. A national guideline that links coastal zone planning with fisheries regulation would make it easier to designate restoration areas, enforce harvest moratoria and direct community-based aquaculture toward sites that complement rather than compromise reef recovery. Mandating regular reporting of water quality, recruitment and harvest data would feed the decision support tools already described and keep projects accountable. Policies built on transparency, shared metrics and local participation will therefore give oyster restoration the regulatory stability it needs to deliver long term ecological and economic returns.

University of Ghana http://ugspace.ug.edu.gh

2.7.2 Community engagement

Projects that restore oyster reefs succeed more often when the people who depend on the coast help design and run them. Practical knowledge from fishers, community leaders and local conservation groups complements scientific surveys and reveals social constraints that may otherwise be missed (Silberberg & Martinez-Bianchi, 2019). Early involvement also builds a sense of ownership that can secure labour for construction work and vigilance against poaching or pollution.

Stakeholder dialogue is most effective when it is continuous rather than limited to a single consultation round. Decision making workshops, participatory mapping and joint evaluation sessions give residents a clear role in problem solving much as community forums guide planning for public events or neighbourhood renewal (Jordan et al., 2019; Wesley & Parnell, 2020). Transparent communication of goals and progress keeps expectations realistic, and fosters trust between project managers and the wider public (Ramachandra & Naha Abu Mansor, 2014).

Once reefs are in place community stewards can collect basic monitoring data and report breaches of harvest rules. Their presence reduces enforcement costs and strengthens environmental citizenship, leading to better ecological outcomes and higher social returns on investment (Boiral & Heras-Saizarbitoria, 2017). Integrating these participatory practices into policy guidelines therefore completes the link between national conservation aims and the everyday realities of coastal livelihoods, giving oyster restoration an anchor in the communities it is meant to serve.

2.7.3 Ecosystem-service framing

Biodiversity underpins sustainable fisheries because diverse food webs buffer environmental change and sustain the flows of nutrients and biomass that humans harvest for food and income

University of Ghana http://ugspace.ug.edu.gh

(Hammer, 2016). Oyster reefs make a disproportionate contribution to this diversity by adding three-dimensional structure on the seabed where juvenile fish, crabs and many small invertebrates find shelter and forage. Yet accelerating expansion of open ocean fisheries and destructive gears has removed much of that structure and destabilised marine food webs, which threatens both ecological balance and long-term food security (Dunn et al., 2019).

Such trends point to the limits of single stock management and strengthen the case for an ecosystem-based approach that protects habitat as well as target species. Fishing methods that resuspend sediment and crush reef building organisms erode seabed biodiversity and compromise wider ecosystem functions, prompting calls for gear restrictions and habitat set asides (Thrush et al., 2016). Inland fisheries face a parallel dilemma, where maintaining yields while protecting floodplain and delta habitats demands careful control of effort and gear type (Kolding et al., 2015).

Restoring oyster reefs can reverse part of this decline by recreating habitat complexity and improving water quality through filtration. Dense reefs accelerate nutrient uptake, stabilise shorelines, sequester carbon in shell material and raise the resilience of estuarine and coastal systems to climatic extremes. Quantifying these services in economic terms, as outlined earlier for Anyanui Creek, strengthens the business case for restoration and aligns conservation aims with food security and coastal protection strategies. In this way an ecosystem service perspective not only clarifies the multiple benefits of oyster reef recovery but also provides a unifying framework for policy, community engagement and adaptive management.

2.8 Knowledge Gaps & Future Directions

2.8.1 Standardised metrics & monitoring

Recent literature points to four closely linked gaps that limit progress in oyster reef restoration. First, Blomberg (2022) notes that data are often collected with different methods and stored

University of Ghana http://ugspace.ug.edu.gh

in project specific archives. Without coordinated dissemination and a single set of monitoring protocols researchers struggle to compare outcomes or build regional time-series that reveal long term trends. Second, Dunlop et al. (2023) show that many living shoreline projects are designed largely from an engineering perspective and therefore miss opportunities to exploit biological processes that would improve reef self-maintenance. Morris et al. (2019) reach a similar conclusion and call for teams that blend geomorphology hydrodynamics and shellfish biology from the outset of each project. Third, La Peyre et al. (2014) demonstrate that even basic performance measures such as vertical relief persistence or juvenile oyster density are recorded inconsistently which prevents meta-analyses and slows the identification of best practice. Finally, although oyster reefs are widely promoted as natural breakwaters the empirical evidence for large scale shoreline protection remains scattered and sometimes contradictory. More field experiments that link reef design to wave attenuation and erosion rates are required before managers can set defensible targets for coastal defence.

2.8.2 Emerging technologies

Recent advances in observation tools and ecological engineering are reshaping oyster reef restoration. Digital monitoring platforms now link field sensors, mobile applications and cloud databases, giving practitioners near real time access to environmental data and project performance. A coordinated approach of this kind answers earlier calls for better data dissemination and more consistent evaluation methods (Blomberg et al. 2018).

Remote sensing and geographic information systems have moved from coarse mapping to fine scale habitat assessment as drone photography and modern satellite constellations deliver images measured in centimetres. Detailed surface models help locate remnant reef outcrops, map sediment plumes and verify recruitment hot spots without extensive boat time (Casella et al., 2017). These data streams feed directly into adaptive management dashboards described in section 2.7 and speed the adjustment of field protocols when conditions change.

University of Ghana http://ugspace.ug.edu.gh

Construction methods have also evolved. Ecological engineering groups are testing biodegradable meshes and modular units shaped through three-dimensional printing that create varied microhabitats and can flex with local hydrodynamics. Early trials show that the added surface complexity boosts larval settlement and increases survival of juvenile oysters while reducing the risk of structural failure under storm waves (Morris et al. 2019).

At the organism level high throughput genetic screening is opening new options for selective breeding. Molecular markers now identify strains with enhanced disease tolerance and thermal resilience, information that can guide hatchery production and maintain genetic diversity in restoration stock (Yoris-Nobile et al., 2023). Paired with environmental DNA surveys, these tools also allow rapid detection of invasive species or pathogens before they become established.

Together these technological advances close several of the knowledge gaps highlighted earlier. They standardise data collection, strengthen design testing and improve the match between reef structure and ecological function. As costs fall and training expands the same innovations can be applied in data poor settings such as Anyanui Creek, supporting both local management and international comparisons of restoration success.

2.8.3 Socio-economic integration

Oyster reef restoration delivers its greatest benefits when ecological goals are woven into the economic and social fabric of coastal communities. Pultrone (2022) argues that effective projects bridge science, local economies, legislation, spatial planning and public values rather than treating each realm in isolation. This comprehensive view is especially relevant in settings such as Anyanui Creek where many livelihoods depend directly on the health of nearshore ecosystems.

University of Ghana http://ugspace.ug.edu.gh

Embedding ethical principles, social equity and ecological security in project design ensures that gains are shared fairly and that restoration does not intensify existing inequalities. The development literature shows that programmes centred on these principles generate stronger public support and longer lasting economic returns (Sinha et al., 2013). In practice this means directing training and employment toward local residents, protecting customary access rights and linking reef recovery to community enterprises such as small-scale oyster farming or eco-tourism.

Sustainability also requires a policy environment that aligns restoration with coastal zoning, fisheries regulation and climate adaptation plans. Yáñez-Arancibia et al. (2013) calls for legal and economic instruments that recognise the full set of ecosystem services provided by reefs, from water filtration and shoreline stabilisation to enhanced fishery productivity. Integrating these services into municipal budgets and development strategies strengthens the case for continued investment.

Collaboration among scientists, government agencies, industry partners and civil society is therefore vital. Joint planning sessions can translate ecological targets into job creation schemes and revenue streams that match community aspirations. Well-designed funding mechanisms, such as payment for ecosystem service schemes or blue carbon credits, then provide the financial continuity needed to move beyond short pilot phases to large scale and enduring restoration (Meyers et al., 2020). In this way socio economic integration turns reef rebuilding from a narrowly ecological exercise into a catalyst for resilient coastal development.

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

CHAPTER THREE

METHODOLOGY

3.1. Study area

Anyanui Creek (ANC) lies on the south-eastern coast of Ghana between 5° 45 ′ and 5° 49′ N and 0° 42′ and 0° 50′ E (Figure 2). The flowing channel is about twenty-six kilometres long, running from Atorkor through Dzita and Anyanui before reaching its former mouth at Fuveme. Persistent shoreline retreat and sand-bar accretion have removed most of Fuveme's land area; the site is now a narrow, tidally inundated sand spit with scattered concrete ruins, and the displaced community has resettled inland at Agorkedzi and other nearby villages (Bokpe, 2021; This study). Small tributaries enter the creek along its course, but the dominant upstream inflow comes from the lower portions Keta Lagoon, whose farming catchment enriches the water with nitrogen and phosphorus (Mahu, Danso, Edusei, & deGraft-Johnson, 2023). The channel averages about 3 meters deep, with certain portions exceeding >20 metres. Vegetation ranges from marsh and freshwater grassland in the upper reaches to dense *Avicennia* and *Rhizophora* mangrove cover along the middle and lower banks. Near the mouth, the banks give way to sandy barrier-beach ridges lined with coconut and mature palm, reflecting the combined influence of tidal exchange and active coastal processes.

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

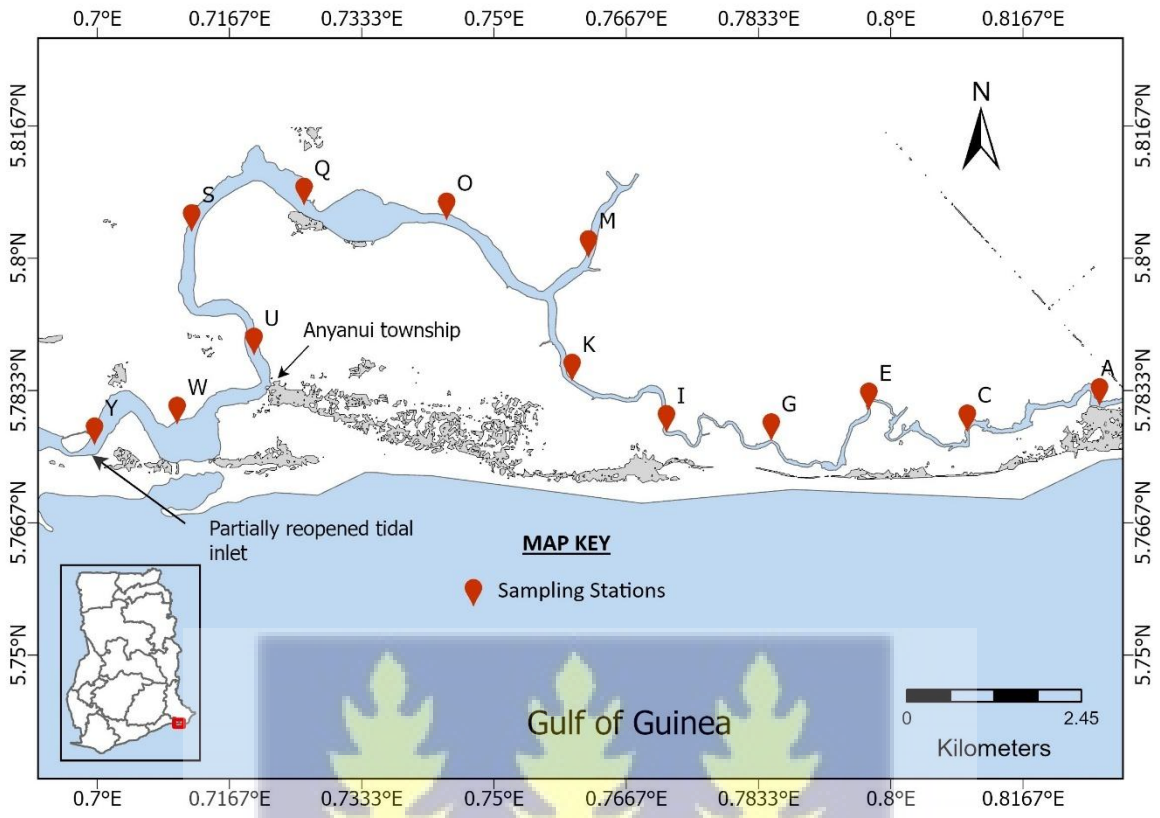


Figure 2: Map of the study area (Anyanui creek).

Communities situated along the Anyanui Creek including Anyanui, Glikpe and Dzita, support several thousand people despite their narrow coastal setting. The 2010 Population and Housing Census counted 4,864 residents in the Dzita–Agbledomi cluster and 1,783 in Anyanui, whereas settlements such as Glikpe fall well below the urban threshold of 5,000 inhabitants, each registering <1,000 people (Ghana Statistical, 2010). Most households combine small-scale aquaculture, crop farming and the cutting and trading of mangrove wood (**Figure 3a**). Anyanui functions as the main redistribution hub for *Rhizophora* poles and fuelwood harvested throughout the lower creek.

University of Ghana http://ugspace.ug.edu.gh

Local bylaws and periodic NGO campaigns have tried to control cutting seasons, impose diameter limits and insist on replanting, yet enforcement remains weak. Nunoo and Agyekumhene (2022) show that more than seventy per cent of cutters in the Volta delta earn at least half of their annual income from mangrove harvesting, a dependence that keeps illicit felling attractive even when fines are threatened. Continuous removal of mature trees eliminates the prop-root structures on which wild *Crassostrea tulipa* spat would normally settle, hastening the decline of natural oyster reefs.

Waste-management shortfalls compound the ecological damage. District records indicate that forty-eight per cent of households dispose of solid waste at open dumps (**Figure 3b**) and forty-nine per cent pour liquid waste directly onto streets or into surface drains (Ghana Statistical, 2010), practices that feed nutrient and pathogen loads into the creek. Together, population pressure, economic reliance on mangrove wood and inadequate sanitation create supporting response that degrades oyster habitat faster than it can recover.

Figure 3: Picture showing some of the factors affecting *C. tulipa* populations within ANC. a) Harvested mangrove ready to be sold and distributed. b) Areas very close to ANC used for waste disposal.

The coastline lies within a persistently warm tropical belt. Rainfall follows a bimodal pattern structured by the movements of two contrasting air masses. A major rainy season usually

University of Ghana http://ugspace.ug.edu.gh

begins in April and ends in July, and a shorter minor rainy season runs from September to November; the longest dry spell then extends from December through March when the continental harmattan returns (The World Bank, 2021). The sequence results from the annual alternation of a moist south-westerly monsoon and a dry north-easterly trade wind, the latter locally felt as the harmattan (Gentilli et al., 2009). Recent analyses of station records around Accra show that extreme downpours have become more frequent since the early 2000s and that the peak months of the rains are shifting (Padi et al., 2021), a trend consistent with emerging climate-change signals as seen in **Table 2**.

Table 2. Illustration of notable environmental fluctuations (mean ± standard deviation based on 12 observations) during the Dry and Rainy months at Anyanui Creek from March 2023 – February 2024. DO = Dissolved oxygen; Chla = Chlorophyll a; NO3 = Nitrates; PO4 = Phosphates; SiO3 = Silicates.

Major parameters	Dry	Rainy	Annual average
Water temperature (°C)	32.15 ± 0.21	31.21 ± 0.38	31.68 ± 0.26
Salinity (ppt)	10.42 ± 2.63	8.09 ± 2.34	9.26 ± 2.46
DO (mg/L)	4.31 ± 2.28	4.45 ± 1.01	4.38 ± 1.59
pH	7.55 ± 0.15	7.62 ± 0.09	7.59 ± 0.11
Chla (µg/L)	984.95 ± 318.87	584.94 ± 235.93	784.95 ± 155.39
Transparency (m)	1.02 ± 0.11	0.96 ± 0.14	0.99 ± 0.11
NO3 (µg/L)	537.97 ± 139.99	64.99 ± 9.98	301.48 ± 70.35
PO4 (µg/L)	28.26 ± 9.56	58.33 ± 7.77	43.30 ± 7.57
SiO3 (µg/L)	4830.48 ± 287.91	5212.82 ± 399.98	5021.63 ± 293.91

3.2 Collection of datasets related to environmental variables.

Environmental data were collected at 13 stations spaced roughly two kilometres apart along the full 26 km course of Anyanui Creek. Sampling campaigns were carried out on the last

University of Ghana http://ugspace.ug.edu.gh

Friday of every month from March 2023 through February 2024 and each campaign covered both high-tide and low-tide windows to capture tidal variability. At every station surface water temperature, salinity, dissolved oxygen and total pH were measured with a handheld multiparameter probe (HORIBA U-50). The probe was calibrated in the field at the start of each survey with manufacturer-supplied pH buffers, a 35 ppt conductivity standard and air-saturated water for dissolved-oxygen span checks to ensure data traceability.

Chlorophyll-a was determined spectrophotometrically with an Angstrom-Advance UV-1800 after extraction of 100 mL water samples in 10ml of 90% acetone following Aminot and Rey (2000). Absorbance was read at 663, 645 and 630 nm against an acetone blank immediately after filtration and a three-point calibration verified linearity of the spectrophotometer each laboratory day. Depth was logged continuously with a Deeper CHIRP + 2 sonar towed at three to 10 knots; sonar draught and sound-speed settings were checked against lead-line readings at two anchor points during every survey. Instrument accuracies and calibration frequencies are summarised in Table 3, providing confidence limits for all reported variables.

Table 3: Summary of Instruments, Variables, and Measurement Accuracy Used in Water Quality Monitoring.

Variable	Unit	Instrument name and model	Accuracy (±)
Temp	(°C)	HORIBA probe - U-5000G	JIS class B platinum thermometer sensor (±0.30 + 0.005 |t|)
Sal	(ppt)	HORIBA probe - U-5000G	±3.00
DO	mg/L	HORIBA probe - U-5000G	0 to 20 mg/L: ±0.20 mg/L, 20 to 50 mg/L: ±0.50 mg/L
Total pH (pH_T)		HORIBA probe - U-5000G	±0.10

University of Ghana http://ugspace.ug.edu.gh

Chl-a	µg/L	ANGSTROM ADVANCE spectrophotometer - UV-1800PC	±0.02
Water depth	(m)	Deeper Sonar CHIRP +2	Dual frequency sonar

3.3. Analytical hierarchical process (AHP) for weight selection

The analytic hierarchy process was adopted as a structured decision model because it fits three working assumptions of this study. First, the main drivers of *C. tulipa* habitat quality (Water quality factors, food availability proxy and Bathymetry) act independently enough for their effects to be evaluated separately. Second, expert judgements about those drivers can be expressed on a common ratio scale, for example by asking which of two factors is "**equally important**", "**moderately more important**" or "**strongly more important**" for oyster restoration. Third, the relative suitability of individual creek reaches does not alter the meaning of the criteria themselves, so the hierarchy remains stable once defined.

The decision goal, the 3 criteria and the 13 proposed restoration reaches were therefore arranged in a hierarchy as illustrated in Figure 4. After identifying the goal, each criterion was compared with every other criterion two at a time so that a pair always consisted of exactly two criteria drawn from the same level of the hierarchy. Nine specialists familiar with Oyster ecology and culture filled in a nine-point Saaty scale (a ratio scale that assigns the integers 1-9 to stated intensities ranging from "equal importance" to "extreme importance") for every pair, producing a three-by-three reciprocal matrix (Saaty, 2016).

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

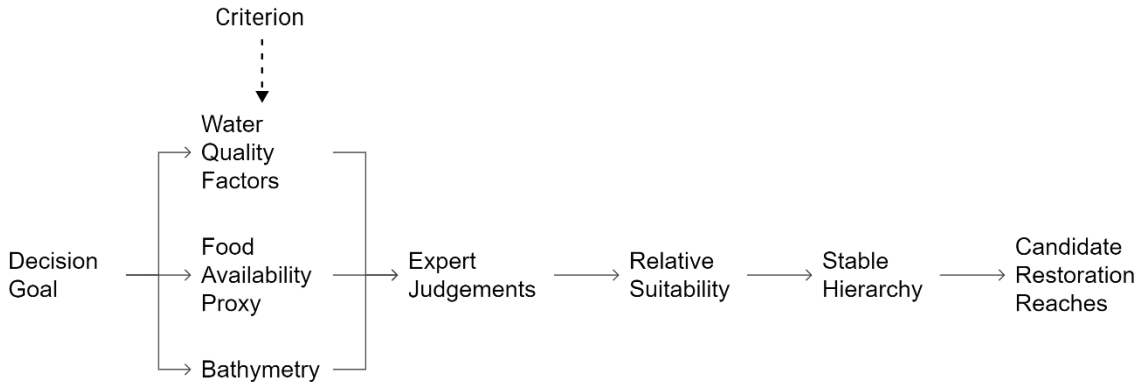


Figure 4: Hierarchy model for AHP process.

Weights for the criteria were obtained by solving for the principal eigenvector of that matrix and then dividing every element of the vector by the sum of all elements so that the final weights add to "1", a normalisation that turns them into direct proportions of total influence. The logical coherence of each judgement set was checked with the consistency ratio (CR). The consistency ratio (CR) was calculated by the formula:

$$CR = CI / RI \quad (1)$$

The consistency index (CI) is defined by (ref) as the difference between the principal eigenvalue λ_{max} and the matrix order n, divided by $n - 1$ (Wan & Tummala). It is calculated using the expression

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (2)$$

Where λ_{max} is the maximum eigenvalue obtained from the pairwise comparison matrix and n is the number of criteria or alternatives being evaluated. The random index (RI) is a tabulated mean of CI values generated from randomly produced reciprocal matrices of the same order and is used in combination with CI to compute the consistency ratio. Saaty (2016) recommends that CR remain below zero point one; In this study the CR calculated from the matrices of the

University of Ghana http://ugspace.ug.edu.gh

Water quality factors, Food availability proxy and bathymetry were 0.09, 0.03 and 0.02 respectively, so no judgement set required revision. The resulting criterion weights deduced appear in Table 4.

3.4. Suitability functions and Indices selection

Seven indices were selected as suitability factors for *Crassostrea tulipa reef* restoration assessment. These were based on Matthiessen (2008) and Yankson (1990), who stated that factors such as salinity and temperature are important due to their effects on fertilization success and larval yield. Table 4 shows the selected indices used for estimating the suitability of *C. tulipa* for reef restoration. The table included three layers of indices: water quality factors, primary production (food availability), and bathymetry.

Table 4. Selected Indices for C. tulipa reef restoration suitability assessment and assigned weights using the AHP approach adopted from Wang et al. (2023).

Selected Indices (First layer)	Variables (Description)	Weights	Selected Indices (Second layer)	Weights
Water quality factors	V3 (temperature for growth)	0.77	Water temperature	0.25
	V4 (Salinity for growth)		Salinity	0.21
	V6		Dissolved oxygen	0.17
	V5		pH	0.14
Food availability proxy	V6	0.13	Chlorophyll a conc.	0.13
Bathymetry	V7	0.10	Water depth	0.10
Water quality factors (Larval)	V1 (Salinity for Larval yield)	1.00	Salinity	0.48

University of Ghana http://ugspace.ug.edu.gh

	V2 (temperature for Larval yield)	Water temperature	0.52

The weights assigned to each index indicated their importance in the assessment. The highest weight after AHP was given to water quality factors, with water temperature, salinity, dissolved oxygen, pH, and water transparency as sub-indices. Food availability had moderate weight, with chlorophyll a concentration as a sub-index. Bathymetry was assigned to a relatively lower weight, with water depth as a sub-index.

3.5. Comprehensive depiction of model, explanation of its design, components, and functionalities

The habitat suitability index devised for *Crassostrea tulipa* combines two linked sub-models that mirror the species' principal ecological phases. The first estimates the fraction of eyed pediveligers that complete metamorphosis and attach successfully to hard substrata, and the second evaluates the growth and survival probability of spat and adults. Planktonic eggs and earlier veligers are excluded because they remain pelagic and experience habitat conditions governed chiefly by the timing and location of spawning rather than by local benthic features.

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

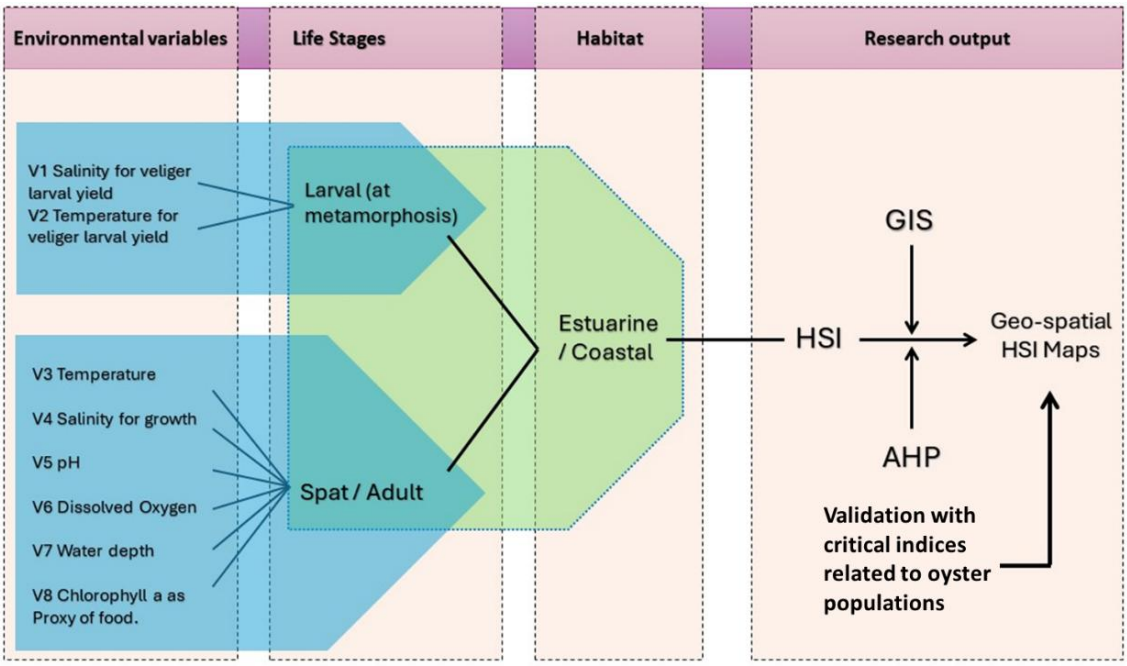


Figure 5: A tree diagram visually representing the interconnections among environmental variables, life stages, and habitat types utilized in establishing the Habitat Suitability Index (HSI) for the West African mangrove oyster, C. tulipa.

Figure 5 depicts the three-level hierarchy that organises the model. The enhancement of *C. tulipa* populations forms the goal at the apex; six environmental drivers occupy the middle tier; and thirteen candidate restoration reaches make up the base. Temperature, salinity, pH, dissolved oxygen, chlorophyll-a and depth were retained because tolerance experiments and field studies identify them as the strongest constraints on larval settlement or post-settlement performance in tropical estuaries (Yankson 1990; Dolmer et al. 2014; Mahu et al. 2022; Osei et al. 2022). Their lower and upper limits together with their optimum ranges are collated in Table 5.

Table 5. Environmental variables, ranges, and data sources for oysters to be used in the indicator systems HSI model.

University of Ghana http://ugspace.ug.edu.gh

Environmental variable	Suitable ranges	References
Water temperature	18 - 33 °C (tolerable), 25 - 30 °C (fertilization, larval dev.)	Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al. (2022), Yankson (1990)
Salinity	4 - 50 ppt (tolerable), 20 – 35 ppt (fertilization, larval dev.).	Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al. (2022), Yankson (1990)
Dissolved oxygen	> 1 mg/L (tolerable), > 5, mg/L (Optimal)	Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al. (2022), Osei et al. (2022)
pH	6 - 8.5 (Suitable), > 7.6 (suitable for larval dev., ≈7.9 (Optimal)	Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al. (2022), Thiyagarajan and Ko (2012), Clements et al. (2021)
Chlorophyll a conc.	10 - 60 µg/L	Chowdhury, Wijsman, et al. (2019)
Water depth	0 - 1 m (Optimal), 2.5 – 6.0 m (farming depths), low tide line – 10m (tolerable)	Dolmer et al. (2014), Mizuta et al. (2012), Wang et al. (2023)

Each environmental variable was converted into a continuous response graph that converts any field observation into a dimensionless suitability score between zero and one. Temperature and salinity graphs (V1 and V2) apply to larval yield, whereas the remaining four graphs (V3–V8) govern the post-settlement stage; the full set is plotted in Figure 6. The graphs were constructed from the published tolerance ranges in Table 5 and smoothed with cubic splines so that intermediate values behave monotonically and realistically. Monthly measurements from the thirteen stations are fed into these functions to generate eight partial indices that are combined multiplicatively into a single habitat-suitability index for every survey. The numerical outputs and the spatio-temporal patterns they reveal appear in the Results, but the transfer functions themselves remain in the Methodology because they define the model inputs and enable replication.

University of Ghana http://ugspace.ug.edu.gh

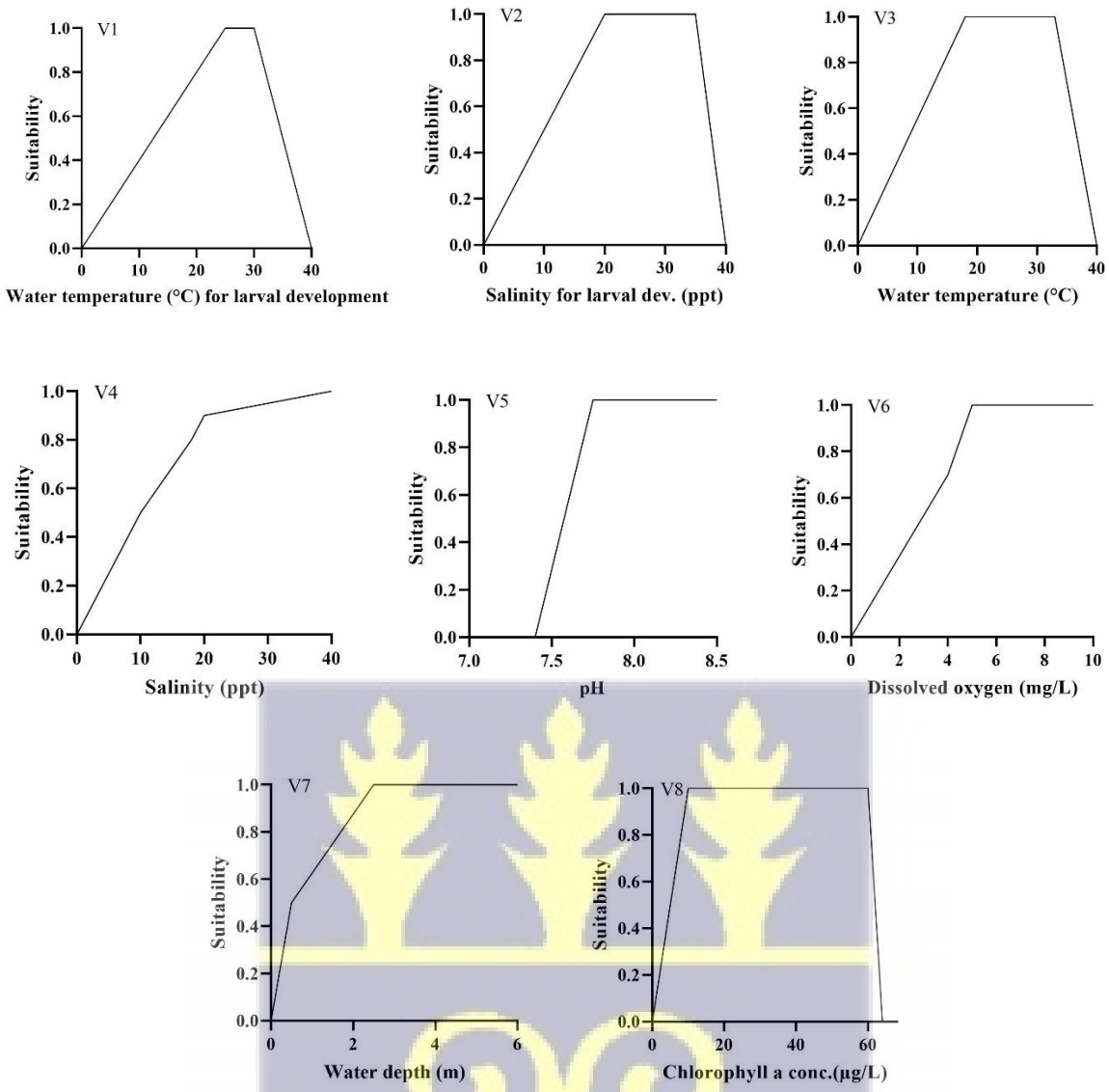


Figure 6: Connection between environmental variables and their corresponding habitat suitability values for the West African mangrove oyster *C. tulipa*.

3.5.1 Percentage embryonic development sub-model

A multilayer perceptron (MLP) neural network was implemented to estimate the proportion of embryos that complete development under the controlled temperature (T) and salinity (S) conditions obtained from laboratory rearing trials of *Crassostrea tulipa* (Yankson, 1990). The input vector was therefore $X = [T, S]$.

University of Ghana http://ugspace.ug.edu.gh

Activation in the first hidden layer followed

$$h_j^{(l)} = \sigma\left(w_{j1i}^{(1)} T + w_{j2}^{(1)} S + b_j^{(l)}\right), \quad (3)$$

While activations in subsequent layers $l = 2,3, \ldots, L$ were given by

$$h_j^{(l)} = \sigma\left(\sum_{i=1}^{n_{l-1}} w_{ji}^{(l)}\, h_i^{(l-1)} + b_j^{(l)},\right), \quad (4)$$

where σ is the rectified-linear-unit function (Goodfellow et al., 2016). A linear output neuron returned the predicted percentage embryonic development

$$\hat{\mathrm{E}} = \sum_{j=1}^{n_l} w_j^{(L)} h_j^{(L)} + b_{out.} \quad (5)$$

Model training minimised

$$Loss = \frac{1}{m}\sum_{i=1}^{m}(\hat{\mathrm{E}}^{(i)} - E^{(i)})^2 + \lambda \sum_{l=1}^{L}\sum_{j=1}^{n_l} ||w_j^{(l)}||^2, \quad (6)$$

where the second term is an L2 (ridge) penalty that discourages large weights (Hoerl & Kennard, 1970). During every training epoch a fraction p of hidden-layer activations was set to zero:

$$h_j^{(l)} = \sigma\left(\sum_{i=1}^{n_{l-1}} p_i\, w_{ji}^{(l)} h_i^{(l-1)} + b_j^{(l)}\right), \quad (7)$$

implementing the dropout procedure that improves generalisation (Srivastava et al., 2014).

Hyper-parameters λ, p, the number of hidden layers and the number of neurons per layer were tuned with an exhaustive grid search and five-fold cross-validation in scikit-learn (Pedregosa et al., 2011). Model skill was assessed with mean-squared error as defined in Equation 6 and with the coefficient of determination

$$R^2 = 1 - \frac{\sum_{i=1}^{m}\left(\hat{\mathrm{E}}^{(i)} - E^{(i)}\right)^2}{\sum_{i=1}^{m}(E^{(i)} - \bar{\mathrm{E}})^2}$$

University of Ghana http://ugspace.ug.edu.gh

Global sensitivity analysis used partial rank correlation coefficients to quantify the influence of each tuned hyperparameter on R^2 (Saltelli et al., 2008). Regularisation strength and dropout rate both showed elasticities below 0.05, whereas doubling the width of the second hidden layer increased R^2 by 4% points, confirming that additional model capacity rather than penalty terms delivered the largest performance gain.

3.5.2 Post-settlement sub-model

The post settlement sub model renders post-settlement drivers (V3-V8; Figure 5) into a single habitat suitability score. Each driver first passes through a bespoke response function that is calibrated to the optimum and tolerable thresholds reported in earlier tolerance studies of *C. tulipa* (Table 5). The functions are normalised so that a value of "1" marks fully favourable condition, a value of "0" marks conditions that are unfavourable to said species, and intermediate values decline smoothly across the tolerance margins as shown in Figure 5.

Expert judgement from AHP model supplied the relative importance of the six drivers; the resulting weights sum to "1" and therefore express each driver as a proportion of total influence. The composite habitat suitability index for any station and month is the weighted sum

$$HSI = \sum_{i=1}^{6} w_i S_i,$$

Where S_i is the normalised suitability score for driver i and w_i is its corresponding weight from AHP model. Suitable ranges represent conditions in which oysters can grow and reproduce, whereas tolerable ranges indicate limits that permit survival but incur physiological stress. Together these thresholds provide the backbone of the model and link the measured field data to a quantitative estimate of habitat quality.

University of Ghana http://ugspace.ug.edu.gh

3.6 Map generation and validation.

To map the distribution of Habitat Suitability Index (HSI) values (post-settlement), Inverse Distance Weighting (IDW) interpolation was employed in ArcGIS Pro. The process began by preparing a point layer with HSI values and a shape file representing the study area. The IDW tool was then used, with the point layer as the input, and the appropriate field for HSI values selected as the Z value. Parameters such as Power and Search Radius were adjusted to optimize the interpolation. Following the interpolation, the resulting raster was masked using the study area shapefile via the **Extent of Layer** and **Mask** tool to ensure the raster output was confined to the area of interest. The final masked raster was reviewed for accuracy and saved for further analysis.

3.7 Field Validation of Oyster Population and Habitat Suitability.

Field validation proceeded concurrently with the monthly environmental surveys. At every sampling station two habitat zones were examined, a near-shore fringe beneath the mangroves and a mid-channel strip over the sand–mud bottom. Within each zone 2 square quadrats measuring 1m on a side were positioned at random, giving 4 replicate quadrats per station. Depth at the quadrat zones ranged from 0.5 to 2.0 metres. When a quadrat contained no live oysters, the count was recorded as 0; when oysters were present the shells were detached carefully to avoid breakage and separated from empty valves. Live individuals were rinsed free of epibionts, placed on ice and transported to the laboratory. There the maximum shell height and whole wet mass were recorded, after which the soft tissue was extracted, oven-dried for twelve hours at 60°C and weighed. These measurements provided an independent dataset against which to compare the habitat suitability scores predicted by the model.

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

3.8 Estimating the Condition Index of *C. tulipa* in the Creek

The Condition Index is a quantitative measure used to assess the health and physiological state of bivalves, including oysters. It reflects the energy reserves and overall well-being of the organism by comparing the weight of the soft tissue to the weight or volume of the shell. A higher CI indicates a better nutritional status, which is essential for growth, reproduction, and survival (Rainer & Mann, 1992). In this study, evaluating the CI provides insight into the oysters' response to environmental conditions at the study site.

The Condition Index was calculated using the following formula:

$$Condition\ Index\ (CI) = \left(\frac{Dry\ Meat\ weight\ (g)}{Dry\ shell\ Weight\ (g)}\right) x\ 100$$

after both tissue and shell had been oven-dried to constant weight. Morphometric data were collected from a total of 50 live oysters obtained at stations G, O and Y during 7 consecutive monthly surveys conducted before mid-October 2023. On 15 September 2023 the Volta River Authority began an emergency release of water from Akosombo Dam. On 9 October the dam release was increased to nearly three times its normal rate, sending a strong pulse of fresh water through the delta (Citi, 2023). This killed most of the intertidal oysters. In the surveys that followed, only a few live oysters were found, so the samples collected before the release are the only dependable record of their normal condition.

3.9 Statistical analysis

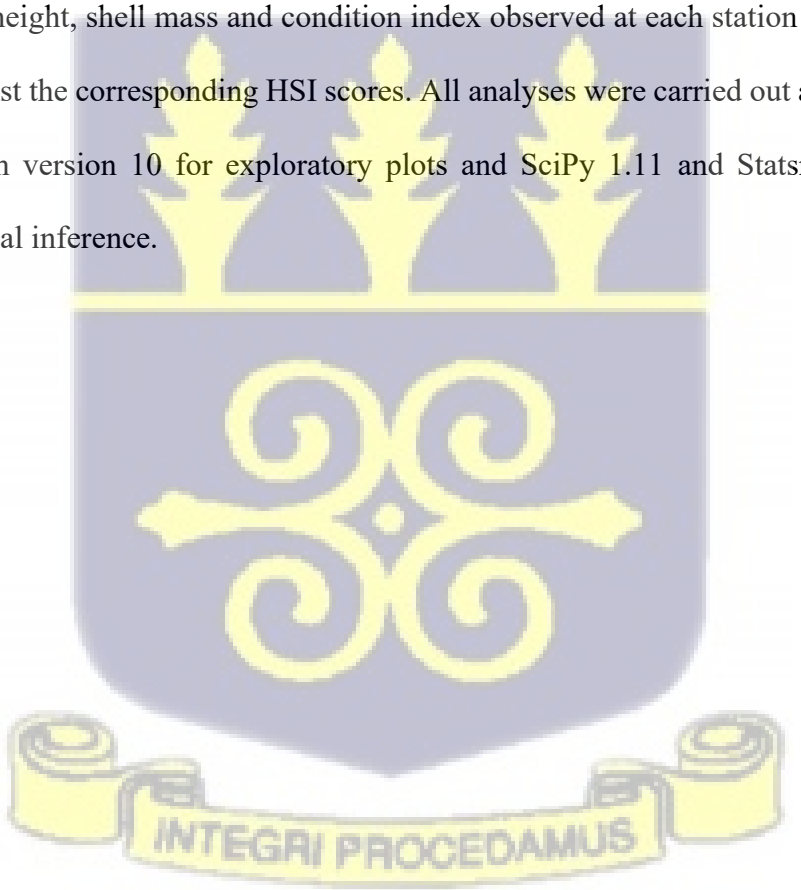
Multiple linear regression was used to relate oyster performance to prevailing water conditions. The response variables were shell height, whole-shell mass and the condition index computed as dry tissue mass divided by shell cavity volume following (Rainer & Mann, 1992). Predictor

University of Ghana http://ugspace.ug.edu.gh

variables comprised in-situ temperature, salinity, pH, dissolved oxygen and chlorophyll-a concentration measured at the time of collection.

Before fitting each model, the distributions of all variables were checked for normality with the Kolmogorov–Smirnov test, and equality of variances was verified with Levene's test. Variance-inflation factors were then calculated to detect multicollinearity among the predictors; no factor exceeded the conventional threshold of five, so all predictors were retained. Model residuals were inspected graphically to confirm that linearity and homoscedasticity assumptions held.

To evaluate how well the post-settlement habitat-suitability index reproduces field patterns, the ranges of shell height, shell mass and condition index observed at each station were regressed separately against the corresponding HSI scores. All analyses were carried out at $\alpha = 0.05$ with GraphPad Prism version 10 for exploratory plots and SciPy 1.11 and Statsmodels 0.14 in Python for formal inference.



University of Ghana http://ugspace.ug.edu.gh

CHAPTER FOUR

RESULTS

4.1. Temporal Variability of Physicochemical parameters and Chlorophyll-a concentrations.

Temperature ranged from 28.70 to 34.49 °C with an overall median of 31.80 °C and an interquartile range of 30.99 to 32.47 °C (Fig. 7). The lowest monthly median was 29.01 °C in July 2023 and the highest was 33.14 °C in May 2023. No measurement lay within the reported optimum band of 18 to 28 °C for *C. tulipa* growth and development . Salinity varied from 2.95 to 21.00 ppt. The median was 7.47 ppt with an interquartile range of 5.64 to 11.27 ppt. The monthly median reached its minimum at 5.05 ppt in May 2023 and its maximum at 14.91 ppt in March 2023. Only one value fell inside the optimum band of 20 to 35 ppt and the remainder were lower as seen in Figure 7.

Dissolved oxygen spanned 0.00 to 11.46 mg L^{-1}. The overall median was 5.00 mg L^{-1} and the interquartile range was 2.94 to 6.04 mg L^{-1} (Fig. 7). Monthly medians were lowest in November 2023 at 2.44 mg L^{-1} and highest in February 2024 at 7.40 mg L^{-1}. Measured pH ranged between 6.86 and 8.41 with a median of 7.62 and an interquartile range of 7.30 to 7.81. The lowest monthly median was 7.20 in October 2023 and the highest was 8.25 in July 2023. Forty observations were within the optimum band of 7.8 to 8.4, one was higher and one hundred fifteen were lower.

Chlorophyll-a concentrations varied widely from 21.54 to 3485.92 µg L^{-1}. The median was 461.17 µg L^{-1} with an interquartile range of 212.93 to 863.39 µg L^{-1}. The monthly median reached a minimum of 159.48 µg L^{-1} in May 2023 and a maximum of 1433.80 µg L^{-1} in September 2023.

University of Ghana http://ugspace.ug.edu.gh

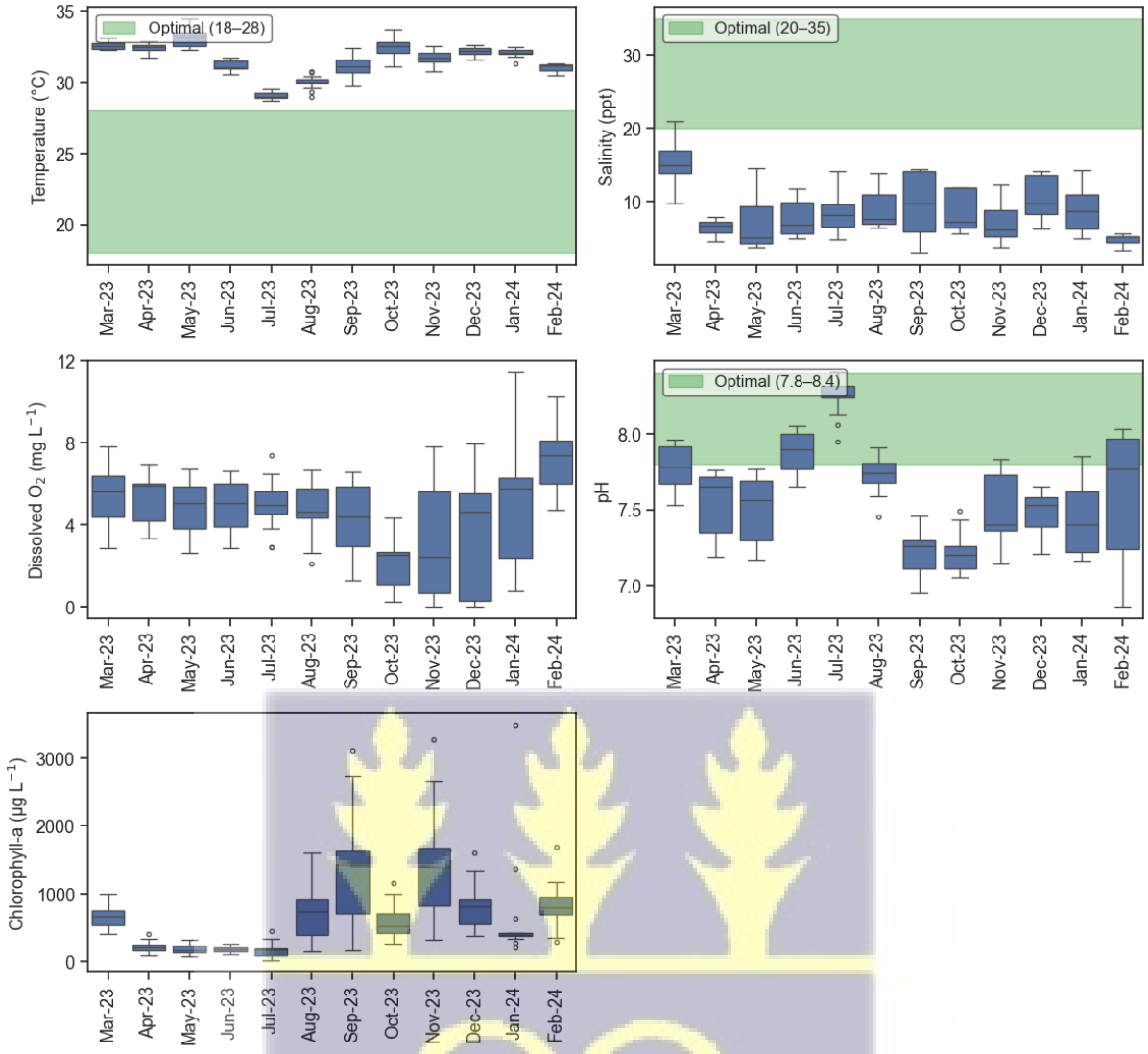


Figure 7: Monthly box-and-whisker plots of Temperature (°C), Salinity (ppt), Dissolved O (mgL^{-1}), pH, and Chlorophyll-a (μgL^{-1}) recorded at Anyanui Creek from Mar-23 to Feb-24. Boxes represent the interquartile range with the median marked; whiskers extend to 1.5 × IQR and points denote outliers. Translucent green bands indicate reference 'optimal' ranges for Temperature (°C), Salinity (ppt), and pH.

INTEGRI PROCEDAMUS

4.2. Spatial and temporal variability in veliger success

Figure 8 presents the spatial and temporal distribution of veliger success across stations A to Y from March 2023 to February 2024. Percentages ranged from about five to slightly above nine per cent. The lowest values occurred at lagoon-proximal stations A and C during March

University of Ghana http://ugspace.ug.edu.gh

and May 2023 when percentages approached five. Beginning in June 2023 veliger success increased across most stations and exceeded eight per cent through July, August and September 2023. A local maximum above eight and a half per cent was recorded at station Q in September 2023. From October 2023 onward high percentages were maintained creek-wide, and by February 2024 values were uniformly close to the upper end of the observed range.

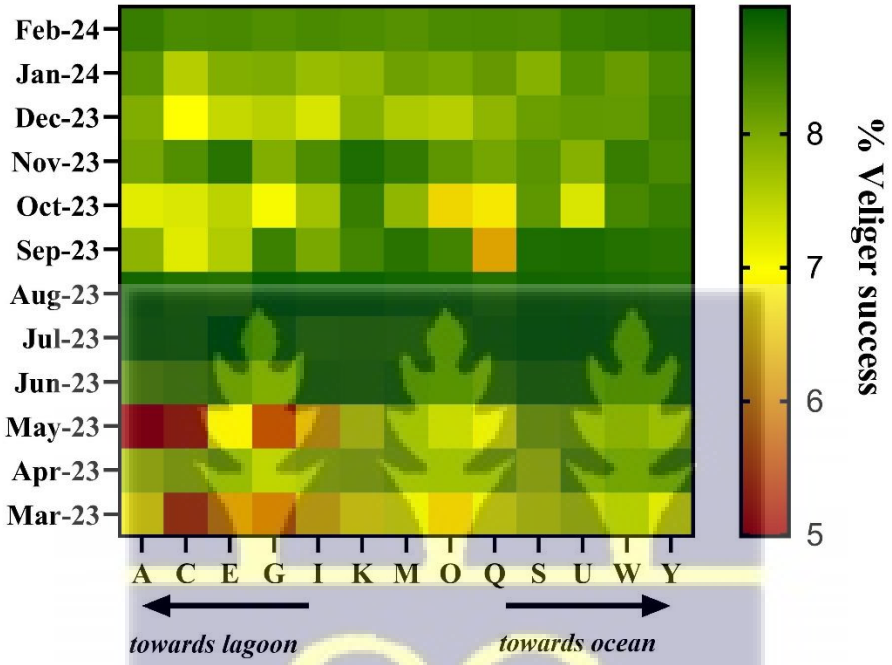


Figure 8. The temporally estimated percentage of embryonic development (success rate) for each of the sample stations was estimated using the ANN model. (March 2023 – February 2024).

4.3. Goodness of fit of linear regression models

Table 5 summarises the linear regression results for 50 oysters sampled across all quadrats during the study. The Condition Index model was significant with $p = 0.02$. It explained 85% of the variance with an R^2 of 0.85 and an adjusted R^2 of 0.72 and a standard error of 0.33.

University of Ghana http://ugspace.ug.edu.gh

Temperature showed a coefficient of -0.32 with p = 0.02, and salinity showed a coefficient of 0.14 with the same probability. Dissolved oxygen, pH and chlorophyll a were not significant.

The Shell Weight model was not significant with p = 0.19. It accounted for 64% of the variance with an adjusted value of 35% and a standard error of 4.78. None of its predictors were significant.

The Shell Height model was also not significant with p = 0.59. It explained 40% forty percent of the variance with an adjusted value of -0.10 and a standard error of 0.66. No predictor variables were significant in this model.

Table 5. Summary of linear regression models

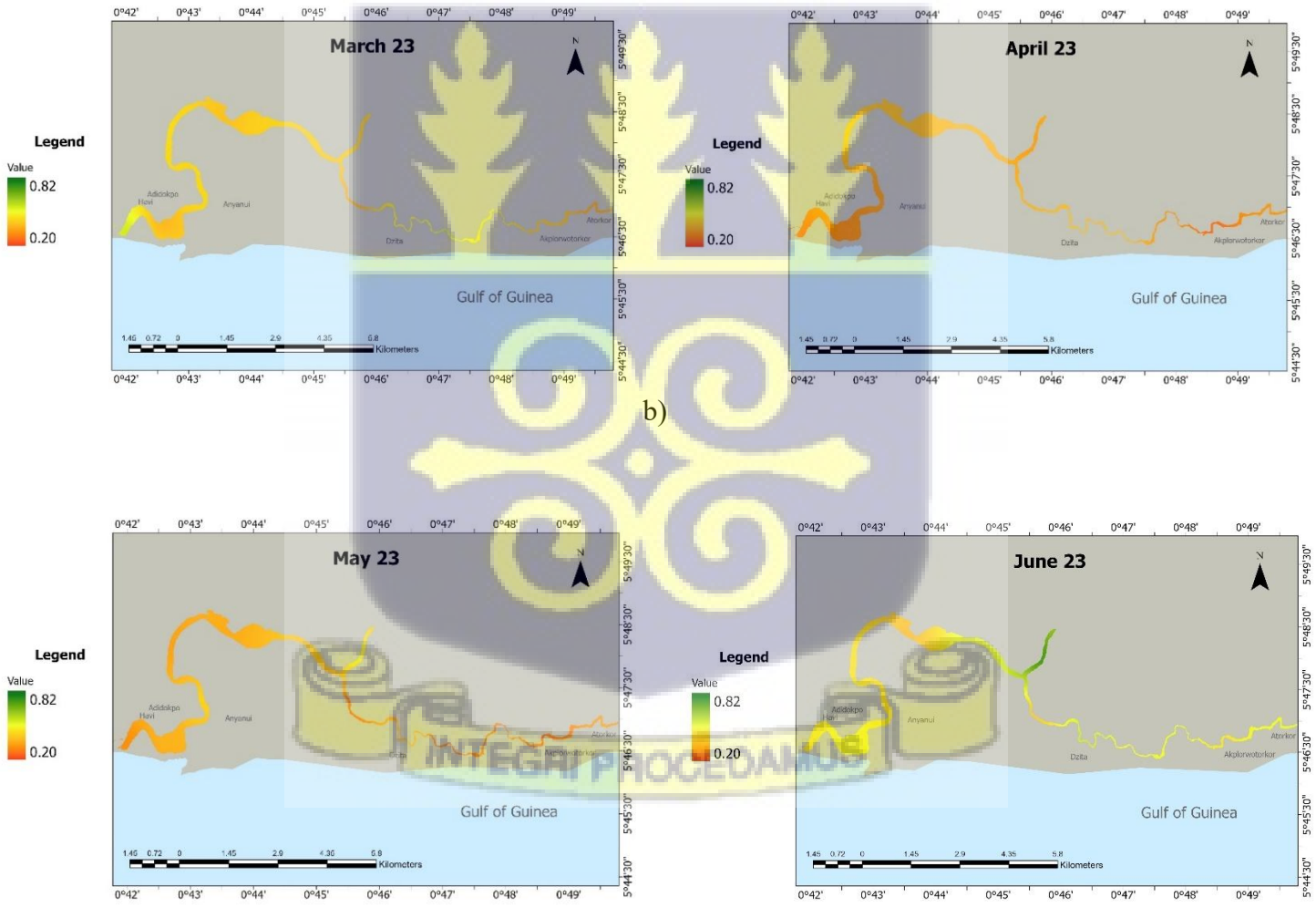
	R square	*Adjusted R Square*	*Std. Error of the Estimate*	*Significance of F-statistic (p-value)*
Cond. Index	0.85	0.72	0.33	0.02
Shell weight	0.64	0.35	4.78	0.19
Shell Height	0.40	-0.10	0.66	0.59

4.4. Spatial and Temporal Dynamics of Habitat Suitability for *C. tulipa*

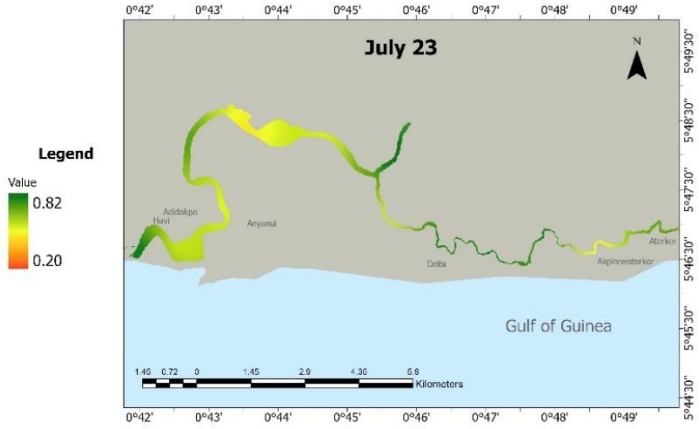
Figure 9 depicts the monthly spatial distribution of the index along Anyanui Creek from March 2023 to February 2024. Values throughout the record ranged from about 0.20 to 0.82. In March the channel showed mostly yellow and light-orange classes centred near values of 0.60. April and May retained this moderate pattern, although isolated orange to red patches near the mouth and in the central bends indicated local minima close to 0.30. In June extensive green areas above 0.75 appeared in the mid reach and extended upstream toward Salo (Location M; see Figure 2). Green and yellow classes dominated in July, with only short western segments remaining moderate.

University of Ghana http://ugspace.ug.edu.gh

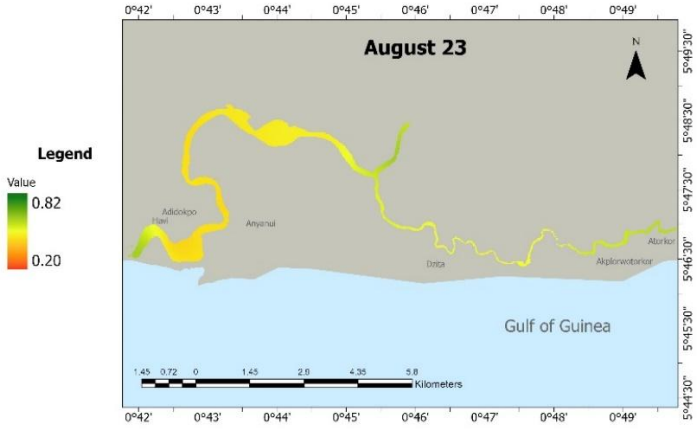
In August the green zone contracted and most of the creek returned to yellow tones between about 0.55 and 0.65. September marked the onset of a gradual decrease and orange classes became widespread; by October the upper and mid reaches recorded the lowest values of the series, close to 0.20. A modest rebound followed in November and December as yellow values reappeared, though green classes did not return. January 2024 remained largely orange in the upper and mid reaches while yellow tones persisted near the mouth and western bends. February 2024 showed a slight increase in the central channel where yellow classes near 0.65 replaced some orange areas, yet the creek as a whole stayed below moderate, and no green classes were present.



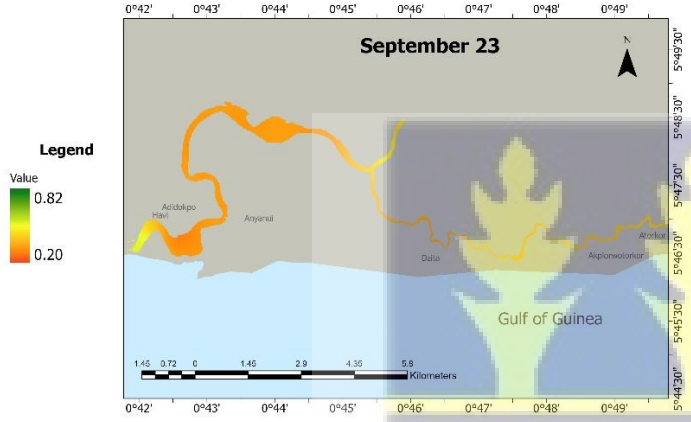
University of Ghana http://ugspace.ug.edu.gh



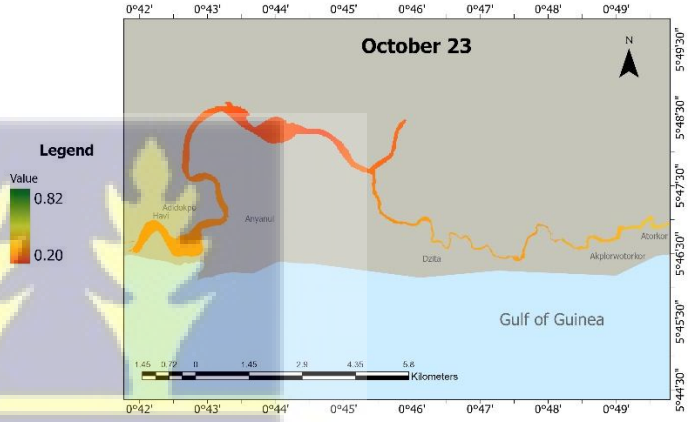
e)



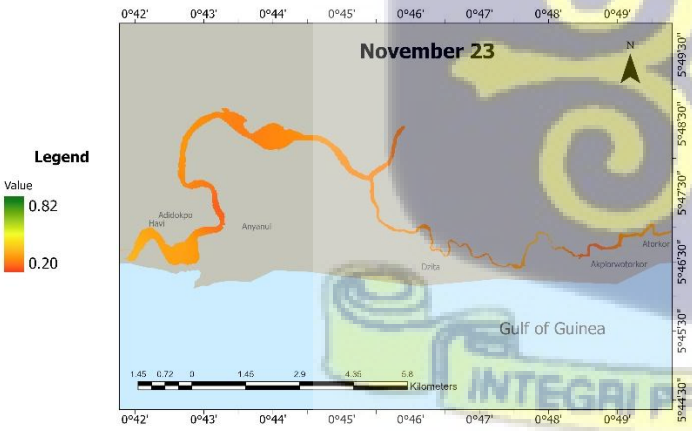
f)



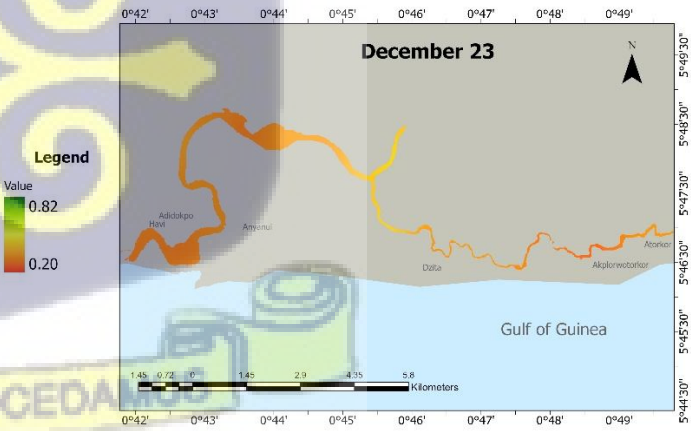
g)



h)

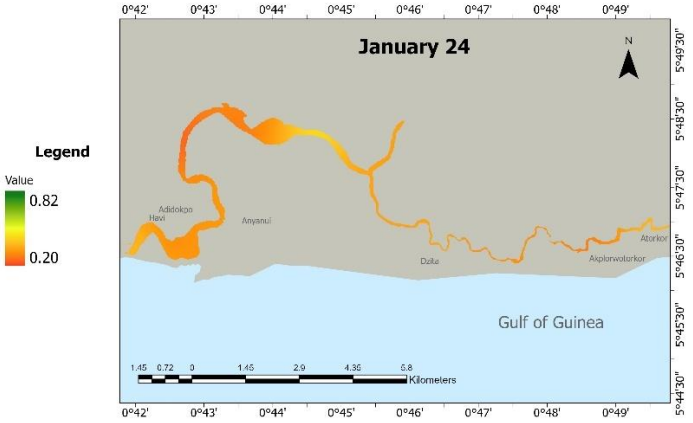


i)

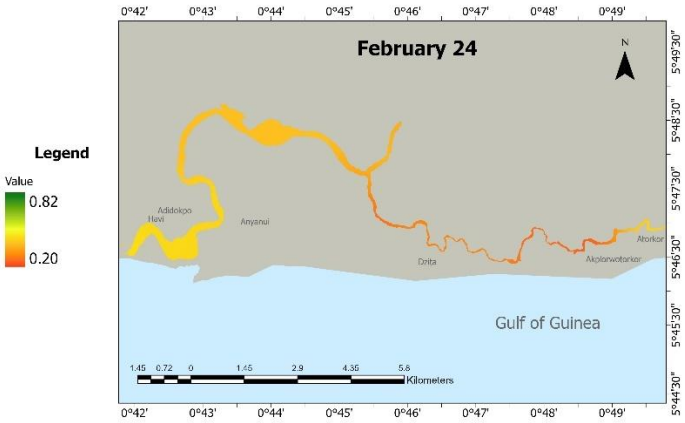


j)

University of Ghana http://ugspace.ug.edu.gh



k)



l)

Figure 9: Spatial distribution of estimated HSI index model values for post settlement. (a = March 23, b = April 23, c = May 23, d = June 23, e = July 23, f = August 23, g = September 23, h = October 23, i = November 23, j = December 23, k = January 24, l = February 24)

4.5. Temporal variability in mean habitat suitability

Monthly mean Habitat Suitability Index HSI averaged across all sampling locations ranged from 0.31 to 0.65 between April 2023 and March 2024 (Fig. 10). The series began at 0.45 in April 2023 then declined to 0.35 in May and 0.34 in June. A rise followed with 0.50 in July and a peak of 0.65 in August. The mean fell to 0.52 in September and 0.42 in October before reaching its lowest value of 0.31 in November. Slight increases were observed thereafter with 0.32 in December 0.34 in both January and February 2024 and 0.36 in March 2024. The grey envelope shows monthly standard deviation which widened during the July to September peak and narrowed during months with lower means. The red reference line at 0.50 denotes the moderate suitability threshold and was exceeded only in July, August and September. A fitted linear trend declined from about 0.46 at the start of the record to about 0.34 at the end.

University of Ghana http://ugspace.ug.edu.gh

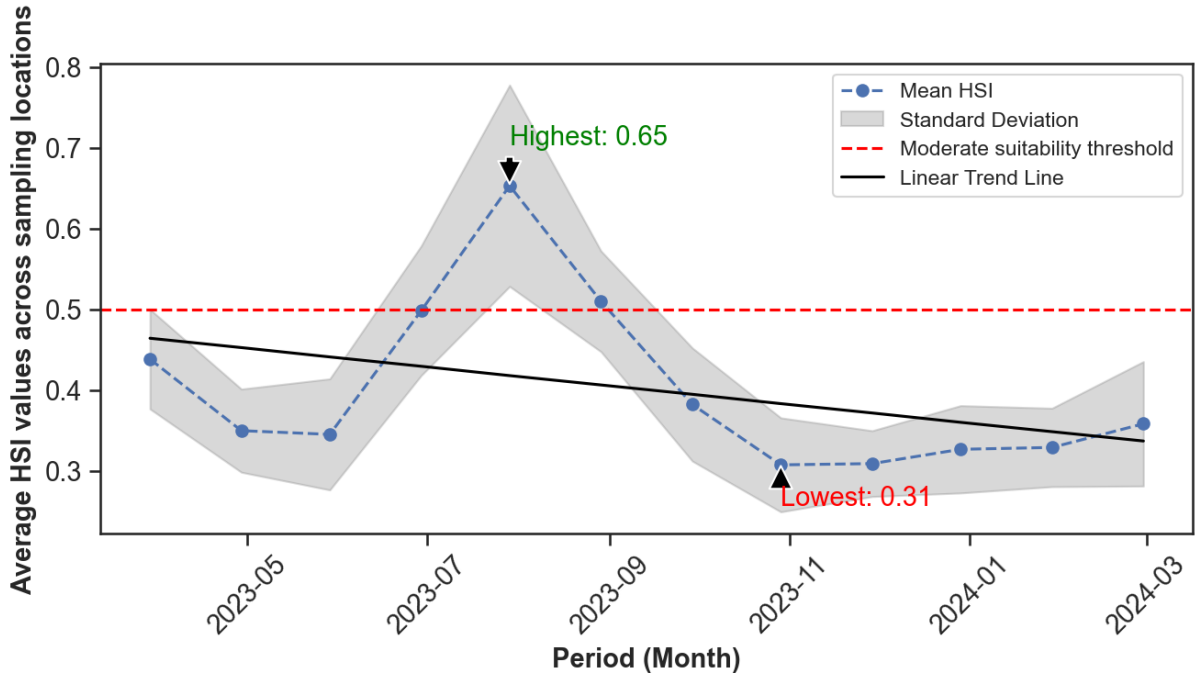


Figure 10: Monthly Average Habitat Suitability Index (HSI) from March to February, showing temporal variations in habitat suitability.

4.6. Spatial variation in percentage consistency

Percentage consistency across sampling locations varied from 0.00 % to 33.33 % (Fig. 11). Location Q, situated near 5.81° N and 0.72° E, registered 0.00 % and was the only site coloured red. The highest value, 33.33 %, occurred at location G around 5.79° N and 0.78° E, marked by the darkest green symbol. Most other sites displayed yellow-to-light-green tones that corresponded to intermediate consistencies of approximately 15 % – 30 %. Green and yellow markers were distributed along the main channel, whereas orange symbols indicating lower consistency appeared at two bends west of location Q.

University of Ghana http://ugspace.ug.edu.gh

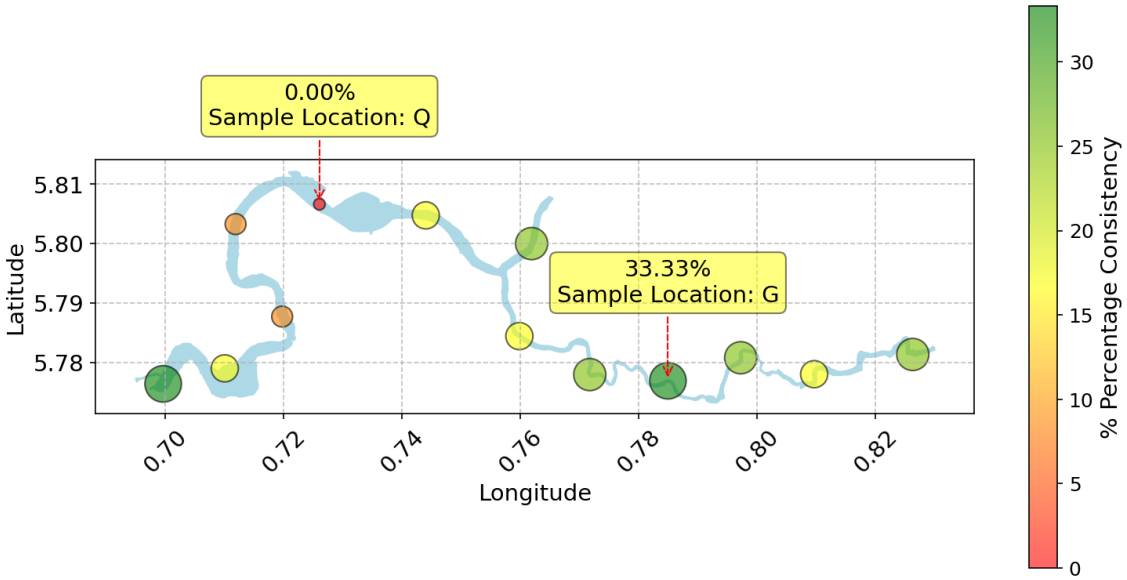


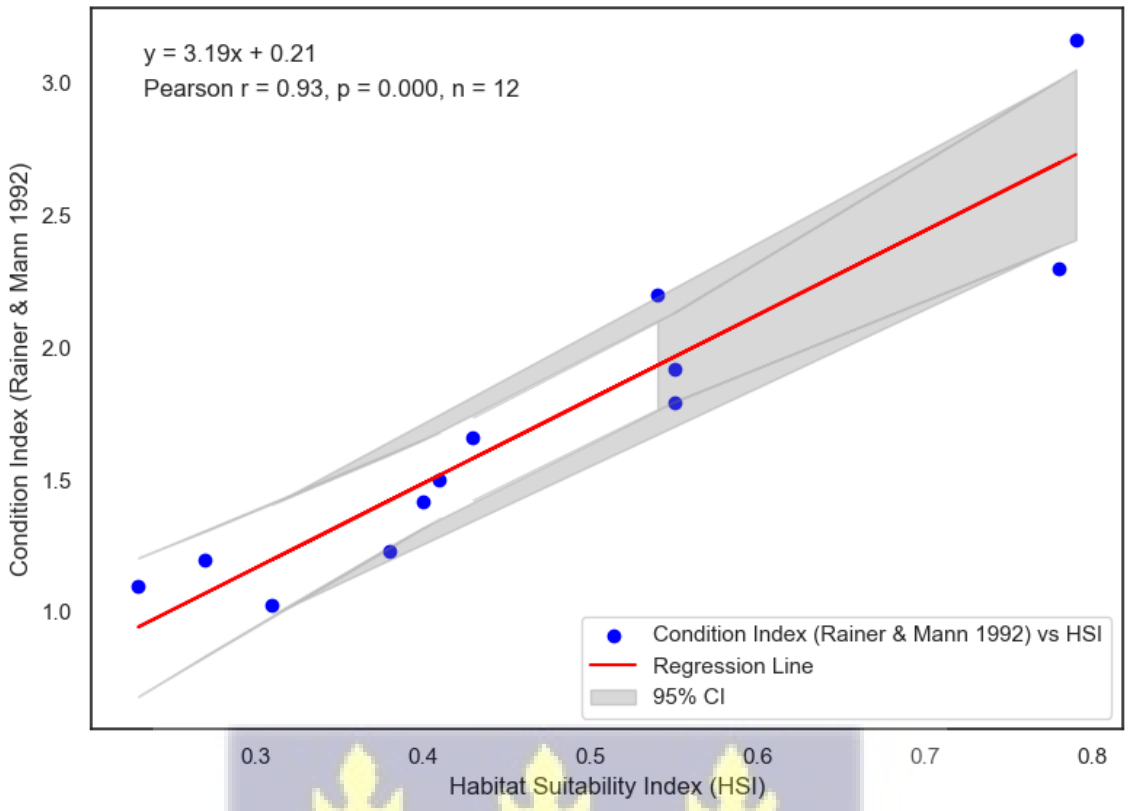
Figure 11: Percentage of Months Exceeding HSI Threshold by Station between March 2023 and February 2024. This map shows the percentage of months in which each station recorded HSI values exceeding the suitability threshold of 0.5, representing moderately suitable conditions for *C. tulipa* culture.

4.7. Biometric validation of habitat suitability index

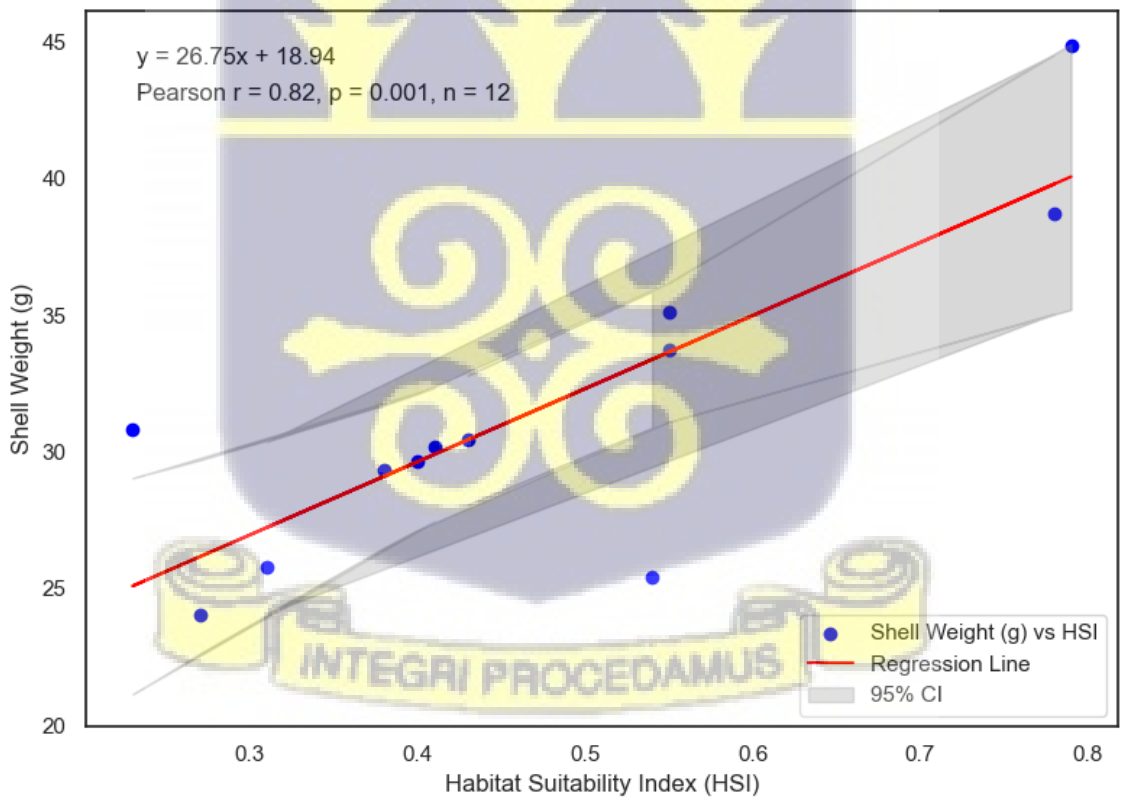
Condition Index increased with Habitat Suitability Index HSI following the equation y = 3.19x + 0.21. Pearson r was 0.93 with p = 0.000 and the sample size was 12 (Fig. 12a). Shell Weight also rose with HSI according to y = 26.75x + 18.94. Pearson r = 0.82 with p = 0.001 and n = 12 (Fig. 12b).

Shell Length showed a positive relationship described by y = 2.38x + 6.60. Pearson r reached 0.68 with p = 0.014 and n = 12 (Fig. 12c). Each panel includes the fitted regression line and the shaded 95 % confidence interval.

University of Ghana http://ugspace.ug.edu.gh

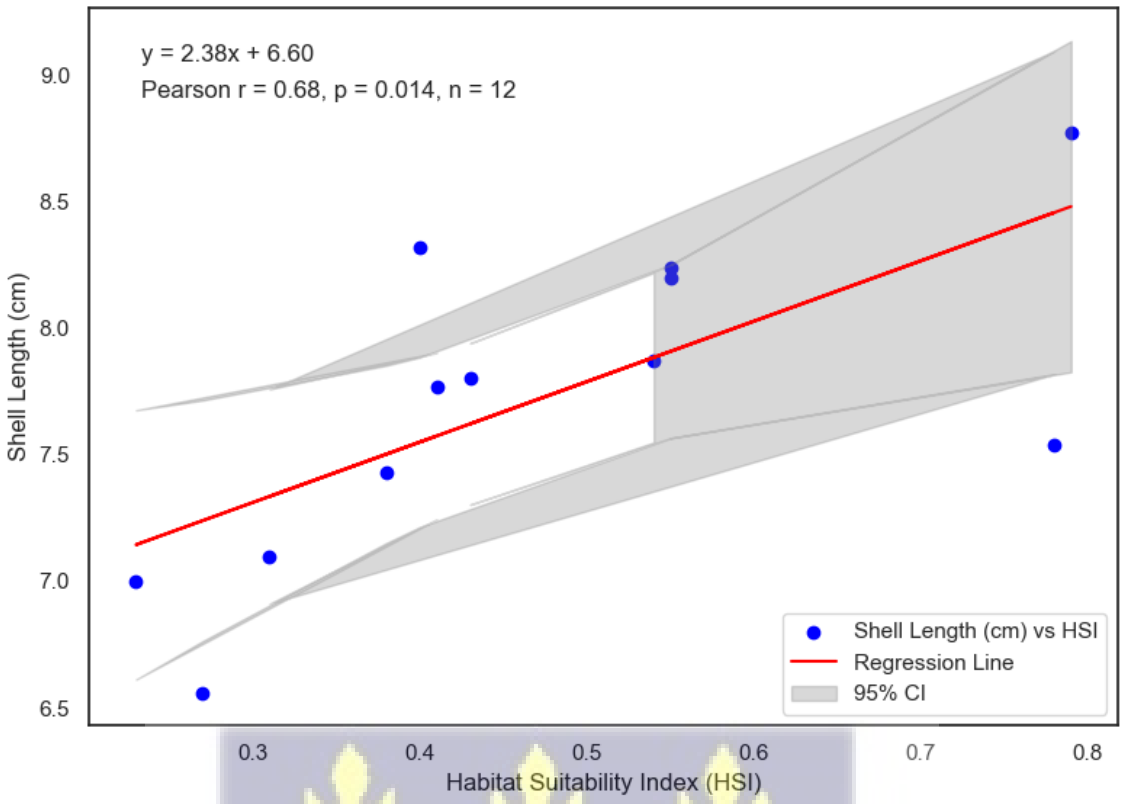


(a)



(b)

University of Ghana http://ugspace.ug.edu.gh



(c)

Figure 12: Correlation between Habitat Suitability Index (HSI) and Oyster Biometrics.

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

CHAPTER FIVE

DISCUSSION

5.1. Spatial and temporal variation in physicochemical conditions.

Sediment deposition has built a semi-permanent sand-bar across the creek mouth, restricting tidal exchange with the Gulf of Guinea. Similar bar-blocking processes are well known to prolong water residence time and modify hydrodynamics in small, wave-dominated or river-dominated estuaries (Davies-Vollum et al., 2019; Dronkers, 2025). In the present system this geomorphic change, rather than atmospheric forcing alone, governs seasonal and spatial patterns in temperature, salinity, dissolved oxygen, pH and chlorophyll-a. Surface-water temperature stayed above the published optimum band (18 – 28 °C) throughout the record, with monthly medians rising from 29.0 °C in July 2023 to 33.1 °C in May 2023 (Fig. 6a). Reduced flushing after mouth closure and reduction in water depth limits advective heat loss, a mechanism previously linked to elevated temperatures and enhanced stratification in bar-blocked estuaries (Chen et al., 2023).

Salinity responded sharply to the bimodal rainfall cycle. Site-A (upper reaches of the creek), for example, declined from 21 ppt in March 2023 to 4.2 ppt by March 2024. River discharge and direct rainfall are primary controls on salinity intrusion length in tropical estuaries and tributaries that flow into them, especially when tidal mixing is weakened by restricted exchange (P. J. Statham, 2012; Hlaing et al., 2024). Only one of 156 observations fell inside the marine optimum band (20 – 35 ppt), underlining the strength of freshwater dilution.

Dissolved-oxygen concentrations showed pronounced spatial heterogeneity. During the major rainy season DO reached 7.4 mg L^{-1} at site Q, whereas mid-channel site E fell below 3 mg L^{-1} in December 2023 (Fig. 6c). Local variation in depth, organic-matter loading and current speed can generate sparse hypoxia in estuaries with long residence times (Chen et al., 2023). pH remained within a slightly alkaline range (7.5 – 8.3) at most stations, with a brief minimum of

University of Ghana http://ugspace.ug.edu.gh

7.2 in October 2023 and a maximum of 8.3 in March 2024 (Fig. 6d). Comparable buffering has been reported for well-mixed tropical estuaries where carbonate alkalinity offsets seasonal CO_2 inputs (P. J. Statham, 2012).

Chlorophyll-a exhibited the widest variability (22 – 3486 µg L^{-1}). Concentrations increased sharply during the late rainy season, with Chl-a concentrations reaching it highest in September 2023 at lagoon-proximal stations (A-E) (Fig. 6e). Elevated loads of nitrate and phosphate from catchment agriculture have recently been documented for the adjacent Keta Lagoon Complex and are consistent with the timing and location of these blooms (Mahu, Danso, Edusei, & Atta deGraft-Johnson, 2023). Seasonal nutrient pulses, coupled with reduced flushing, are well-known drivers of phytoplankton accumulation and potential eutrophication in small tropical estuaries (Peter J. Statham, 2012; Chen et al., 2023).

5.2. Environmental controls on *C. tulipa* early life stages and adult condition

Spatial patterns in veliger success (Fig. 7) and monthly trends in the condition index (Fig. 12a) mirrored the gradients in temperature and salinity described in Section 5.1. A multiple-linear regression that included temperature and salinity explained 85 % of the variance in the condition index, indicating that these two variables were the main environmental drivers of oyster performance during the study period.

Surface-water temperature exceeded 30 °C between March and May 2023, a range well above the 24–28 °C window reported for optimal embryo development in tropical oysters, where higher values accelerate metabolism and increase mortality (Shumway, 1996). The regression slope for temperature was negative, consistent with these physiological limits, and stations that recorded the highest temperatures in early dry-season months showed the lowest veliger success.

University of Ghana http://ugspace.ug.edu.gh

Salinity remained below 15 ppt at lagoon-proximal stations for most of the year, with minima of 4 ppt during the April–June rainy season. Laboratory studies show that embryo survival falls sharply below 10 ppt and approaches zero at 5 ppt, whereas maximum survival occurs near 25–30 ppt (Ng et al., 2016). In the field a positive regression slope linked salinity to the condition index, and veliger success rose at ocean-proximal stations after June 2023 when salinity increased above 15 ppt.

Restricted tidal exchange amplified the freshwater influence. Mouth closure in bar-built estuaries is known to prolong residence time and maintain low salinity until the barrier breaches (Montagna et al., 2023). The persistence of sub-optimal salinity in the upper creek therefore reflects geomorphic control rather than seasonal rainfall alone.

pH varied only between 7.5 and 8.3 and was not a significant predictor in the regression model ($p > 0.05$). This narrow range lies within values that support normal calcification in oysters and is unlikely to have limited development during the study.

Regression models for shell weight and shell length were not significant ($p = 0.19$ and $p = 0.59$, respectively). These traits integrate growth over longer periods than the three-month windows used for water-quality sampling, so transient temperature and salinity anomalies may not be captured in the annual morphometrics.

Together these results show that departures from the established thermal and salinity optima explain the low embryonic success recorded in March–May 2023 and the improvement observed after oceanic flushing resumed in mid-year.

INTEGRI PROCEDAMUS

5.3. Habitat Suitability Assessment for *C. tulipa*

5.3.1. Seasonal and Anthropogenic effects on variability for Habitat Suitability

The variability in habitat conditions throughout the year seemed to be strongly influenced by seasonal environmental changes, especially the transition between the rainy and dry seasons.

University of Ghana http://ugspace.ug.edu.gh

One of the most notable aspects was the distinct seasonal variation in habitat suitability. The Habitat Suitability Index (HSI) values showed a clear pattern of increasing spatial habitat suitability during the rainy season (June to August), with peak values recorded in July. This suggests that rainfall probably played a critical role in improving the environmental conditions necessary for growth (post-settlement). However, the dam's opening timing aligns with the observed decrease in HSI values from October through to the following months. This suggests that the influx of freshwater may have disturbed the delicate balance of conditions in the creek, crucial for maintaining suitable habitat for the oysters. While model stated seasonal rainfall potentially led to an increase in habitat suitability during the wet months (June to August), the artificial release of freshwater in October may have introduced additional stressors.

Oysters (*C. tulipa*) thrive in estuarine environments where salinity levels are moderate, typically ranging between 20 to 35 ppt (Yankson, 1990) , but conditions 4 – 50 ppt are tolerable (Mahu, Sanko, Kamara, Chuku, Effah, Sohou, et al., 2022). A sudden or substantial influx of freshwater will lower salinity, and this can place substantial stress on oysters. When salinity drops below, oysters become more vulnerable to diseases. A study Motes et al. (1998) conducted on similar *Crassostrea* species indicated that a drop in salinity could increase *V. vulnificus* numbers in oysters, making them more susceptible to infections and potentially leading to mass mortality events. Additionally, reduced salinity levels often cause oysters to slow their feeding and filtration rates, impairing their growth and reproduction (Volety, 2008; Galimany et al., 2017). However, in certain cases, a moderate freshwater influx can temporarily flush out parasites, turbidity, and pollutants that are less tolerant to low salinity, offering a brief benefit to oyster populations (Gibson et al., 2002).

Freshwater inflow also influences nutrient availability, which has both positive and negative impacts on oysters. Freshwater sources often carry nutrients, such as nitrogen and phosphorus, into estuarine environments. These nutrients can fuel the growth of phytoplankton, which

University of Ghana http://ugspace.ug.edu.gh

serves as a food source for oysters. In this sense, a moderate increase in nutrients can initially benefit oysters by enhancing food availability. However, excessive nutrient input can possibly lead to eutrophication, which can trigger harmful algal blooms (HABs) and cause hypoxia in the water. Hypoxic conditions were recorded in most locations in the month of October (following the opening of the dam) and in select areas (towards the Keta lagoon, shallower areas that share boundaries with towns) after the rainy season (Fig. 4.1c). Hypoxic conditions severely threaten oyster survival, as low oxygen levels limit their ability to respire and can result in large-scale die-offs. Over-enrichment of nutrients can also disrupt the ecosystem's natural balance, leading to the dominance of harmful algae that negatively affects water quality and the broader marine environment.

Changes in water temperature resulting from freshwater influx can also profoundly affect oysters. Depending on the season and source, freshwater inflows may either cool or warm the surrounding water. Cooler water temperatures can reduce oysters' metabolic rates (McAfee et al., 2017), slowing their growth and reproductive cycles, while warmer water can increase metabolic rates, promoting faster growth. The initial temperatures in the system were already higher than suitable and tolerable ranges for *C. tulipa* culture, so in this case, the reduction in temperature did more good than harm, which could be a possible reason we recorded higher HSI values in the rainy season. Warmer temperatures like the ones we recorded outside the rainy season can also increase oysters' susceptibility to disease and environmental stressors. Moreover, significant temperature fluctuations combined with changes in salinity can place oysters under physiological stress, potentially pushing them beyond their tolerance thresholds and leading to reduced fitness or higher mortality rates.

5.3.2. Impact of Dam opening on Habitat Suitability

The release of freshwater from the dam in October appears to have had a noticeable impact on habitat suitability for the oysters. The timing of the dam's opening coincided with a drop in

University of Ghana http://ugspace.ug.edu.gh

Habitat Suitability Index (HSI) values observed from October onward (Fig. 4.5), suggesting that the influx of freshwater may have disrupted the delicate environmental balance within the creek. While the typical reduction in temperature during the wet season generally improved conditions for the species, and rainfall and runoff had minimal effects on HSI values, the dam's release in October introduced new challenges that made the habitat less favourable, as indicated by the model.

One immediate effect of the dam's release was the abrupt change in salinity levels. *C. tulipa* thrives in brackish water, maintaining a balanced mix of salt and freshwater. However, the large volume of freshwater from the dam likely reduced salinity significantly, particularly in areas closer to the release point. This sudden drop in salinity could have caused stress on the oysters, as they require a specific salinity range to maintain their physiological functions. A reduction in salinity outside these optimal levels likely contributed to the observed decrease in HSI values following the dam's release.

Another possible impact of the sudden freshwater influx was sediment displacement. The rapid flow likely stirred up sediments within the creek, redistributing them and causing a decrease in water clarity. Reduced water clarity can negatively affect oysters by blocking sunlight, which is essential for phytoplankton growth, the primary food source for oysters (Campbell & Hall, 2019). Additionally, sediment settling on the creek bed may smother the hard surfaces, such as mangrove roots, which oysters need for attachment and growth. The sediment can also clog their feeding apparatus as they filter feed. During the study, turbidity levels initially measured at 30.2 NTU but decreased to 9.56 NTU following the opening of the dam and significant rainfall events. The opening of the dam has likely increased freshwater flow, flushing suspended sediments downstream and reducing turbidity within the estuary. While lower turbidity generally reduces the risk of sediment clogging, the initial high turbidity levels may have already affected the oysters' feeding efficiency. Moreover, sudden changes in turbidity

University of Ghana http://ugspace.ug.edu.gh

can still pose a challenge, as oysters may need time to adjust their filtration mechanisms in response to fluctuating sediment concentrations (Zu Ermgassen et al., 2013).

The release from the dam may also have disturbed nutrient concentrations within the creek. While natural rainfall typically brings nutrients that promote phytoplankton growth, the water released from the dam may have either diluted these nutrients or introduced an excess. If the water lacked essential nutrients, it could have limited phytoplankton growth, reducing food availability for the oysters (Hecky & Kilham, 1988). On the contrary, if the water contained excess nutrients, it could have led to eutrophication, resulting in oxygen depletion (hypoxia) as decaying algae consume oxygen, further reducing habitat suitability. This series of environmental changes highlights the complex potential impact of the dam's opening on habitat conditions for *C. tulipa*, pointing out the need for careful management of dam spillages to protect sensitive ecosystems.

5.3.3. Spatial variability in Habitat Suitability

The observed spatial variability in habitat suitability highlights the influence of localized environmental conditions on the distribution and growth potential of *C. tulipa* within the creek. Notably, areas near coordinates 05.80°N, 000.76°E and 05.78°N, 000.70°E consistently demonstrated higher Habitat Suitability Index (HSI) values, suggesting these zones benefit from favourable hydrodynamic conditions, such as stable water flow and moderate currents. These factors likely support essential processes for oyster growth, including enhanced oxygen availability, efficient nutrient transport, and balanced sediment dynamics, which are crucial for maintaining optimal habitat conditions.

These areas also seem to support a nutrient-rich environment with elevated phytoplankton concentrations, providing a steady food source that further boosts their suitability for oysters. In contrast, lagoon-proximal stations (05.78°N, 000.81°E) and midstream stations (05.78°N,

University of Ghana http://ugspace.ug.edu.gh

000.76°E) showed consistently lower HSI values, particularly at the study's outset and during dry seasons. These regions may face heightened environmental stressors such as limited water quality and potential sedimentation issues, which can impede oyster survival and growth.

This spatial heterogeneity indicates the presence of microhabitats within the creek, shaped by unique combinations of water temperature, salinity, pH, and food availability, creating distinct zones of varying suitability. For example, locations with stable temperature and salinity gradients, coupled with substrates conducive to oyster settlement, may foster optimal growth conditions.

For management and conservation efforts, understanding this spatial variability is vital. Areas with high suitability should be prioritized for conservation, minimizing human disturbances and preventing overharvesting to preserve these prime habitats. Meanwhile, interventions in lower-suitability zones could focus on improving water quality, reducing sedimentation, and managing pollution sources to alleviate stress and enhance habitat conditions for the oysters.

5.4. Choosing the best window and reach for restoration

5.4.1. Peak months and sites

Habitat suitability reached its highest index (HSI = 0.65) in July 2023 (Fig. 9). Spatial mapping for July (Fig. 8) showed optimal suitability (≥ 0.60) concentrated between stations P and T, located approximately 4–6 km upstream from the creek mouth.

July aligns with the peak of the major rainy season, when surface temperatures drop to approximately 29 °C and salinity in the mid-reach rises toward 18–20 ppt (Fig. 6a–b). These environmental conditions approach the optimal temperature (25–30 °C) and salinity (20–35 ppt) ranges identified for larval settlement and adult oyster performance in *C. tulipa* and other tropical oysters (Funo et al., 2015; Osei et al., 2021). Additionally, local oyster farming practices along the Densu Delta prefer rainy-season months for seed collection and grow-out

University of Ghana http://ugspace.ug.edu.gh

activities because oyster survival and growth rates typically increase during this period (Osei et al., 2021). Based on this convergence of evidence, July and similarly June and August when HSI remains above 0.50, is identified as the optimal window for large-scale oyster transplantation or reef-seeding restoration efforts.

Habitat suitability dropped sharply to an HSI of 0.32 in October following the Akosombo–Kpong dam spillage initiated on 15 September 2023. The spill lowered salinity below 10 ppt throughout the creek (Fig. 6b), a threshold previously reported to cause near-total larval mortality in controlled laboratory experiments (Funo et al., 2015). Consequently, restoration activities should be avoided from mid-September through at least early November in years or when controlled dam spillage is anticipated.

Between November and February, the HSI increased gradually, reaching between 0.36 and 0.45, corresponding to a partial recovery in salinity and oxygen levels. This period provides a secondary, though less reliable, restoration opportunity. Therefore, careful monitoring of dam-release schedules and rainfall forecasts is essential before planning restoration activities during these months.

5.4.2. Locations with consistent restoration potential

Stations G and Y consistently maintained high habitat suitability, with HSI values between 0.55 and 0.60 throughout the study period, even as adjacent stations fell below 0.40 during low-salinity events (Fig. 8). This stability reflects two critical local attributes identified in reef-design literature: (1) moderate current velocities that prevent sediment burial without scouring settled spat, and (2) sustained salinity around or above 15 ppt, even during freshwater pulses (Wellman et al., 2022). Similar “hydrodynamic refuges” have proven essential for sustained oyster populations in Texas and North Carolina, where reefs located on gently sloping mid-

University of Ghana http://ugspace.ug.edu.gh

channel bars outperformed shoreline reefs over five-year monitoring periods (Texas General Land, 2022).

However, since estuarine morphology and nutrient loading can shift on annual to decadal scales, optimal restoration locations may also shift over time. Climate vulnerability studies on *C. tulipa* in West Africa predict inland migration of suitable salinity and temperature envelopes under scenarios of increased rainfall intensity and sea-level rise (Mahu, Sanko, Kamara, Chuku, Effah, & Sohou, 2022). Therefore, routine reassessment of HSI, coupled with adaptive management strategies, a now standard practice in U.S. Gulf restoration projects (Deepwater Horizon Natural Resource Damage Assessment, 2019), is recommended. This approach will help confirm the continued priority of Stations G and Y, while also identifying emerging restoration opportunities elsewhere.

5.4.3. Additional applications of the habitat-suitability model

The habitat suitability model provides practical applications beyond initial site selection, including spat collection, harvest management, early-warning alerts, and scenario planning:

Spat-collector placement

Field trials using ceramic tiles and PVC slats collected up to three times more *C. tulipa* spat at locations with modelled HSI values greater than 0.50, compared with lower-HSI control sites (Chuku et al., 2020). Monthly HSI maps can thus guide optimal timing and spatial arrangement for spat collection efforts.

Harvest zoning

Overlaying HSI maps onto oyster-fishing grounds allows management agencies to designate sanctuary reefs in high-HSI core areas, while permitting sustainable harvesting along adjacent moderate-HSI fringes. This zoning approach has effectively enhanced larval supply to harvested reefs in Galveston Bay (Restore America's, 2024).

University of Ghana http://ugspace.ug.edu.gh

Water-quality alerts

Integrating the model with real-time salinity and temperature monitoring could trigger timely alerts whenever HSI falls below critical thresholds, enabling managers to temporarily close grow-out areas to minimize disease outbreaks. Adaptive management frameworks currently employed by coastal fisheries already utilize similar indices to trigger management actions (Pine et al., 2022).

Scenario testing

Hydrodynamic and water-quality models can supply forecasted salinity and temperature data to the HSI algorithm, enabling the evaluation of restoration outcomes under various dam-release or rainfall scenarios. Similar approaches have been applied effectively to assess coastal ecosystem health in temperate estuaries (Ahn & Ronan, 2020).

Collectively, these applications position the habitat-suitability model as a robust decision-support tool for oyster reef restoration, providing essential guidance for short-term actions and long-term planning.

5.5. Model validation and methodological considerations.

5.5.1. Biometric validation of the habitat-suitability model

Pearson correlation tests indicated strong, significant positive relationships between the Habitat Suitability Index (HSI) and three independent biometric measures of *C. tulipa* performance (Fig. 12). Condition index, shell weight, and shell length exhibited correlations of 0.93, 0.82, and 0.68 respectively, demonstrating that habitats rated highly suitable by the model also supported robust oyster growth and physiological condition.

Condition index (CI), which combines soft tissue mass and shell volume, is widely used as a reliable proxy for oyster health and reproductive capacity (Rainer & Mann, 1992). The very

University of Ghana http://ugspace.ug.edu.gh

high correlation ($r = 0.93$, $p < 0.001$) with an R^2 of 0.49 indicates the model effectively captures approximately half of the physiological variability observed in oyster populations (regression: $y = 3.19x + 0.21$).

Shell weight, indicative of cumulative calcification and thus long-term energy allocation to growth (Ricart et al., 2021), showed a strong correlation with HSI ($r = 0.82$, $p = 0.001$, $R^2 = 0.72$). This relationship suggests the model successfully incorporates key environmental drivers controlling sustained mineral deposition in *C. tulipa* shells (regression: $y = 26.75x + 18.94$).

Shell length correlated moderately with HSI ($r = 0.68$, $p = 0.014$, $R^2 = 0.51$). Although the relationship was weaker than those for CI and shell weight, it remained significant. Length is influenced by growth conditions integrated over multiple seasons and can be affected by density, fouling, and micro-habitat factors (Atindana, 2021), which are not explicitly captured by the current HSI model. Despite this limitation, the model still explains roughly half of the variance in linear shell growth (regression: $y = 2.38x + 6.60$).

Overall, these biometric validations confirm that the HSI effectively integrates critical physical and chemical conditions influencing the growth, condition, and overall performance of *C. tulipa.*

5.5.2. Reliability of HSI as a predictor of C. tulipa performance

The strong positive correlations observed between HSI, and condition index ($r = 0.93$), shell weight ($r = 0.82$), and shell length ($r = 0.68$) (Fig. 12) collectively demonstrate that the habitat-suitability model reliably captures multiple environmental factors that influence oyster performance. These biometric measures represent short-term physiological health, long-term calcification, and sustained linear growth, respectively, indicating that the HSI does not merely reflect a single environmental attribute but integrates a combination of factors critical for oyster

University of Ghana http://ugspace.ug.edu.gh

health. Comparable validation studies for Crassostrea virginica similarly report strong associations between habitat suitability indices and oyster density or biomass, reinforcing that robustly constructed HSIs are effective predictors of multiple aspects of oyster performance (Theuerkauf & Lipcius, 2016a).

Agreement across multiple biometric metrics is essential: models that track only a single parameter risk misleading management decision if that parameter responds transiently, such as during temporary algal blooms. The present model satisfies this robustness criterion, making its HSI scores dependable predictors of locations where C. tulipa populations will consistently survive, grow, and reproduce. The demonstrated reliability aligns with recent international trends toward embedding validated HSI outputs into restoration planning and adaptive management frameworks (Geselbracht et al., 2024).

5.5.3. Broader applications and management utility of the HSI model

Targeted restoration

Spatial HSI mapping identifies specific areas (e.g., Stations G and Y, §5.4) where habitat suitability consistently exceeds the critical threshold (HSI > 0.50), even under environmental stress conditions. Previous studies indicate that oyster reefs located in high-HSI areas yield significantly higher oyster densities, up to threefold greater than those sited in marginally suitable areas, highlighting the efficiency of HSI-informed site selection (Theuerkauf & Lipcius, 2016b).

Harvest zoning

HSI maps can be overlaid onto traditional fishing areas to delineate high-HSI sanctuary reefs from adjacent moderate-HSI harvest zones. This zoning strategy stabilized oyster landings in Galveston Bay after five years of implementation, demonstrating the practical benefit of using HSIs to balance resource conservation with sustainable extraction (Soniat & Brody, 1988).

University of Ghana http://ugspace.ug.edu.gh

Early-warning systems

Integrating real-time salinity and temperature sensors with the HSI algorithm would enable automatic alerts when suitability scores decline below critical thresholds. Oyster farmers could then proactively relocate cages or adjust husbandry practices. Such index-triggered alert systems have already proven effective in U.S. Gulf aquaculture management (Florida & Wildlife Conservation, 2017).

Scenario testing

Forecasted environmental data from hydrodynamic and water-quality models can be input into the HSI algorithm to assess the potential impacts of future dam-release operations or climate-induced changes in rainfall patterns. Adaptive HSI modelling frameworks developed for eastern-oyster estuaries provide a template for these scenario-driven "what-if" analyses (Barnes et al., 2007).

These broader applications underscore that the validated HSI model is not merely theoretical but serves as a practical decision-support tool capable of guiding restoration, regulating harvest practices, providing early warnings for environmental stress, and informing long-term management planning.

5.5.4. Limitations, assumptions, and future refinements

The current Habitat Suitability Index (HSI) was calibrated using monthly data collected from 13 stations between March 2023 and February 2024. Consequently, the percentage-consistency maps (Fig. 10) and the reach-averaged HSI time series (Fig. 9) reflect conditions from a single hydrological year. Therefore, caution is necessary when applying these findings beyond this timeframe.

Geographic transferability

University of Ghana http://ugspace.ug.edu.gh

The environmental conditions specific to Anyanui Creek, including tidal range, sediment characteristics, and species interactions, may differ significantly from those in other estuaries. Previous studies indicate that HSIs developed for one estuary often lose predictive accuracy if applied elsewhere without recalibrating the salinity and temperature thresholds (Linhoss & Mickle, 2022). Thus, we assume researchers will recalibrate the current model using at least one year of local data before deploying it in other regions.

Temporal dynamics

Seasonal freshwater pulses alter salinity and dissolved oxygen at timescales shorter than the monthly intervals used in this study. While monthly averages likely capture key conditions influencing oyster larval settlement and adult growth, brief, intense events (e.g., two-day low-salinity episodes) are not detected by monthly sampling. Installing continuous monitoring sensors and updating HSI assessments at weekly or bi-weekly intervals would address this limitation and improve model accuracy.

Omitted variables

The current model includes temperature, salinity, dissolved oxygen, pH, and chlorophyll-a concentrations but excludes factors such as disease prevalence, predation, and preferred food availability. Field research has shown that possible infections (*Vibrio*) and variations in transparency can significantly influence oyster survival independently of the five modelled variables (Fujii et al., 2023). Our model assumes that disease pressure remains uniform across stations and that chlorophyll-a concentrations adequately represents food availability. These assumptions require testing through future monitoring efforts.

Anthropogenic impacts

Human activities such as coastal development, small-scale harvesting, and pollution can rapidly degrade oyster habitats. Including spatial data on shoreline modification and fishing

University of Ghana http://ugspace.ug.edu.gh

pressure enhances the accuracy of HSIs in social-ecological restoration models (Howie et al., 2024). Our current model assumes minimal direct anthropogenic impacts within the study reach, but managers should incorporate such spatial layers in regions experiencing greater human disturbance.

Key model assumptions addressing current limitations:

1. Linear and additive responses of oyster performance to each environmental variable.
2. Stationary relationships between oyster performance and environmental conditions within the one-year calibration period.
3. Uniform disease pressure and fishing intensity across all study stations.
4. Chlorophyll-a concentrations serving as an effective proxy for both particulate food availability and Depth quality for settlement.

Documenting these assumptions clarifies how the HSI simplifies real-world complexity and identifies priority areas for future research. Specifically, future refinements should incorporate high-frequency monitoring data, biotic stressors (e.g., disease and predation), and explicit anthropogenic influences. Such iterative improvements follow best practices in restoration-suitability modelling, ensuring the continued reliability and relevance of the HSI under changing environmental and management conditions (Howie et al., 2024).

INTEGRI PROCEDAMUS

University of Ghana http://ugspace.ug.edu.gh

CHAPTER SIX

CONCLUSION AND RECCOMENDATION

6.1. Conclusion

This study investigated the environmental factors influencing oyster reef restoration in Anyanui Creek, Ghana, with a focus on seasonal patterns, site-specific conditions, and environmental pressures. The findings reveal that the rainy season, particularly in July, offers the most favourable conditions for oyster restoration efforts. During this period, optimal temperature and dissolved oxygen levels were recorded, which are conducive to oyster growth and reproduction. Aligning restoration activities with this seasonal window is crucial, as it maximizes the success rate and enhances the resilience of restored oyster populations. In contrast, observations in October indicated less favourable environmental conditions, highlighting the importance of timing in restoration planning.

Persistent low salinity emerged as a critical stressor affecting oyster health in the creek. The study documented a significant decrease in salinity levels during the rainy season, dropping from an average of 15.39 ppt to 8.41 ppt due to increased freshwater influx from rainfall and the opening of the dam. This reduction places salinity below the optimal range for oysters, leading to reduced condition indices and higher mortality rates. Addressing this challenge requires implementing measures to stabilize salinity levels, such as coordinating dam operations or reopening the blocked lower portions of the creek to enhance restoration outcomes.

Site-specific environmental conditions varied notably among the upstream, midstream, and downstream stations. Midstream stations maintained more stable conditions, with moderate salinity and temperature levels, making them more suitable for restoration efforts. This variability necessitates customized restoration strategies tailored to the specific conditions of each site. By understanding and addressing the unique environmental challenges at each

University of Ghana http://ugspace.ug.edu.gh

location, restoration activities can be more effectively planned and implemented, increasing the likelihood of success.

This study highlighted the possible influence of nutrient influx and turbidity on oyster health. During the rainy season, increased 'Chlorophyll a' concentrations were observed, indicating phytoplankton growth and providing a rich food source for oysters. However, this also presents the risk of eutrophication, potentially leading to hypoxic conditions that are detrimental to oyster populations. Managing nutrient inputs is therefore crucial to prevent water quality degradation while maximizing the benefits for oyster growth.

Dam operations were found to significantly alter environmental conditions by affecting freshwater inflows into the estuary. The opening of the dam led to abrupt changes in already low salinity and turbidity, directly impacting oyster health and survival. These findings highlight the importance of coordinated water resource management to support oyster restoration efforts. Regular environmental monitoring proved essential for the success of restoration activities, enabling timely detection of changes and allowing for adaptive management in response to fluctuating conditions.

In conclusion, restoring oyster reefs in Ghana presents both challenges and opportunities shaped by seasonal dynamics, site-specific factors, and environmental pressures. By strategically timing restoration efforts to coincide with the rainy season, particularly in July, and by tailoring strategies to the specific conditions of each site, restoration practitioners can enhance the success rates of oyster reef restoration. Addressing critical stressors such as persistent low salinity and managing nutrient and sediment inputs are vital for improving oyster survival and achieving long-term restoration goals. Regular monitoring and adaptive management, coupled with coordinated dam operations, are essential for the sustainable restoration of oyster reefs in Anyanui Creek. The insights gained from this study contribute

University of Ghana http://ugspace.ug.edu.gh

valuable knowledge to oyster restoration initiatives in Ghana and offer guidance for similar efforts in estuarine environments worldwide.

6.2. Recommendations for Anyanui Creek and similar Ghanaian estuaries

The recommendations outlined below directly reflect the seasonal and spatial patterns documented in this study (Figs 6–10). They are presented sequentially to guide restoration managers through a logical annual planning cycle, running from July through June.

Initially, restoration activities should be timed to align with the seasonal peak in habitat suitability. Early July is identified as optimal, coinciding with the highest observed Habitat Suitability Index (HSI ≈ 0.65) and favourable water temperatures (approximately 29°C). The Ministry of Fisheries and Aquaculture Development (MoFAD), in collaboration with the University of Ghana's Department of Marine and Fisheries Sciences (DMFS), should issue clear annual guidelines stating that large-scale oyster transplantation and reef-seeding must commence within the first two weeks of July. These guidelines should be reviewed each May using rainfall forecasts from the Ghana Meteorological Agency. Preferred restoration sites during this window lie within the mid-reach sector, particularly between stations G and M, where HSI consistently exceeds or stays at 0.50.

Secondly, mitigating salinity stress caused by freshwater pulses from dam releases is critical. The Volta River Authority (VRA) and the Water Resources Commission (WRC) should coordinate dam spills to avoid peak oyster settlement months (July–August). If a September spill cannot be avoided, stakeholders should be notified at least two weeks in advance. This advance notice will enable oyster growers to relocate or elevate culture units, protecting their stock from harmful low-salinity conditions (<10.00 ppt). Priority attention should be directed toward mid- and lower-reach stations most impacted by these salinity reductions.

University of Ghana http://ugspace.ug.edu.gh

An important hydrological consideration specific to Anyanui Creek is that its lower reaches, historically open to tidal flushing and salinity intrusion from the adjacent ocean via the Volta Estuary, have become increasingly blocked by sediment deposition and island formation. Reopening these obstructed lower reaches, subject to thorough hydrodynamic assessment, could significantly enhance oyster habitat quality by restoring tidal exchange and stabilizing salinity regimes within the creek. Such restoration would likely improve flushing of organic matter, reduce stagnation-induced eutrophication, and moderate abrupt salinity fluctuations associated with freshwater pulses. MoFAD and DMFS, supported by the Environmental Protection Agency (EPA-Ghana) and local municipalities, should commission a feasibility study within the next year to evaluate the ecological benefits and practical constraints associated with reopening the creek mouth to enhance estuarine connectivity.

In parallel, reef designs should be tailored to site-specific environmental conditions. Restoration contractors, supervised by MoFAD, should construct bagged or caged-shell reefs at mid-reach stations where currents are stable, and employ vertical racks in lagoon-proximal stations characterized by softer sediments. Site-specific reef designs should be finalized and approved during annual site visits in June, guided by the micro-habitat maps.

Continuous monitoring of key water-quality parameters is essential for adaptive management. The Ghana Hydrological Authority, with technical support from DMFS, should install multiparameter sensors measuring salinity, temperature, and dissolved oxygen at representative index stations. Data should be streamed in real-time, if possible, to a public online dashboard and trigger automated SMS alerts whenever salinity falls below 12.00 ppt or dissolved oxygen dips below 3.00 mg L^{-1}. Regular monthly maintenance of these instruments is crucial to ensure data quality and reliability.

University of Ghana http://ugspace.ug.edu.gh

To prevent rainy-season possible eutrophication, municipal assemblies, in collaboration with EPA-Ghana, should enforce vegetated buffer strips of at least 20m along agricultural tributaries and pilot constructed wetland projects at major storm-drain outfalls in adjacent towns. Buffer compliance should be monitored each planting season, while the effectiveness of constructed wetlands should be evaluated possibly every six months.

Active engagement of local communities is critical to the success of restoration efforts. Non-governmental organizations such as "Hen Mpoano" and ORF Ghana, in cooperation with traditional authorities, should look into training at least 50 locals in effective spat collection, reef maintenance, and water-quality monitoring practices. Additionally, community-led management schemes should be established to provide alternatives as against mangrove harvesting and related habitat degradation. Training sessions should be scheduled each June, with the community watch active year-round, focusing initially on the settlements of Anyanui, Akplorwotorkor, and Atiteti.

Finally, embedding oyster aquaculture into national policy frameworks is recommended. MoFAD's Policy Directorate should develop an "Oyster Aquaculture and Restoration Framework," establishing HSI values of 0.50 or higher as the biological benchmark for licensing oyster grow-out sites nationwide. This framework should integrate oyster aquaculture into possibly Ghana's broader Blue Economy Strategy. Development of the policy should occur within the next fe months, with subsequent review and updates conducted every five years. The framework would be applicable across all Ghanaian coastal lagoons and estuaries.

Collectively, these recommendations translate the scientific insights from this study into actionable management strategies. By explicitly addressing hydrological connectivity, salinity management, site-specific restoration practices, monitoring, community involvement, and national policy integration, these strategies provide a comprehensive roadmap for sustainable

University of Ghana http://ugspace.ug.edu.gh

oyster restoration and aquaculture in Anyanui Creek and similar coastal ecosystems across Ghana.

University of Ghana http://ugspace.ug.edu.gh

REFERENCES

1. Adda, A. J. (2016). *The influence of land tenure and ownership regimes on sustainable conservation of mangroves in the Songhor and Keta lagoon complex ramsar sites in Ghana*
2. Adeyemo, O. K. (2003). Consequences of pollution and degradation of Nigerian aquatic environment on fisheries resources. *Environmentalist*, *23*, 297-306.
3. Ahn, J. E., & Ronan, A. D. (2020). Development of a model to assess coastal ecosystem health using oysters as the indicator species. *Estuarine, Coastal and Shelf Science*, *233*, 106528. https://doi.org/10.1016/j.ecss.2019.106528
4. Ajao, E. (1994). Coastal aquatic ecosystems, conservation and management strategies in Nigeria. *Southern African Journal of Aquatic Science*, *20*(1-2), 3-22.
5. Almeida, M. J., Machado, J., & Coimbra, J. (1999). Growth and biochemical composition of Crassostrea gigas (Thunberg) and Ostrea edulis (Linne) in two estuaries from the North of Portugal. *Journal of Shellfish Research*, *18*(1), 139-146.
6. Aminot, A., & Rey, F. (2000). Standard procedure for the determination of chlorophyll a by spectroscopic methods. *International Council for the Exploration of the Sea*, *112*(25), 1-2.
7. Asare, B., Obodai, E. A., & Acheampong, E. (2019). Mangrove oyster farming: Prospects as supplementary livelihood for a Ghanaian fishing community. *Journal of Fisheries and Coastal Management*, *1*(1), 7-14.
8. Atindana, S. A. (2021). *Modelling The Relationship Between The West African Mangrove Oyster (Crassostrea Tulipa, L. 1819) And The Aquatic And Climatic Environment For Use As A Bio-Indicator In The Densu Estuary* University of Ghana].

University of Ghana http://ugspace.ug.edu.gh

9. Atindana, S. A., Fagbola, O., Ajani, E., Alhassan, E. H., & Ampofo-Yeboah, A. (2020). Coping with climate variability and non-climate stressors in the West African Oyster (Crassostrea tulipa) fishery in coastal Ghana. *Maritime Studies*, *19*, 81-92.
10. Bae, P., Pyen, C., Ko, C., Kim, Y., & Kang, P. (1978). Studies on suspended culture of oyster, Crassostrea gigas, in the Korean coastal (III) on the growth rate of oyster depending on the environmental factors in each growing area. *Bulletin of Fisheries Research Development Agency*, *20*, 109-111.
11. Baggett, L. P., Powers, S. P., Brumbaugh, R. D., Coen, L. D., DeAngelis, B. M., Greene, J. K., Hancock, B. T., Morlock, S. M., Allen, B. L., & Breitburg, D. L. (2015). Guidelines for evaluating performance of oyster habitat restoration. *Restoration Ecology*, *23*(6), 737-745.
12. Barber, B. J. (1996). Gametogenesis of eastern oysters, Crassostrea virginica(Gmelin, 1791), and Pacific oysters, Crassostrea gigas(Thunberg, 1793) in disease-endemic lower Chesapeake Bay. *Journal of Shellfish Research*, *15*(2), 285-290.
13. Barnes, T., Volety, A., Chartier, K., Mazzotti, F., & Pearlstine, L. (2007). A habitat suitability index model for the eastern oyster (Crassostrea virginica), a tool for restoration of the Caloosahatchee Estuary, Florida. *Journal of Shellfish Research*, *26*(4), 949-959.
14. Bascetin, A. (2007). A decision support system using analytical hierarchy process (AHP) for the optimal environmental reclamation of an open-pit mine. *Environmental Geology*, *52*, 663-672.
15. Beck, M. W., Brumbaugh, R. D., Airoldi, L., Carranza, A., Coen, L. D., Crawford, C., Defeo, O., Edgar, G. J., Hancock, B., & Kay, M. C. (2011). Oyster reefs at risk and recommendations for conservation, restoration, and management. *Bioscience*, *61*(2), 107-116.

University of Ghana http://ugspace.ug.edu.gh

16. Beck, M. W., Brumbaugh, R. D., Airoldi, L., Carranza, A., Coen, L. D., Crawford, C., & Zhang, G. (2011). Oyster reefs at risk and recommendations for conservation, restoration, and management. *BioScience*, *61*(2), 107-116. https://doi.org/10.1525/bio.2011.61.2.5

17. Beseres Pollack, J., Cleveland, A., Palmer, T. A., Reisinger, A. S., & Montagna, P. A. (2012). A restoration suitability index model for the eastern oyster (Crassostrea virginica) in the Mission-Aransas Estuary, TX, USA. *PloS one*, *7*(7), e40839.

18. Bishop, M. J., Lanham, B. S., Esquivel-Muelbert, J. R., Cole, V. J., Faelnar, K. M., Jenkins, C., Keating, J., Martínez-Baena, F., & O'Connor, W. A. (2023). Oyster reef restoration-aquaculture interactions: maximizing positive synergies. *Frontiers in Marine Science*, *10*, 1-12.

19. Blomberg, L. (2022). Biodiversity conservation and international funding–perceptions of current challenges and development needs by stakeholders operating in Madagascar. *Forest Ecology and Management*.

20. Boiral, O., & Heras-Saizarbitoria, I. (2017). Managing biodiversity through stakeholder involvement: Why, who, and for what initiatives? *Journal of Business Ethics*, *140*(3), 403-421.

21. Bokpe, S. J. (2021). Fuveme: Before and after the destructive tidal waves. *The Fourth Estate*. https://thefourthestategh.com/2021/11/fuveme-before-and-after-the-destructive-tidal-waves/

22. Borges, M. E., E. Dos-Santos, N.J. Cazzaniga. (2002). *Density and growth of pacific oyster Crassostrea gigas in an intertidal oyster reef in the Southern Atlantic Coast of Buenos Aires Province, Argentina.*

23. Calabrese, A., Costa, R., Levialdi, N., & Menichini, T. (2019). Integrating sustainability into strategic decision-making: A fuzzy AHP method for the selection

University of Ghana http://ugspace.ug.edu.gh

of relevant sustainability issues. *Technological Forecasting and Social Change*, *139*, 155-168.

24. Campbell, M. D., & Hall, S. G. (2019). Hydrodynamic effects on oyster aquaculture systems: a review. *Reviews in Aquaculture*, *11*(3), 896-906.
25. Casella, E., Collin, A., Harris, D., Ferse, S., Bejarano, S., Parravicini, V., Hench, J. L., & Rovere, A. (2017). Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. *Coral Reefs*, *36*, 269-275.
26. Chen, J., Glibert, P. M., Cai, W.-J., & Huang, D. (2023). Editorial: Eutrophication, algal bloom, hypoxia and ocean acidification in large river estuaries, volume II. *Frontiers in Marine Science*, *10*, 1225903. https://doi.org/10.3389/fmars.2023.1225903
27. Cho, Y., Lee, W.-C., Hong, S., Kim, H.-C., & Kim, J. B. (2012). GIS-based suitable site selection using habitat suitability index for oyster farms in Geoje-Hansan Bay, Korea. *Ocean & Coastal Management*, *56*, 10-16.
28. Chowdhury, M. S. N., La Peyre, M., Coen, L. D., Morris, R. L., Luckenbach, M. W., Ysebaert, T., Walles, B., & Smaal, A. C. (2021). Ecological engineering with oysters enhances coastal resilience efforts. *Ecological engineering*, *169*, 106320.
29. Chowdhury, M. S. N., Walles, B., Sharifuzzaman, S., Shahadat Hossain, M., Ysebaert, T., & Smaal, A. C. (2019). Oyster breakwater reefs promote adjacent mudflat stability and salt marsh growth in a monsoon dominated subtropical coast. *Scientific reports*, *9*(1), 8549.
30. Chowdhury, M. S. N., Wijsman, J. W., Hossain, M. S., Ysebaert, T., & Smaal, A. C. (2019). A verified habitat suitability model for the intertidal rock oyster, Saccostrea cucullata. *PloS one*, *14*(6), e0217688.

University of Ghana http://ugspace.ug.edu.gh

31. Chuku, E. O. (2019). *Promoting oyster culture in Ghana: Strategies for optimising seed collection and growth of crassostrea tulipa (lamarck, 1819) in coastal water bodies* University of Cape Coast].

32. Chuku, E. O., Yankson, K., Obodai, E. A., Acheampong, E., & Aheto, D. W. (2023). Spatiotemporal spatfall dynamics and prevailing estuarine conditions for optimal oyster (Crassostrea tulipa) spat availability in selected Gulf of Guinea brackish systems. *Frontiers in Marine Science*, *10*, 1075313.

33. Chuku, E. O., Yankson, K., Obodai, E. A., Acheampong, E., & Boahemaa-Kobil, E. E. (2020). Effectiveness of different substrates for collecting wild spat of the oyster Crassostrea tulipa along the coast of Ghana. *Aquaculture Reports*, *18*, 1-11. https://doi.org/10.1016/j.aqrep.2020.100493

34. Citi, N. (2023). Akosombo Dam spillage: We won't leave anyone behind – VRA assures affected residents. *Citi Newsroom*. https://citinewsroom.com/2023/10/akosombo-dam-spillage-we-wont-leave-anyone-behind-vra-assures-affected-residents/

35. Clements, J. C., Carver, C. E., Mallet, M. A., Comeau, L. A., & Mallet, A. L. (2021). CO2-induced low pH in an eastern oyster (Crassostrea virginica) hatchery positively affects reproductive development and larval survival but negatively affects larval shape and size, with no intergenerational linkages. *ICES Journal of Marine Science*, *78*(1), 349-359.

36. Coen, L. D., Brumbaugh, R. D., Bushek, D., Grizzle, R., Luckenbach, M. W., Posey, M. H., Powers, S. P., & Tolley, S. G. (2007). Ecosystem services related to oyster restoration. *Marine ecology progress series*, *341*, 303-307.

University of Ghana http://ugspace.ug.edu.gh

37. Coen, L. D., & Luckenbach, M. W. (2000). Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation? *Ecological engineering*, *15*(3-4), 323-343.

38. Coen, L. D., Luckenbach, M. W., & Breitburg, D. L. (1999). The role of oyster reefs as essential fish habitat: a review of current knowledge and some new perspectives. American fisheries society symposium,

39. Colsoul, B., Boudry, P., Pérez-Parallé, M. L., Bratoš Cetinić, A., Hugh-Jones, T., Arzul, I., Mérou, N., Wegner, K. M., Peter, C., Merk, V., & Pogoda, B. (2021). Sustainable large-scale production of European flat oyster (Ostrea edulis) seed for ecological restoration and aquaculture: a review. *Reviews in Aquaculture*, *13*(3), 1423-1468. https://doi.org/https://doi.org/10.1111/raq.12529

40. Colsoul, B., Boudry, P., Pérez-Parallé, M. L., Bratoš Cetinić, A., Hugh-Jones, T., Arzul, I., Mérou, N., Wegner, K. M., Peter, C., & Merk, V. (2021). Sustainable large-scale production of European flat oyster (Ostrea edulis) seed for ecological restoration and aquaculture: a review. *Reviews in Aquaculture*, *13*(3), 1423-1468.

41. Costa-Pierce, B. A. (2010). Sustainable ecological aquaculture systems: the need for a new social contract for aquaculture development. *Marine Technology Society Journal*, *44*(3), 88-112.

42. Council, N. R. (1995). *Understanding marine biodiversity*. National Academies Press.

43. Dame, R., & Libes, S. (1993). Oyster reefs and nutrient retention in tidal creeks. *Journal of Experimental Marine Biology and Ecology*, *171*(2), 251-258.

44. Dame, R. F., & Kenneth, M. J. (2011). *Ecology of marine bivalves: an ecosystem approach*. Taylor & Francis.

45. Davies-Vollum, K. S., Zhang, Z., & Agyekumhene, A. (2019). Impacts of lagoon opening and implications for coastal management: case study from Muni-Pomadze

University of Ghana http://ugspace.ug.edu.gh

lagoon, Ghana. *Journal of Coastal Conservation*, *23*(2), 293-301. https://doi.org/10.1007/s11852-018-0658-1

46. Deepwater Horizon Natural Resource Damage Assessment, T. (2019). *Monitoring and Adaptive Management Procedures and Guidelines Manual Version 1.0 Attachment E.10: Restore Oyster Reef Habitat: Monitoring Guidance*. https://www.gulfspillrestoration.noaa.gov/media/document/2019-08-mammanualattachmente10-restore-oyster-reef-habitatmonitoringguidance-2017pdf
47. Dolmer, P., Holm, M. W., Strand, Å., Lindegarth, S., Bodvin, T., Norling, P., & Mortensen, S. (2014). The invasive Pacific oyster, Crassostrea gigas, in Scandinavia coastal waters: A risk assessment on the impact in different habitats and climate conditions.
48. Dronkers, J. (2025). Morphology of estuaries. *Coastal Wiki*. https://www.coastalwiki.org/wiki/Morphology_of_estuaries
49. Duarte, C. M., Agusti, S., Barbier, E., Britten, G. L., Castilla, J. C., Gattuso, J.-P., Fulweiler, R. W., Hughes, T. P., Knowlton, N., & Lovelock, C. E. (2020). Rebuilding marine life. *Nature*, *580*(7801), 39-51.
50. Dunlop, T., Glamore, W., & Felder, S. (2023). Restoring estuarine ecosystems using nature-based solutions: Towards an integrated eco-engineering design guideline. *Science of The Total Environment*, *873*, 162362.
51. Dunn, D. C., Crespo, G. O., & Halpin, P. N. (2019). Incorporating the dynamic and connected nature of the open ocean into governance of marine biodiversity beyond national jurisdiction. In *Predicting Future Oceans* (pp. 425-435). Elsevier.
52. Favretto, N., Stringer, L. C., Dougill, A. J., & Kruger, L. (2022). Knowledge exchange enhances engagement in ecological restoration and rehabilitation initiatives. *Restoration Ecology*, *30*(2), e13565.

University of Ghana http://ugspace.ug.edu.gh

53. Fisheries, N. (2025). Oyster Reef Habitat. https://www.fisheries.noaa.gov/national/habitat-conservation/oyster-reef-habitat

54. Florida, F., & Wildlife Conservation, C. (2017). *Conducting habitat suitability analyses to identify optimal oyster restoration locations along Florida's Gulf coast* (Restoration Planning Activity Implementation Plan, Issue. https://www.fws.gov/doiddata/dwh-ar-documents/7002/DWH-ARZ010239.pdf

55. Freeman, L. A., Corbett, D. R., Fitzgerald, A. M., Lemley, D. A., Quigg, A., & Steppe, C. N. (2019). Impacts of urbanization and development on estuarine ecosystems and water quality. *Estuaries and Coasts*, *42*, 1821-1838.

56. Fujii, M., Hamanoue, R., Bernardo, L. P. C., Ono, T., Dazai, A., Oomoto, S., Wakita, M., & Tanaka, T. (2023). Assessing impacts of coastal warming, acidification, and deoxygenation on Pacific oyster (Crassostrea gigas) farming: a case study in the Hinase area, Okayama Prefecture, and Shizugawa Bay, Miyagi Prefecture, Japan. *Biogeosciences*, *20*(22), 4527-4549.

57. Funo, I. C. d. S. A., Antonio, Í. G., Marinho, Y. F., & Gálvez, A. O. (2015). Influence of salinity on survival and growth of Crassostrea gasar. *Boletim do Instituto de Pesca*, *41*(4), 837-847. https://institutodepesca.org/index.php/bip/article/view/1076

58. Galimany, E., Lunt, J., Freeman, C. J., Reed, S., Segura-García, I., & Paul, V. J. (2017). Feeding behavior of eastern oysters Crassostrea virginica and hard clams Mercenaria mercenaria in shallow estuaries. *Marine Ecology Progress Series*, *567*, 125-137.

59. Gallardi, D. (2014). Effects of bivalve aquaculture on the environment and their possible mitigation: a review. *Fisheries and Aquaculture Journal*, *5*(3).

60. Gann, G. D., McDonald, T., Walder, B., Aronson, J., Nelson, C. R., Jonson, J., Hallett, J. G., Eisenberg, C., Guariguata, M. R., & Liu, J. (2019). International

University of Ghana http://ugspace.ug.edu.gh

principles and standards for the practice of ecological restoration. *Restoration Ecology*, *27*(S1), S1-S46.

61. Gassett, P. (2022). *Building monitoring and response capacity for ocean and coastal acidification in the northeast United States*. The University of Maine.
62. Gentilli, J., Smith, P. J., & Krishnamurti, T. N. (2009). West African monsoon. *Encyclopaedia Britannica*. https://www.britannica.com/science/West-African-monsoon
63. Geselbracht, L., Johnston, M., DeAngelis, B., & Birch, A. (2024). Estuary-specific and adaptive habitat suitability index model for the eastern oyster Crassostrea Virginica in the Pensacola Bay System, Florida, USA. *Coastal Management*, *52*(1-2), 17-34.
64. Ghana Statistical, S. (2010). *2010 District Analytical Report: Volta Region – Keta Municipal*. https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Volta/KETA%20MUNICIPAL.pdf?utm_source=chatgpt.com
65. Gibson, R., Barnes, M., & Atkinson, R. (2002). Impact of changes in flow of freshwater on estuarine and open coastal habitats and the associated organisms. *Oceanography and marine biology: an annual review*, *40*, 233.
66. Goldstein, B. E., & Butler, W. H. (2010). Expanding the scope and impact of collaborative planning: combining multi-stakeholder collaboration and communities of practice in a learning network. *Journal of the American Planning Association*, *76*(2), 238-249.
67. Gomes, D. F. P. (2019). *GIS-based site selection and dynamic modelling of Magallana oyster in the Sado Estuary, Portugal* Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa].

University of Ghana http://ugspace.ug.edu.gh

68. Goodfellow, I., Bengio, Y., & Courville, A. (2016). *Deep Learning*. MIT Press. https://alvarestech.com/temp/deep/Deep%20Learning%20by%20Ian%20Goodfellow%2C%20Yoshua%20Bengio%2C%20Aaron%20Courville%20%28z-lib.org%29

69. Gottlieb, S. J., & Schweighofer, M. E. (1996). Oysters and the Chesapeake Bay ecosystem: a case for exotic species introduction to improve environmental quality? *Estuaries*, *19*, 639-650.

70. Grabowski, J. H., Brumbaugh, R. D., Conrad, R. F., Keeler, A. G., Opaluch, J. J., Peterson, C. H., Piehler, M. F., Powers, S. P., & Smyth, A. R. (2012). Economic valuation of ecosystem services provided by oyster reefs. *Bioscience*, *62*(10), 900-909.

71. Grabowski, J. H., Hughes, A. R., Kimbro, D. L., & Dolan, M. A. (2005). How habitat setting influences restored oyster reef communities. *Ecology*, *86*(7), 1926-1935.

72. Grabowski, J. H., & Peterson, C. H. (2007). Restoring oyster reefs to recover ecosystem services. *Ecosystem engineers: plants to protists*, *4*, 281-298.

73. Graham, P. M., Palmer, T. A., & Beseres Pollack, J. (2017). Oyster reef restoration: substrate suitability may depend on specific restoration goals. *Restoration Ecology*, *25*(3), 459-470.

74. Häder, D.-P., Banaszak, A. T., Villafañe, V. E., Narvarte, M. A., González, R. A., & Helbling, E. W. (2020). Anthropogenic pollution of aquatic ecosystems: Emerging problems with global implications. *Science of the Total environment*, *713*, 136586.

75. Hammer, M. (2016). The ecosystem management approach: implications for marine governance. In *Governing Europe's Marine Environment* (pp. 75-92). Routledge.

76. Hecky, R., & Kilham, P. (1988). Nutrient limitation of phytoplankton in freshwater and marine environments: a review of recent evidence on the effects of enrichment 1. *Limnology and oceanography*, *33*(4part2), 796-822.

University of Ghana http://ugspace.ug.edu.gh

77. Hemmerling, S. A., Barra, M., Bienn, H. C., Baustian, M. M., Jung, H., Meselhe, E., Wang, Y., & White, E. (2020). Elevating local knowledge through participatory modeling: active community engagement in restoration planning in coastal Louisiana. *Journal of Geographical Systems*, *22*, 241-266.

78. Hemraj, D. A., Bishop, M. J., Hancock, B., Minuti, J. J., Thurstan, R. H., Zu Ermgassen, P. S., & Russell, B. D. (2022). Oyster reef restoration fails to recoup global historic ecosystem losses despite substantial biodiversity gain. *Science Advances*, *8*(47), eabp8747.

79. Hlaing, N. O., Azhikodan, G., & Yokoyama, K. (2024). Effect of monsoonal rainfall and tides on salinity intrusion and mixing dynamics in a macrotidal estuary. *Marine Environmental Research*, *202*, 106791. https://doi.org/10.1016/j.marenvres.2024.106791

80. Hoerl, A. E., & Kennard, R. W. (1970). Ridge Regression: Biased Estimation for Non-Orthogonal Problems. *Technometrics*, *12*(1), 55-67. https://doi.org/10.1080/00401706.1970.10488634

81. Howie, A. H., Reeves, S. E., Gillies, C. L., & Bishop, M. J. (2024). Integration of social data into restoration suitability modelling for oyster reefs. *Ecological Indicators*, *158*, 111531.

82. Ibrahim, A.-M., David, S., Bruno, G., Mark, C., & Mohammed, A.-M. (2018). Decline in oyster populations in traditional fishing grounds; is habitat damage by static fishing gear a contributory factor in ecosystem degradation? *Journal of Sea Research*, *140*, 40-51.

83. Ishizaka, A., & Nemery, P. (2013). Analytic hierarchy process.

University of Ghana http://ugspace.ug.edu.gh

84. Islam, M. S., & Tanaka, M. (2004). Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. *Marine pollution bulletin*, *48*(7-8), 624-649.

85. Jamil, A., Ahmad, A., Zhao, Y., Zhao, Y., Yang, C., Li, Y., Tu, J., Niu, F., Kong, W., & Liu, X. (2024). Advances in Global Oyster Reef Restoration: Innovations and Sustainable Ecological Approaches. *Sustainability*, *16*(22), 9795.

86. Jiang, K., Chen, C., Jiang, G., Chi, Y., Xu, C., Kong, L., Yu, H., Liu, S., & Li, Q. (2024). Genetic improvement of oysters: Current status, challenges, and prospects. *Reviews in Aquaculture*, *16*(2), 796-817.

87. Jordan, T., Gibson, F., Stinnett, B., & Howard, D. (2019). Stakeholder engagement in event planning: A case study of one rural community's process. *Event management*, *23*(1), 61-74.

88. Kamara, A. (1982). Preliminary studies to culture mangrove oysters, Crassostrea tulipa, in Sierra Leone. *Aquaculture*, *27*(3), 285-294.

89. Kasmini, L., & Batubara, A. S. (2022). Biology and ecological functional of Genus Crassostrea (Bivalvia: Ostreidae): a review. *Depik*, *11*(1), 75-84.

90. Kellogg, M. L., Smyth, A. R., Luckenbach, M. W., Carmichael, R. H., Brown, B. L., Cornwell, J. C., Piehler, M. F., Owens, M. S., Dalrymple, D. J., & Higgins, C. B. (2014). Use of oysters to mitigate eutrophication in coastal waters. *Estuarine, Coastal and Shelf Science*, *151*, 156-168.

91. Kennedy, V. S., Newell, R. I., & Shumway, S. (1996). Natural environmental factors. *The eastern oyster Crassostrea virginica. Maryland Sea Grant: College Park*, *467*, 513.

92. Kennish, M. J. (2002). Environmental threats and environmental future of estuaries. *Environmental conservation*, *29*(1), 78-107.

University of Ghana http://ugspace.ug.edu.gh

93. Knoche, S., Ihde, T. F., Samonte, G., Townsend, H., Lipton, D. W., Lewis, K. A., & Steinback, S. R. (2020). Estimating ecological benefits and socio-economic impacts from oyster reef restoration in the Choptank River complex, Chesapeake Bay.

94. Kolding, J., van Zwieten, P., & Mosepele, K. (2015). Where there is water there is fish–Small-scale inland fisheries in Africa: dynamics and importance. *Hist Water*, *3*.

95. Kondra, M. (2019). The status of the wetlands in the Greater Accra Region.

96. Konisky, R., Grizzle, R. E., Ward, K. M., & McKeton, K. (2012). Restoring oyster reefs in Great Bay Estuary, NH 2012 Annual Program Report.

97. Kreeger, D. A., Gatenby, C. M., & Bergstrom, P. W. (2018). Restoration potential of several native species of bivalve molluscs for water quality improvement in mid-Atlantic watersheds. *Journal of Shellfish Research*, *37*(5), 1121-1157.

98. La Peyre, M., Furlong, J., Brown, L. A., Piazza, B. P., & Brown, K. (2014). Oyster reef restoration in the northern Gulf of Mexico: extent, methods and outcomes. *Ocean & Coastal Management*, *89*, 20-28.

99. La Peyre, M. K., Eberline, B. S., Soniat, T. M., & La Peyre, J. F. (2013). Differences in extreme low salinity timing and duration differentially affect eastern oyster (Crassostrea virginica) size class growth and mortality in Breton Sound, LA. *Estuarine, Coastal and Shelf Science*, *135*, 146-157.

100. Laing, I., Walker, P., & Areal, F. (2006). Return of the native–is European oyster (Ostrea edulis) stock restoration in the UK feasible? *Aquatic Living Resources*, *19*(3), 283-287.

101. Ledezma, K. D. (2024). Effects of Dissolved Oxygen and pH on Eastern Oyster (Crassostrea virginica) Growth.

University of Ghana http://ugspace.ug.edu.gh

102. Li, X.-N., Song, H.-L., Li, W., Lu, X.-W., & Nishimura, O. (2010). An integrated ecological floating-bed employing plant, freshwater clam and biofilm carrier for purification of eutrophic water. *Ecological engineering*, *36*(4), 382-390.

103. Linhoss, A., & Mickle, P. (2022). A Field Validated Model of Temporal Variability in Oyster Habitat Suitability. *Frontiers in Marine Science*, *9*, 778936.

104. Lord, J. P. (2014). Effect of Temperature Changes on Competitive and Predator-Prey Interactions in Coastal Epi-Benthic Communities.

105. Mahu, E., Danso, P., Edusei, M. O., & Atta deGraft-Johnson, K. A. (2023). Impact of agricultural practices on ecosystem health of lagoons: a case study of the Keta Lagoon Complex in Ghana, West Africa. *Environmental Monitoring and Assessment*, *195*, 622. https://doi.org/10.1007/s10661-023-11253-2

106. Mahu, E., Danso, P., Edusei, M. O., & deGraft-Johnson, K. A. A. (2023). Impact of agricultural practices on ecosystem health of lagoons: a case study of the Keta Lagoon Complex in Ghana, West Africa. *Environmental Monitoring and Assessment*, *195*(5), 622.

107. Mahu, E., Sanko, S., Kamara, A., Chuku, E. O., Effah, E., & Sohou, Z. (2022). Climate Resilience and Adaptation in West African Oyster Fisheries: An Expert-Based Assessment of the Vulnerability of the Oyster Crassostrea tulipa to Climate Change. *Fishes*, *7*(4), 205. https://doi.org/10.3390/fishes7040205

108. Mahu, E., Sanko, S., Kamara, A., Chuku, E. O., Effah, E., Sohou, Z., Zounon, Y., Akinjogunla, V., Akinnigbagbe, R. O., & Diadhiou, H. D. (2022). Climate resilience and adaptation in West African oyster fisheries: an expert-based assessment of the vulnerability of the oyster Crassostrea tulipa to climate change. *Fishes*, *7*(4), 205.

109. Matthiessen, G. C. (2008). *Oyster culture*. John Wiley & Sons.

University of Ghana http://ugspace.ug.edu.gh

110. Mawusi, E. J. A., Adzesiwor, O. E., & Kesse, M. K. (2022). Assessment of genetic diversity and population structure in wild populations of Crassostrea tulipa in Ghana. *Scientific African*, *18*, e01420.

111. McAfee, D. (2018). *Can oysters provide a refuge to coastal biodiversity in a changing world?* Macquarie University].

112. McAfee, D., McLeod, I. M., Boström-Einarsson, L., & Gillies, C. L. (2020). The value and opportunity of restoring Australia's lost rock oyster reefs. *Restoration Ecology*, *28*(2), 304-314.

113. McAfee, D., O'Connor, W. A., & Bishop, M. J. (2017). Fast-growing oysters show reduced capacity to provide a thermal refuge to intertidal biodiversity at high temperatures. *Journal of Animal Ecology*, *86*(6), 1352-1362.

114. McLeod, I. M., zu Ermgassen, P. S., Gillies, C. L., Hancock, B., & Humphries, A. (2019). Can bivalve habitat restoration improve degraded estuaries? In *Coasts and Estuaries* (pp. 427-442). Elsevier.

115. Merk, V., Colsoul, B., & Pogoda, B. (2020). Return of the native: survival, growth and condition of European oysters reintroduced to German offshore waters. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(11), 2180-2190.

116. Meyers, D., Bohorquez, J., Cumming, T., Emerton, L., Heuvel, O., Riva, M., & Victurine, R. (2020). Conservation finance: a framework. *Conservation Finance Alliance*, 1-45.

117. minds. What is the Analytic Hierarchy Process (AHP)? *1000minds*. https://www.1000minds.com/decision-making/analytic-hierarchy-process-ahp

118. Mizuta, D. D., Júnior, N. S., Fischer, C., & Lemos, D. (2012). Interannual variation in commercial oyster (Crassostrea gigas) farming in the sea (Florianópolis,

University of Ghana http://ugspace.ug.edu.gh

Brazil, 27 44′ S; 48 33′ W) in relation to temperature, chlorophyll a and associated oceanographic conditions. *Aquaculture*, *366*, 105-114.

119. Montagna, P. A., Palmer, T. A., & Beseres Pollack, J. (2023). Effect of Temporarily Opening and Closing the Marine Connection of a River Estuary. *Estuaries and Coasts*, *46*, 2208-2219. https://doi.org/10.1007/s12237-022-01159-6

120. Morris, R. L., Heery, E. C., Loke, L. H., Lau, E., Strain, E., Airoldi, L., Alexander, K. A., Bishop, M. J., Coleman, R. A., & Cordell, J. R. (2019). Design options, implementation issues and evaluating success of ecologically engineered shorelines. *Oceanography and marine biology*.

121. Motes, M., DePaola, A., Cook, D., Veazey, J., Hunsucker, J., Garthright, W., Blodgett, R., & Chirtel, S. (1998). Influence of water temperature and salinity on Vibrio vulnificus in Northern Gulf and Atlantic Coast oysters (Crassostrea virginica). *Applied and environmental microbiology*, *64*(4), 1459-1465.

122. Mumby, P. J. (2006). Connectivity of reef fish between mangroves and coral reefs: algorithms for the design of marine reserves at seascape scales. *Biological Conservation*, *128*(2), 215-222.

123. Nelson, K. A., Leonard, L. A., Posey, M. H., Alphin, T. D., & Mallin, M. A. (2004). Using transplanted oyster (Crassostrea virginica) beds to improve water quality in small tidal creeks: a pilot study. *Journal of Experimental Marine Biology and Ecology*, *298*(2), 347-368.

124. Neto, R. M., Zeni, T. O., Ludwig, S., Horodesky, A., Girotto, M. V., Castilho-Westphal, G. G., & Ostrensky, A. (2013). Influence of environmental variables on the growth and reproductive cycle of Crassostrea (Mollusca, Bivalvia) in Guaratuba Bay, Brazil. *Invertebrate reproduction & Development*, *57*(3), 208-218.

University of Ghana http://ugspace.ug.edu.gh

125. Newell, R. I. E. (2004). Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve molluscs: A review. *Journal of Shellfish Research*, *23*(1), 51-61. https://doi.org/10.2983/0730-8000(2004)023[0051:EIONAC]2.0.CO;2

126. Ng, A. P. F., Teh, C. P., Yen, P. K., Yasin, Z., & Tan Shau Hwai, A. (2016). Effect of Salinity on Embryo and Larval Development of Oyster Crassostrea iredalei. *Tropical Life Sciences Research*, *27*(supp1), 23-29. https://doi.org/10.21315/tlsr2016.27.3.4

127. Nix, E. A. (2011). *Developing a Gulf-wide oyster reef restoration plan: identification of spatial, socio-economic and geo-political constraints*. Louisiana State University and Agricultural & Mechanical College.

128. Null, S. E., & Lund, J. (2012). Fish habitat optimization to prioritize river restoration decisions. *River research and applications*, *28*(9), 1378-1393.

129. Nunoo, F. K., & Agyekumhene, A. (2022). Mangrove degradation and management practices along the coast of Ghana. *Agricultural Sciences*, *13*(10), 1057-1079.

130. Okon, E. M., Birikorang, H. N., Munir, M. B., Kari, Z. A., Téllez-Isaías, G., Khalifa, N. E., Abdelnour, S. A., Eissa, M. E., Al-Farga, A., & Dighiesh, H. S. (2023). A global analysis of climate change and the impacts on oyster diseases. *Sustainability*, *15*(17), 12775.

131. Ortega-Álvarez, R., Tobon, W., Urquiza-Haas, T., Ruiz-González, S. P., & Koleff, P. (2022). Exploring local perceptions, implementation, benefits, and limitations of community-based restoration projects in Mexico. *Restoration Ecology*, *30*(7), e13604.

University of Ghana http://ugspace.ug.edu.gh

132. Osei, I. K., Chuku, E. O., Effah, E., Kent, K., & Crawford, B. (2021). *Participatory Assessment of Shellfisheries in the Estuarine and Mangrove Ecosystems of Ghana*. https://ccm.ucc.edu.gh/sites/default/files/2022-07/GHANA-Shellfisheries-Assessment-PA00Z67F.pdf

133. Osei, I. K., Yankson, K., & Obodai, E. A. (2022). Comparative analysis of growth performance and survival of the West African mangrove oyster, Crassostrea tulipa (Lamarck, 1819) cultivated by suspension and bottom culture methods in the Densu Estuary, Ghana. *Aquaculture, Fish and Fisheries*, *2*(3), 233-242.

134. Osei, K., & Agyekumhene, M. (2021). *Participatory Assessment of Oyster-Harvesting Capacity in Anyanui Creek, Ghana*.

135. Ozbay, G., Reckenbeil, B., Marenghi, F., & Erbland, P. (2014). Eastern oyster (Crassostrea virginica) aquaculture and diversity of associated species. *Oysters: Biology, Consumption, and Ecological Importance. NOVA Publishing. Book*, 128.

136. Ozbay, G., Reckenbeil, B., Marenghi, F., & Erbland, P. (2017). Eastern oyster (Crassostrea virginica) aquaculture and diversity of associated species. *Oysters: Biology, Consumption and Ecological Importance. Marine Biology. Nova Science Publishers, Incorporated, Hauppauge, NY*, 1-54.

137. Padi, M., Foli, B. A. K., Nyadjro, E. S., Owusu, K., & Wiafe, G. (2021). Extreme rainfall events over Accra, Ghana, in recent years. *Remote Sensing in Earth Systems Sciences*, *5*(1-2), 71-82. https://doi.org/10.1007/s41976-021-00062-1

138. Paolisso, M., & Dery, N. (2010). A cultural model assessment of oyster restoration alternatives for the Chesapeake Bay. *Human Organization*, *69*(2), 169-179.

139. Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M., Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A.,

University of Ghana http://ugspace.ug.edu.gh

Cournapeau, D., Brucher, M., Perrot, M., & Duchesnay, É. (2011). Scikit-learn: Machine Learning in Python. *Journal of Machine Learning Research*, *12*, 2825-2830. https://www.jmlr.org/papers/volume12/pedregosa11a/

140. Petes, L. E., Brown, A. J., & Knight, C. R. (2012). Impacts of upstream drought and water withdrawals on the health and survival of downstream estuarine oyster populations. *Ecology and evolution*, *2*(7), 1712-1724.

141. Pine, W. E., Johnson, F. A., Frederick, P. C., & Coggins, L. G. (2022). Adaptive Management in Practice and the Problem of Application at Multiple Scales—Insights from Oyster Reef Restoration on Florida's Gulf Coast. *Marine and Coastal Fisheries*, *14*(1), e10192. https://doi.org/10.1002/mcf2.10192

142. Pogoda, B. (2019). Current status of European oyster decline and restoration in Germany. *Humanities*, *8*(1), 9.

143. Pogoda, B., Brown, J., Hancock, B., Preston, J., Pouvreau, S., Kamermans, P., Sanderson, W., & Von Nordheim, H. (2019). The Native Oyster Restoration Alliance (NORA) and the Berlin Oyster Recommendation: bringing back a key ecosystem engineer by developing and supporting best practice in Europe. *Aquatic Living Resources*, *32*, 13.

144. Pogoda, B., Merk, V., Colsoul, B., Hausen, T., Peter, C., Pesch, R., Kramer, M., Jaklin, S., Holler, P., & Bartholomä, A. (2020). Site selection for biogenic reef restoration in offshore environments: The Natura 2000 area Borkum Reef Ground as a case study for native oyster restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *30*(11), 2163-2179.

145. Powell, E. N., & Klinck, J. M. (2007). Is oyster shell a sustainable estuarine resource? *Journal of Shellfish Research*, *26*(1), 181-194.

University of Ghana http://ugspace.ug.edu.gh

146. Pultrone, G. (2022). Combining the Ecological and Digital Transitions: Smart Villages for New Scenarios in the EU Rural Areas. INTERNATIONAL SYMPOSIUM: New Metropolitan Perspectives,

147. Rainer, J. S., & Mann, R. (1992). A comparison of methods for calculating condition index in eastern oysters, Crassostrea virginica (Gmelin, 1791). *Journal of Shellfish Research*, *11*(1), 55-58. https://scholarworks.wm.edu/vimsarticles/720

148. Ramachandra, A., & Naha Abu Mansor, N. (2014). Sustainability of community engagement–in the hands of stakeholders? *Education+ Training*, *56*(7), 588-598.

149. Ramanathan, R. (2001). A note on the use of the analytic hierarchy process for environmental impact assessment. *Journal of environmental management*, *63*(1), 27-35.

150. Reeves, S. E., Renzi, J. J., Fobert, E. K., Silliman, B. R., Hancock, B., & Gillies, C. L. (2020). Facilitating better outcomes: How positive species interactions can improve oyster reef restoration. *Frontiers in Marine Science*, *7*, 656.

151. Restore America's, E. (2024). *Creating Conditions for Oysters to Thrive: Design, Monitoring, and Adaptive Management Strategies for Hybrid Oyster Reef Restoration (Summit Abstracts)*. https://estuaries.org/wp-content/uploads/2024/08/Creating-Conditions-for-Oysters-to-Thrive-1.pdf

152. Reyes-García, V., Fernández-Llamazares, Á., McElwee, P., Molnár, Z., Öllerer, K., Wilson, S. J., & Brondizio, E. S. (2019). The contributions of Indigenous Peoples and local communities to ecological restoration. *Restoration Ecology*, *27*(1), 3-8.

153. Ricart, A. M., Gaylord, B., Hill, T. M., Sigwart, J. D., Shukla, P., Ward, M., Ninokawa, A., & Sanford, E. (2021). Seagrass-driven changes in carbonate chemistry

University of Ghana http://ugspace.ug.edu.gh

enhance oyster shell growth. *Oecologia*, *196*(2), 565-576. https://doi.org/10.1007/s00442-021-04949-0

154. Rice, M. A. (2001). Environmental impacts of shellfish aquaculture: filter feeding to control eutrophication. Marine aquaculture and the environment: a meeting for stakeholders in the Northeast. Cape Cod Press, Falmouth, MA, USA,

155. Rossi-Snook, K., Ozbay, G., & Marenghi, F. (2010). Oyster (Crassostrea virginica) gardening program for restoration in Delaware's Inland Bays, USA. *Aquaculture International*, *18*, 61-67.

156. Rubio Zuazo, A. M. (2007). Environmental influences on the sustainable production of the Sydney rock oyster Saccostrea glomerata: a study in two southeastern Australian estuaries.

157. Ruesink, J. L., Lenihan, H. S., Trimble, A. C., Heiman, K. W., Micheli, F., Byers, J. E., & Kay, M. C. (2005). Introduction of non-native oysters: ecosystem effects and restoration implications. *Annu. Rev. Ecol. Evol. Syst.*, *36*(1), 643-689.

158. Saaty, T. L. (2016). Analytic Hierarchy Process. In S. I. Gass & M. C. Fu (Eds.), *Encyclopedia of Operations Research and Management Science* (pp. 52-64). Springer. https://doi.org/10.1007/978-1-4419-1153-7_31

159. Sahoo, S. K., & Goswami, S. S. (2023). A comprehensive review of multiple criteria decision-making (MCDM) Methods: advancements, applications, and future directions. *Decision Making Advances*, *1*(1), 25-48.

160. Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2008). *Global Sensitivity Analysis: The Primer*. John Wiley & Sons. https://onlinelibrary.wiley.com/doi/book/10.1002/9780470725184

University of Ghana http://ugspace.ug.edu.gh

161. Schellekens, T., Wijsman, J. W. M., & van den Brink, A. (2012). *A habitat suitability model for Pacific oysters (Crassostrea gigas) in the Oosterschelde*. IMARES.

162. Scholes, R. J. (2016). Climate change and ecosystem services. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(4), 537-550.

163. Sciences, N. A. o., Earth, D. o., Studies, L., Science, W., Board, T., Board, O. S., Monitoring, C. o. E. A. f., & Activities, A. G. o. M. R. (2017). *Effective monitoring to evaluate ecological restoration in the Gulf of Mexico*. National Academies Press.

164. Shumway, S. E. (1996). *The Eastern oyster: Crassostrea virginica*. University of Connecticut. https://www.researchgate.net/publication/303919089_The_Eastern_oyster_Crassostrea_virginica

165. Silberberg, M., & Martinez-Bianchi, V. (2019). Community and stakeholder engagement. *Primary Care: Clinics in Office Practice*, *46*(4), 587-594.

166. Silva, C., Ferreira, J., Bricker, S., DelValls, T., Martín-Díaz, M., & Yáñez, E. (2011). Site selection for shellfish aquaculture by means of GIS and farm-scale models, with an emphasis on data-poor environments. *Aquaculture*, *318*(3-4), 444-457.

167. Sinha, R. K., Soni, B., & Shankar, B. (2013). Integration of social, ecological, political and technological issues into economic development programs: Key to sustainable development of human society. *Afr J Environ Econ Manag*, *1*(2), 33-48.

168. Smaal, A., Kater, B., & Wijsman, J. (2009). Introduction, establishment and expansion of the Pacific oyster Crassostrea gigas in the Oosterschelde (SW Netherlands). *Helgoland Marine Research*, *63*, 75-83.

University of Ghana http://ugspace.ug.edu.gh

169. Smith, R. S., & Pruett, J. L. (2024). Oyster restoration to recover ecosystem services. *Annual Review of Marine Science*, *17*.

170. Solomon, O. O., & Ahmed, O. O. (2016). Ecological consequences of oysters culture: A review. *Int. J. Fish. Aquat. Stud*, *4*, 1-6.

171. Soniat, T. M., & Brody, M. S. (1988). Field validation of a habitat suitability index model for the American oyster. *Estuaries*, *11*(2), 87-95.

172. Srivastava, N., Hinton, G., Krizhevsky, A., Sutskever, I., & Salakhutdinov, R. (2014). Dropout: A Simple Way to Prevent Neural Networks from Overfitting. *Journal of Machine Learning Research*, *15*(56), 1929-1958. https://jmlr.org/papers/v15/srivastava14a

173. Statham, P. J. (2012). Nutrients in estuaries--an overview and the potential impacts of climate change. *Science of The Total Environment*, *434*, 213-227. https://doi.org/10.1016/j.scitotenv.2011.09.088

174. Statham, P. J. (2012). Nutrients in estuaries—An overview and the potential impacts of climate change. *Science of The Total Environment*, *434*, 213-227. https://doi.org/10.1016/j.scitotenv.2011.09.088

175. Stechele, B. (2023). *Towards restorative aquaculture of flat oysters (Ostrea edulis) in northern Europe-a modelling approach* Ghent University].

176. Swannack, T. M., Reif, M., & Soniat, T. M. (2014). A robust, spatially explicit model for identifying oyster restoration sites: case studies on the Atlantic and Gulf coasts. *Journal of Shellfish Research*, *33*(2), 395-408.

177. Taljaard, S., Monteiro, P. M., & Botes, W. (2006). A structured ecosystem-scale approach to marine water quality management. *Water Sa*, *32*(4), 535-542.

University of Ghana http://ugspace.ug.edu.gh

178. Texas General Land, O. (2022). *Oyster Reef Resiliency Design Guide*. https://www.glo.texas.gov/sites/default/files/resources/glo/coast/coastal-management/forms/files/design-guides/final_oysterreef_designguide.pdf

179. Thackaberry, E. (2021). Nature-Based Solutions for Climate Change Mitigation: How the Eastern Oyster (Crassostrea virginica) Can Aid in South Carolina Coastal Resilience.

180. The World Bank, G. (2021). Ghana – Climatology | Climate Change Knowledge Portal. *Climate Change Knowledge Portal (World Bank Group)*. https://climateknowledgeportal.worldbank.org/country/ghana/climate-data-historical

181. Theuerkauf, S. J., Eggleston, D. B., & Puckett, B. J. (2019). Integrating ecosystem services considerations within a GIS-based habitat suitability index for oyster restoration. *PloS one*, *14*(1), e0210936.

182. Theuerkauf, S. J., & Lipcius, R. N. (2016a). Quantitative validation of a habitat suitability index for oyster restoration. *Frontiers in Marine Science*, *3*, 64.

183. Theuerkauf, S. J., & Lipcius, R. N. (2016b). Validation of a habitat suitability index for oyster restoration. *bioRxiv*, 039875.

184. Thiyagarajan, V., & Ko, G. W. K. (2012). Larval growth response of the Portuguese oyster (Crassostrea angulata) to multiple climate change stressors. *Aquaculture*, *370*, 90-95.

185. Thrush, S. F., Ellingsen, K. E., & Davis, K. (2016). Implications of fisheries impacts to seabed biodiversity and ecosystem-based management. *ICES Journal of Marine Science*, *73*(suppl_1), i44-i50.

186. Thurstan, R. H., McCormick, H., Preston, J., Ashton, E. C., Bennema, F. P., Cetinić, A. B., Brown, J. H., Cameron, T. C., Da Costa, F., & Donnan, D. W. (2024).

University of Ghana http://ugspace.ug.edu.gh

Records reveal the vast historical extent of European oyster reef ecosystems. *Nature Sustainability*, *7*(12), 1719-1729.

187. Volety, A. K. (2008). Effects of salinity, heavy metals and pesticides on health and physiology of oysters in the Caloosahatchee Estuary, Florida. *Ecotoxicology*, *17*, 579-590.

188. Volety, A. K., Haynes, L., Goodman, P., & Gorman, P. (2014). Ecological condition and value of oyster reefs of the Southwest Florida shelf ecosystem. *Ecological Indicators*, *44*, 108-119.

189. Walles, B., Troost, K., van den Ende, D., Nieuwhof, S., Smaal, A. C., & Ysebaert, T. (2016). From artificial structures to self-sustaining oyster reefs. *Journal of Sea Research*, *108*, 1-9.

190. Wan, Y., & Tummala, V. M. R. Analytical Hierarchy Process. *ScienceDirect Topics*. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/analytical-hierarchy-process

191. Wang, X., Zhang, J., Zhong, Y., Liu, Y., & Wu, W. (2023). GIS-based spatial suitability assessment for pacific oyster Crassostrea gigas reef restoration: A case study of Laizhou Bay, China. *Marine Pollution Bulletin*, *186*, 114416.

192. Wasson, K., Gossard, D. J., Gardner, L., Hain, P. R., Zabin, C. J., Fork, S., Ridlon, A. D., Bible, J. M., Deck, A. K., & Hughes, B. B. (2020). A scientific framework for conservation aquaculture: a case study of oyster restoration in central California. *Biological Conservation*, *250*, 108745.

193. Webber, J. L., Tyler, C. R., Carless, D., Jackson, B., Tingley, D., Stewart-Sinclair, P., Artioli, Y., Torres, R., Galli, G., & Miller, P. I. (2021). Impacts of land use on water quality and the viability of bivalve shellfish mariculture in the UK: A

University of Ghana http://ugspace.ug.edu.gh

case study and review for SW England. *Environmental Science & Policy*, *126*, 122-131.

194. Wellman, E. H., Baillie, C. J., Puckett, B. J., Donaher, S. E., Trackenberg, S. N., & Gittman, R. K. (2022). Reef design and site hydrodynamics mediate oyster restoration and marsh stabilization outcomes. *Ecological applications*, *32*(2), e2506. https://doi.org/10.1002/eap.2506

195. Wesley, A., & Parnell, A. (2020). Advising and Prior Learning Assessment for Degree Completion. Recognition of Prior Learning in the 21st Century. *Western Interstate Commission for Higher Education*.

196. *WoRMS taxon details of Crassostrea.* (2021). http://www.marinespecies.org/aphia.php?p=taxdetails&id=138297&allchildren=1.

197. Yáñez-Arancibia, A., Day, J. W., & Reyes, E. (2013). Understanding the coastal ecosystem-based management approach in the Gulf of Mexico. *Journal of Coastal Research*(63), 244-262.

198. Yankson, K. (1990). Preliminary studies on the rearing of the West African Mangrove Oyster, Crassostrea tulipa, in the laboratory. *Discovery and Innovation*, *2*(4), 45-51.

199. Yoris-Nobile, A. I., Slebi-Acevedo, C. J., Lizasoain-Arteaga, E., Indacoechea-Vega, I., Blanco-Fernandez, E., Castro-Fresno, D., Alonso-Estebanez, A., Alonso-Cañon, S., Real-Gutierrez, C., & Boukhelf, F. (2023). Artificial reefs built by 3D printing: Systematisation in the design, material selection and fabrication. *Construction and Building Materials*, *362*, 129766.

200. Zhao, F., & Wu, J. (2024). The Role of Shellfish Aquaculture in Coastal Habitat Restoration. *International Journal of Marine Science*, *14*.

University of Ghana http://ugspace.ug.edu.gh

201. Zu Ermgassen, P. S., Bonačić, K., Boudry, P., Bromley, C. A., Cameron, T. C., Colsoul, B., Coolen, J. W., Frankić, A., Hancock, B., & van Der Have, T. M. (2020). Forty questions of importance to the policy and practice of native oyster reef restoration in Europe. *Aquatic conservation: marine and freshwater ecosystems*, *30*(11), 2038-2049.

202. Zu Ermgassen, P. S., Spalding, M. D., Grizzle, R. E., & Brumbaugh, R. D. (2013). Quantifying the loss of a marine ecosystem service: filtration by the eastern oyster in US estuaries. *Estuaries and Coasts*, *36*, 36-43.

203. Zwerschke, N., Hollyman, P. R., Wild, R., Strigner, R., Turner, J. R., & King, J. W. (2018). Limited impact of an invasive oyster on intertidal assemblage structure and biodiversity: the importance of environmental context and functional equivalency with native species. *Marine biology*, *165*, 1-13.

204. Zwerschke, N., Kochmann, J., Ashton, E. C., Crowe, T. P., Roberts, D., & O'connor, N. E. (2018). Co-occurrence of native Ostrea edulis and non-native Crassostrea gigas revealed by monitoring of intertidal oyster populations. *Journal of the Marine Biological Association of the United Kingdom*, *98*(8), 2029-2038.

INTEGRI PROCEDAMUS