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Climate Resilience and Adaptation in West African Oyster Fisheries: An Expert-Based Assessment of the Vulnerability of the Oyster *Crassostrea tulipa* to Climate Change

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Abstract: Globally, over 85% of oyster reefs have been lost, and the combined effects of climate change, ocean acidification, and environmental degradation, including pollution and mangrove overharvesting, could further reduce global oyster fisheries in the coming decades. To understand the level of impact of climate change on the oyster fishery in West Africa, an expert-based vulnerability assessment to climate change was conducted for the West African mangrove oyster (*Crassostrea tulipa*, Lamarck 1819). Using a combination of the exposure of the oyster to climatic stressors (estuarine temperature, salinity, river flow, surface run-off, sea level rise, and estuarine circulation) together with an assessment of sensitivity to these stressors, we estimate the overall vulnerability of *C. tulipa* to climate change. A very high overall climate vulnerability score of 12 on a scale of 16 was calculated for *C. tulipa*. While the overall climate exposure score in the West African coastal region remained high, the high sensitivity of *C. tulipa* to hydrographic conditions of its habitat, in particular salinity, coupled with its sessile and habitat-specific nature, pushed the overall vulnerability to very high. Early life history settlement requirements, adult mobility, and sensitivity to salinity were the three most important biological and sensitivity attributes that determined the vulnerability score. By leaving each of these three sensitivity attributes out of the analysis, the overall vulnerability score was reduced to 9 (i.e., from very high to high). A negative directional effect of climate change, coupled with a low potential for change in distribution, threatens the *C. tulipa* fishery in a long-term adverse climate scenario. We recommend management efforts that incorporate climate resilience and adaptation practices to prioritize recruitment success, as well as the development of breeding lines with climate-resilient traits.

Keywords: oyster; climatic stressors; very high vulnerability; distribution change

Citation: Mahu, E.; Sanko, S.; Kamara, A.; Chuku, E.O.; Effah, E.; Sohou, Z.; Zounon, Y.; Akinjogunla, V.; Akinnigbagbe, R.O.; Diadhiou, H.D.; et al. 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* **2022**, *7*, 205. https://doi.org/10.3390/fishes7040205

Academic Editors: Bianca Maria Lombardo, Francesco Tiralongo and Giacomo Bernardi

Received: 11 July 2022
Accepted: 9 August 2022
Published: 16 August 2022

1. Introduction

Climate change is having a range of direct and indirect impacts on marine fisheries, with implications for fisheries-dependent economies, coastal communities, and fisherfolk [1,2]. Given the overexploited status of many wild fish stocks and the limited supply of livestock and crop production, securing food, particularly protein, is a primary global concern for a growing human population. Oyster fisheries are an important and unique sub-sector of the artisanal fisheries industry within the Guinea Current Large Marine Ecosystem, with significant economic importance in Ghana, Benin, Sierra Leone, The Gambia, Senegal, and Nigeria [3–6]. Aside from contributing significantly to the nutrition and income needs of vulnerable populations, the oyster fishery in West Africa is dominated by women, thus helping to address the gender gap that exists in the wider fishery industry and the access to and use of marine resources [3,4,6]. The role of women in the oyster industry has contributed significantly to poverty alleviation and enhancing food security within deprived communities across the region [3–5]. In addition to promoting food security and enhancing livelihoods, oysters are crucial to global ocean health, providing shelter and habitat for many estuarine organisms, filtering and cleaning the water, reducing bank erosion, and acting as a buffer from extreme weather events such as hurricanes [7–9].

Despite their importance, their populations have been reported to have declined significantly in the past decades. Beck and Brumbaugh [10] reported that over 85% of oyster reefs have already been lost globally, while the condition of the remaining 15% is reported to be declining. Recent studies have, therefore, focused on the potential for culture, sustainable farming business, and improvement of wild stocks of the mangrove oyster towards enhancing production and supporting livelihoods [11–13]. Both climatic factors (e.g., temperature, precipitation, and their variability) and non-climatic factors (overharvesting, pollution, mangrove degradation, and disease outbreaks) are the key drivers behind declining oyster populations [10]. Oyster growth is highly dependent on prevailing environmental conditions, and a change in these will affect their growth rates or lead to mortality [14]. Changes in water temperature, pH, salinity, and water flow directly impact their ability to filter food, reproduce, and build shells or indirectly by causing a shift in their food preference [15–18]. Climate change is resulting in increased variability in precipitation, higher water temperatures, and increased upwelling, and the combined effects of these changes are projected to inflict greater stress on oysters putting their population at further risk of decline [10]. Compared to other fish species, oysters are particularly disadvantaged due to the sessile nature of their adults, which prevents them from moving and tracking changing water conditions.

Understanding the extent to which the West African Mangrove Oyster is vulnerable to climate change is very important for improving its resilience and increasing adaptive capacity. While climate change vulnerability assessments have been routinely applied to some wild and farmed fish stocks globally [19–21], our understanding of the exposure of shell and finfish to climate-induced stress in West Africa is limited, and the impacts are not well understood. Yet, the African continent is among the most vulnerable to climate change [22] with its ecosystems and human systems being among the most impacted globally [2]. It has been projected that climate change will result in a substantial reduction in marine fish production and fish protein supply in West Africa by the 2050s [1]. When combined with economic parameters, a 21% drop in annual landed value, a 50% decline in fisheries-related jobs, and a total annual loss of US $311 million in the economy of West Africa is anticipated by 2050 [1].

This study applies an expert-based climate change vulnerability assessment, developed for marine shellfish and finfish, to the West African mangrove oyster. The goal is to quantify the extent to which the mangrove oyster is vulnerable to climate change by combining the exposure of the oyster to climate-induced stressors and its sensitivity to these stressors. Furthermore, the study seeks to understand the directional effect of climate change on the West African mangrove oyster and assess the potential for any distributional change for this resource.

2. Literature Review

Climate change is one of the most important challenges of the 21st century. The World Bank estimates that its effects could push an additional 100 million people below the poverty line by 2030 and cause over 200 million people to migrate within their own countries by 2050 [23]. According to the IPCC's Regional analysis of climate change impacts, developing countries and poor communities within these developing countries are the most vulnerable to the consequences of climate change [24]. Developing countries have high sensitivity to climate disruptions but limited capacity to adapt and limited resources with which to mitigate the impacts.

The fishing industry, in particular marine fisheries, plays an important role in the nutrition and livelihood needs of people in West Africa, although there are huge uncertainties surrounding the region's fish stock due to climatic and non-climatic stress [19,25]. The small-scale fishing sector accounts for approximately 60% of the total fish catch in West Africa yet is highly vulnerable to climate change [26]. Stocks have declined, and most artisanal stocks, including shellfish, are overexploited [27,28]. The status of fisheries in the region is suboptimal for achieving food security (with respect to catches, incomes, and profits) and ecological sustainability objectives [1]. Even without considering the impact of climate change, it is predicted that approximately 6% of the population in sub-Saharan Africa will suffer from chronic hunger or undernourishment by 2050 [29]. With climate change, crop and fish production is negatively affected in many West African countries [30,31]. The shellfish industry plays an important role in West Africa's small-scale fisheries sector by contributing to food security, poverty alleviation, ecosystem enhancement, and improving gender diversity [32,33]. However, the industry faces huge uncertainties as fishing pressure is continuously increasing in combination with environmental degradation and climate change impacts [34].

Oyster environments and their reefs are affected by climate change in several ways. The acidification of seawater, resulting from increasing CO_2 emissions, threatens the shell strength of oysters and the ensuing structure of reefs. As seawater becomes more acidic, juvenile oysters struggle to grow their shells, leading to reduced growth, limiting their ability to construct reefs, and causing existing shell reefs to disintegrate more quickly [35]. Changes in precipitation will alter the salinity in estuaries both directly (from rainfall) and indirectly by changing the volume of river water flowing into estuaries [36]. High and frequent precipitation in monsoon regions is likely to change the salinity regimes of oyster reefs to freshwater, affecting biological processes such as reproduction and feeding [15,37]. Global warming may push water temperatures beyond the optimal range for oyster physiological needs [38], and harmful algal blooms may become frequent or severe leading to increased oyster mortality [39]. Higher than optimal temperatures will also decrease the filtering efficiency of oysters, thereby reducing their food intake [40]. The different conditions brought on by climate change will lead to altered interactions between oysters and their predators.

Knowledge of vulnerability provides the foundation for planning and developing actions that minimize impacts on people while maximizing the sustainability of ecosystem goods and services. To evaluate the potential risks posed by climate change on marine organisms, two strategies are commonly used [41]. The first approach combines population models with climate models to develop mechanistic frameworks that are projected into the future using expected future environmental parameters as driving forces [42]. This approach is validated using environmental conditions from the past, allowing one to hindcast the population dynamics and compare them with population observations [43]. The second method uses a trait-based vulnerability assessment to climate change to identify the most vulnerable parts of marine systems, including both exploited organisms and exploiting communities [20,41]. This method uses expert judgement to estimate the character of species vulnerability, such as the level of exposure to environmental change, or their resilience [44]. The approach addresses the need for a broad, transparent, and relatively quick evaluation of the vulnerability of multiple species.

3. Methodology

Expert elicitation/judgement is a structured approach to systematically consulting experts on uncertain issues. It is most often used to quantify ranges for poorly known parameters but may also be useful to further develop qualitative issues such as definitions, assumptions, or conceptual (causal) models. Thorough preparation and systematic design and execution of an expert elicitation process may increase the validity of its outcomes and the transparency and trustworthiness of its conclusions. Various expert elicitation protocols and methods exist. However, these are often not universally applicable and need customization to suit the needs of a specific study. In this paper, we adapted the Methodology for assessing the vulnerability of marine fish and shellfish species to a changing climate used by [45]. The framework comprises four steps, namely planning, materials preparation, assessment, and analyses of the scores summarized in Figure 1 and discussed in subsequent sub-sections.

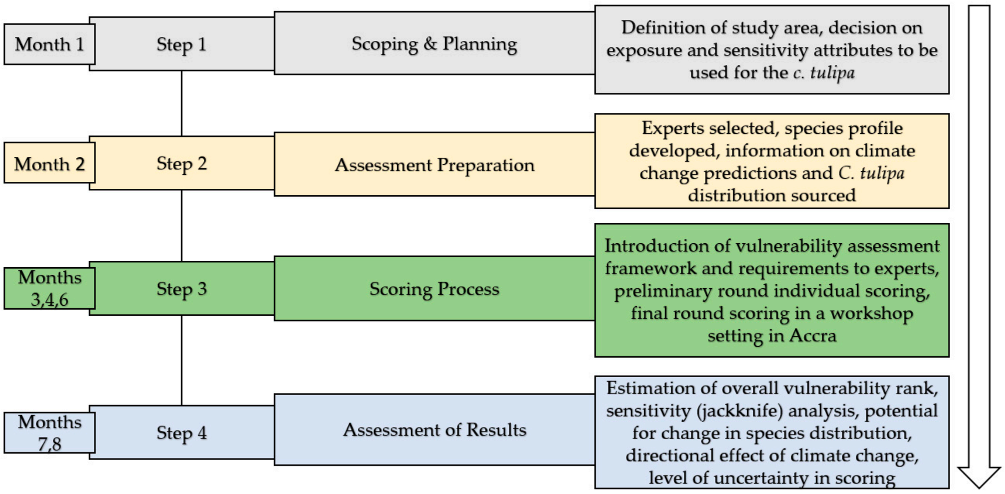

Figure 1. Summary of the four-step vulnerability assessment framework used in the study.

3.1. Scoping, Planning, and Assessment Preparation

Spatial Region of the Assessment: The vulnerability assessment spanned the Western and parts of the Central Coasts of Africa where the *C tulipa* is found (Figure 2). This area of the Western to Central African coastline falls within four of the five bioclimatic regions of the continent, comprising the Sahelian (Senegal), Sudanian (Gambia), Guinean (Guinea Bissau, central and east coast of Ghana, Togo, Benin, and west coast of Nigeria), and Guineo-Congolian (Sierra Leone, Liberia, Côte D'Ivoire, west coast of Ghana, east coast of Nigeria, Cameroun, Gabon, Congo, and Angola) [46]. The region is characterized by arid, semi-arid, to humid climates, which define the salinity regime of its estuaries, typically ranging from normal brackish conditions (0.5‰ to 30‰) to extremely hypersaline inverse ones such as the Saloum and Casamance estuaries in Senegal where salinity is as high as 70‰. Areas within the Guinean Coast have a mean annual temperature of approximately 26 °C with a range of 1.7–2.8 °C and the diurnal range is 5.6–8.3 °C [46]. Between Guinean Coast and the Sahel areas, the mean monthly temperatures can rise to 30 °C with an annual range of 9 °C and a diurnal range of 14 °C to 17 °C. The General rainfall pattern of the Guinean region, generally defined by average annual rainfall between 1200 and 2200 mm, is modified by ocean currents and physiographic features [46]. The Guineo-Congolian Region is the wettest of the regions, with average annual rainfall between 2200 and 5000 mm [46].

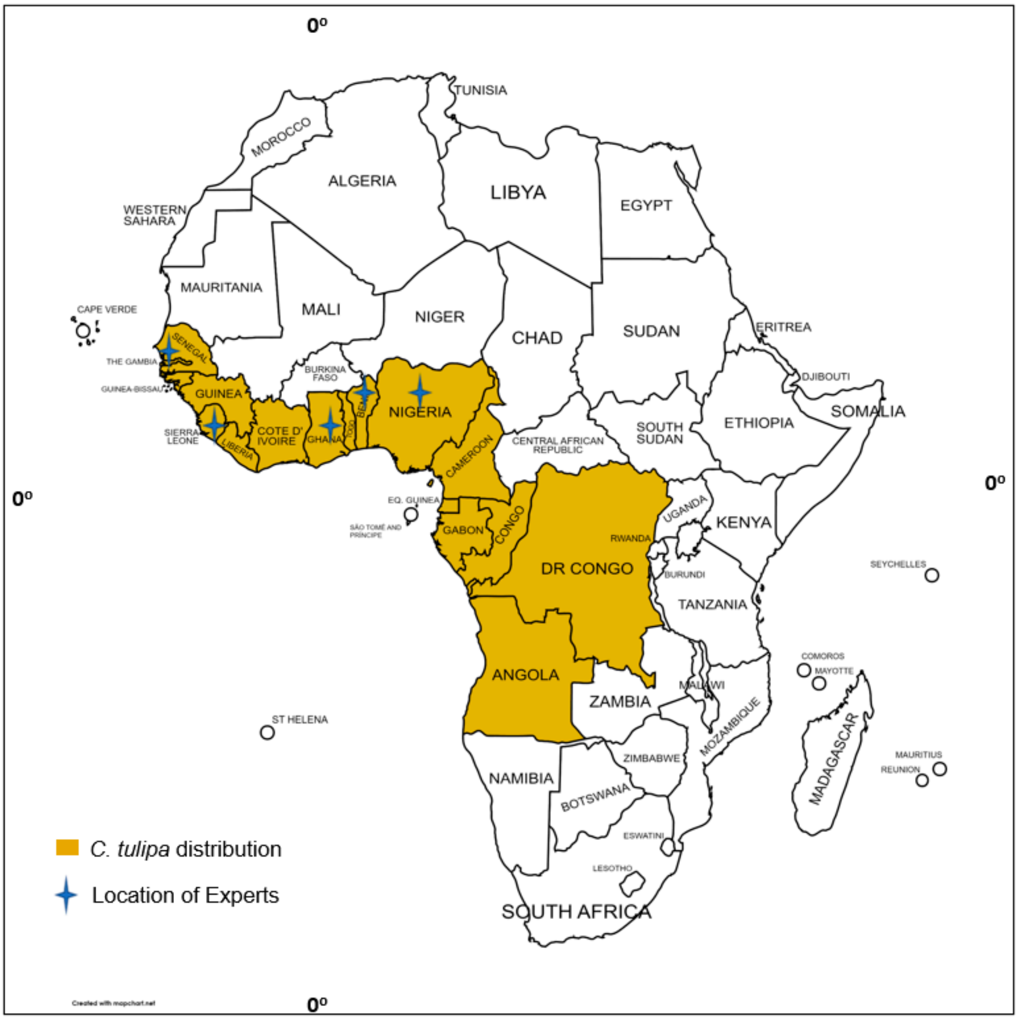

Figure 2. Spatial region of the vulnerability assessment and locations of experts.

Climate Exposure and Sensitivity Attributes used in the Assessment: The exposure factors included in the assessment were modified from those recommended in [45]. Nine exposure factors (i.e., air temperature, estuarine salinity, estuarine temperature, precipitation, estuarine pH, surface run-off, river flow, currents) and their variabilities were selected for the assessment (see Table S1). The information in Supplementary Sheet S1 provides a detailed explanation of each exposure and sensitivity attribute, including goals and scoring criteria. These exposure variables have the potential to impact the ecology, biology, population, and distribution of *C. tulipa*. Salinity, for example, is among the most important factors influencing the distribution, abundance, growth, and survival of oysters. Salinity can directly affect the physiological processes of its larvae, interfering with their feeding capacity, duration of the planktonic phase, and ability to select settlement sites [47]. Both juvenile and adult *C. tulipa* have been observed to suffer heavy mortality during the wet season when the salinity of the water drops to 0.5‰ [47]. Similar to salinity, pH plays an important role in the growth and survival of oysters from larvae to adults. At low pH (acidic waters), shell building is affected, and oysters expend additional energy to build their shell. All factors were weighted equally to cater for any limitations in knowledge regarding the magnitude of effects and the oyster's response to these factors [20]. The exposure score included information about the magnitude of the expected climate change by comparing the 1986–2005 to 2006–2055 periods, and in some cases, in relation to the oyster's tolerance to these factors. All 12 sensitivity attributes described in Morrison, Nelson [45] for fin and shellfish were used in the assessment (Table S1).

Expert Selection and preparation: The expert group consisted of nine climate and shellfish scientists from Senegal, Sierra Leone, Ghana, Benin, and Nigeria with extensive experience in the biology, ecology, and population studies of *C. tulipa* and general oceanography of the West African coastline (Table 1). While experience in shellfish research was considered the number one priority in the selection of experts, we also considered inclusivity as key to projecting wider views, hence the expert group was carefully formulated to satisfy both gender and generational diversity.

Table 1. Summary of background of experts.

Expert Code	Gender	Shellfish (Fishery, Biology, Ecology, Aquaculture	Climate Change (Science, Socio-Ecology, Development	Years of Experience
E1	Male	Yes	Yes	8
E2	Female	Yes	Yes	5
E3	Female	Yes	Yes	13
E4	Male	Yes	Yes	10
E5	Female	Yes	Yes	15
E6	Male	Yes	Yes	30
E7	Female	Yes	Yes	6
E8	Male	Yes	Yes	6
E9	Male	Yes	Yes	30

Species profile: As required in the vulnerability assessment framework, a species profile (Table 2) was developed for *C. tulipa* by the experts to guide the scoring process. The profile included important information on the biology, ecology, and environmental requirements of *C. tulipa*. The species profile development consisted of reviewing existing literature on *C. tulipa* and general expert knowledge on the subject matter. During the reviewing process, experts became aware of significant data gaps that must be addressed in future research. Experts accounted for these data gaps in their scores using the criteria for scoring data quality in the vulnerability assessment framework.

Table 2. Summary of species profile developed for *C. tulipa* for the assessment.

Exposure/Sensitivity Attributes	Requirements
Temperature	Thrives in a temperature range of 18–33 °C. Temperatures below 10 °C and above 35 °C may be lethal.
Salinity	Thrives in a salinity range of 4 ppt and 50‰. Salinities below 4 ppt and above 50‰ are potentially detrimental to growth and survival. Prolonged exposure to a salinity of 0 ppt causes mortalities.
pH	Thrives in a pH range of 6–8.5. Extremely low and high pH has significant detrimental effects on shell development.
Dissolved Oxygen	Thrives in low concentrations of DO up to about 1 mg/L.
Water Flow/Residual Current	Thrive within 0.5 m/s to 1.5 m/s. Stagnant water (0 m/s will disrupt filter feeding and high-speed flowing water (above 1.5 m/s) will not allow spats to settle on suitable substrate.
Length of submergence in water and exposure to air at low tide	Survives up to 36 h out of the marine environment whilst exposure periods beyond 3 days lead to mortality. Growth is retarded in long periods of exposure as feeding halts during exposure.
Turbidity	Excess silt smothers the gills, hampers the flow of food during filter feeding and leads to mortalities.

Table 2. *Cont.*

Exposure/Sensitivity Attributes	Requirements
Habitat Specificity	A habitat specialist adapted to the near shore intertidal areas where its prime habitat is the stilt roots of red mangroves. The pediveliger larvae fasten to available hard stable substrates when settling. Thrives well in brackish environments with almost no survival in freshwater environments.
Prey specificity	Has a specific prey item. The preferred diet is Phytoplankton.
Stock size and status	Depends on environmental conditions for spat, availability of substrates for attachment and the ability of parent stocks to reproduce. Stock size has declined in some ecosystems; more data needed to quantify the rate of decline.
Adult mobility	The adult form has no active movement. Movement may be passive floating substrates.
Spawning cycle	Spawn all-year round. Spawn depending on conducive environmental conditions.
Reproductive strategy (including any complexity)	Broadcast fertilization: Males and female gametes are released into the open water environment and fertilization occurs at random. The species is highly proliferous with several thousands of egg cells released per individual during spawning. It exhibits protandric sequential hermaphroditism, i.e., the matured form differentiates first as male, then later as female in an individual organism.
Early life history survival and settlement	The eggs are fertilized in the water and within hours, develop into microscopic larvae that drift in the plankton, guided by the tides and currents. For up to 4 weeks, the larvae drifts in the coastal and estuaries waters during which they develop transparent shells and a retractable foot. Survival rates during this phase of the life cycle may be very low, however, the millions of eggs and sperms released in one season ensures successful settlement of most larvae. The larvae (about 0.3 mm in length) settle on a clean, hard substrate (surface) using the foot to crawl around to find a suitable site for permanent settlement. Once attached, the foot is reabsorbed into the body of the larvae.
Dispersal of early life stages	Dispersal of larvae from parent stocks by water currents through swimming is aided by ciliated velum. Larval settlement stage is about 4 weeks.
Population growth rate	Maturity is reached in roughly between 3–12 months with growth rates varying depending on local conditions. No knowledge of data on the population growth rate.
Other stressors	Pollution (plastics, heavy metals, PCBs, sediments, etc.), River flow modifications, mangrove deforestation, fouling organisms, predators, parasites, competition (space, food, etc.), natural disasters (storms, etc.), over exploitation of minerals in oyster beds put pressures on the oysters, invasive species.

Climate Projections: Climate exposures were inferred from an ensemble of global climate models used in the Intergovernmental Panel on Climate Change Assessment Report 5 and other relevant literature (Table 3).

Table 3. Inferred climate exposure resources used for the vulnerability assessment.

Climate Exposure	Source	Model	Region
Temperature	[48]	CMIP-5	West Africa
Temperature	[49]	CMIP-5	West Africa
Temperature	[50]	CMIP-6	Africa
Precipitation	[50]	CMIP-6	Africa
Precipitation	[51]	AOGCM	West Africa
Precipitation	[52]	RegCM3	West Africa
Precipitation	[53]	HiRAM SM2M	West Africa
Surface run-off	[54]	AIM, MINICAM, noLUC	West Africa
Ocean Acidification	[55]	CCSM3, GLODAP	Global
Ocean Acidification	[56]	OCIMP-2	Global
Ocean circulation	[57]	CMIP-3/SRES	Global
Sea level rise	[57]	CMIP-3/SRES	Global

3.2. Scoring Process

Experts were inducted into the vulnerability assessment process through two virtual workshops. These virtual workshops introduced the experts to the vulnerability assessment framework and requirements. At the end of the virtual workshop, each expert was given an initial scoring sheet (Table S2) prepared according to [45] to score the biological and exposure attributes outlined in Table S1. This preliminary scoring process ensured that each expert had an equal opportunity to provide an initial score that is not influenced by other opinions [45]. Experts scored based on four scoring bins (low, moderate, high, and very high) for each exposure factor or sensitivity attribute (see Table S2) using existing information/data and their own knowledge in the field. In data-poor situations, experts were made to use the information on other similar oyster species or general ecological principles to provide a score. Experts also scored the direction of the effect of climate change on *C. tulipa* using a similar tally system in which four tallies were distributed across the three scoring bins (i.e., positive, negative, or neutral response). Experts further provided a data quality score for each attribute using the scoring guideline of [45], where scores of 0, 1, 2, and 3 correspond to no data, expert knowledge, limited data, and adequate data, respectively (Table 4). Upon completing the preliminary scoring process, experts met in person in Ghana during a two-day workshop to deliberate on the scores. The goal of this meeting was to offer experts the chance to explain the rationale behind their scores and a chance to change their scores based on new information provided during the workshop. This scoring process is not intended to gather consensus among the group and make the scoring process not independent; rather, it helped identify and fix errors, reduce individual bias, encourage buy-in from the experts, and increase the precision of the final scores [45]. Experts may or may not choose to change their scores following the outcome of the group work.

Table 4. Data quality scoring guidelines used in scoring the quality of expert scores (from [45]).

Data Quality Score	Description
3	***Adequate Data***. The score is based on data which have been observed, modeled or empirically measured for the *C. tulipa* and comes from a reputable source
2	***Limited Data***. The score is based on data which has a higher degree of uncertainty. The data used to score the attribute may be based on related or similar species, come from outside the study area, or the reliability of the source may be limited.
1	***Expert Judgement***. The attribute score reflects the expert judgement of the reviewer and is based on their general knowledge of the *C. tulipa* and its role in the ecosystem
0	***No data***. No information to base an attribute score on. Very little is known about the *C. tulipa* or related and there is no basis for forming an expert opinion.

3.3. Data Analysis

Overall Vulnerability Rank: To calculate the overall vulnerability rank of *C. tulipa*, the component scores (low, moderate, high, and very high) were assigned numerical values (1, 2, 3, and 4, respectively). An average score for each climate exposure factor and sensitivity attribute was calculated as the weighted mean of the experts' tallies (see Sheet 3 S3 for the dataset on expert scores). The overall exposure and sensitivity score was calculated from the weighted means using a logic rule (Table 5). The final climate vulnerability score was then calculated by multiplying the overall exposure and sensitivity scores. The vulnerability region of *C. tulipa* was then determined using the vulnerability scale defined in [45] as follows: 1–3 low, 4–6 moderate, 8–9 high, and 12–16 very high.

Table 5. Logic rule for calculating overall species' climate exposure and biological sensitivity (from [45]).

Overall Sensitivity or Exposure Score	Numeric Score	Logic Rule
Very High	4	3 or more attributes or factor means $\geq$3.5
High	3	2 or more attributes or factor means $\geq$3.0
Moderate	2	2 or more attributes or factor means $\geq$2.5
Low	1	Less than 2 or more attribute or factor $\geq$2.5

Potential for Change in *C. tulipa* Distribution: The potential for a change in species distribution was estimated using all five attributes and reversing the scores for Adult Mobility, Early Life Stage Dispersal, and Habitat Specificity, and applying the same logic rule as in the general vulnerability calculation.

Directional Effect of Climate Change: To estimate the direction of the effect of climate change on the *C. tulipa* population, the scores for the direction of the effect of climate change (Sheet S3) were converted to numbers (negative = −1, neutral = 0, positive = 1). A weighted average was calculated based on the total of 12 tallies and the direction of the effect classified according to the scale used in Hare, Morrison [20] as follows: Weighted averages <−0.333 imply an overall negative effect, weighted averages between −0.333 and 0.333 imply an overall neutral effect, and weighted averages >0.33 imply an overall positive effect.

Level of Uncertainty in Scoring: To determine the level of certainty in the expert scores, bootstrap analysis was conducted for climate exposures and biological attributes, and directional effects. For climate vulnerability scores, the scores across all experts for a given exposure factor (n = 45; nine experts and five tallies) were drawn randomly with replacement for 10,000 times and the overall score and proportion of these 10,000 repetitions that scored in each overall vulnerability bin was enumerated. The same bootstrapping technique was used for the directional effect scoring (n = 27; nine experts and four tallies).

4. Results

Data Quality: The quality of data used for scoring the various attributes ranged from 1.9 to 2.9 for climatic exposures and 2.3 to 3.0 for sensitivity attributes (Figure 3). For climatic exposures, data were limited for mean surface run-off, mean flow, variability in estuarine pH, estuarine currents, and to some extent, variability in estuarine temperature. In the case of the sensitivity attributes, data were limited for stock size, and to some extent, stress from pollution.

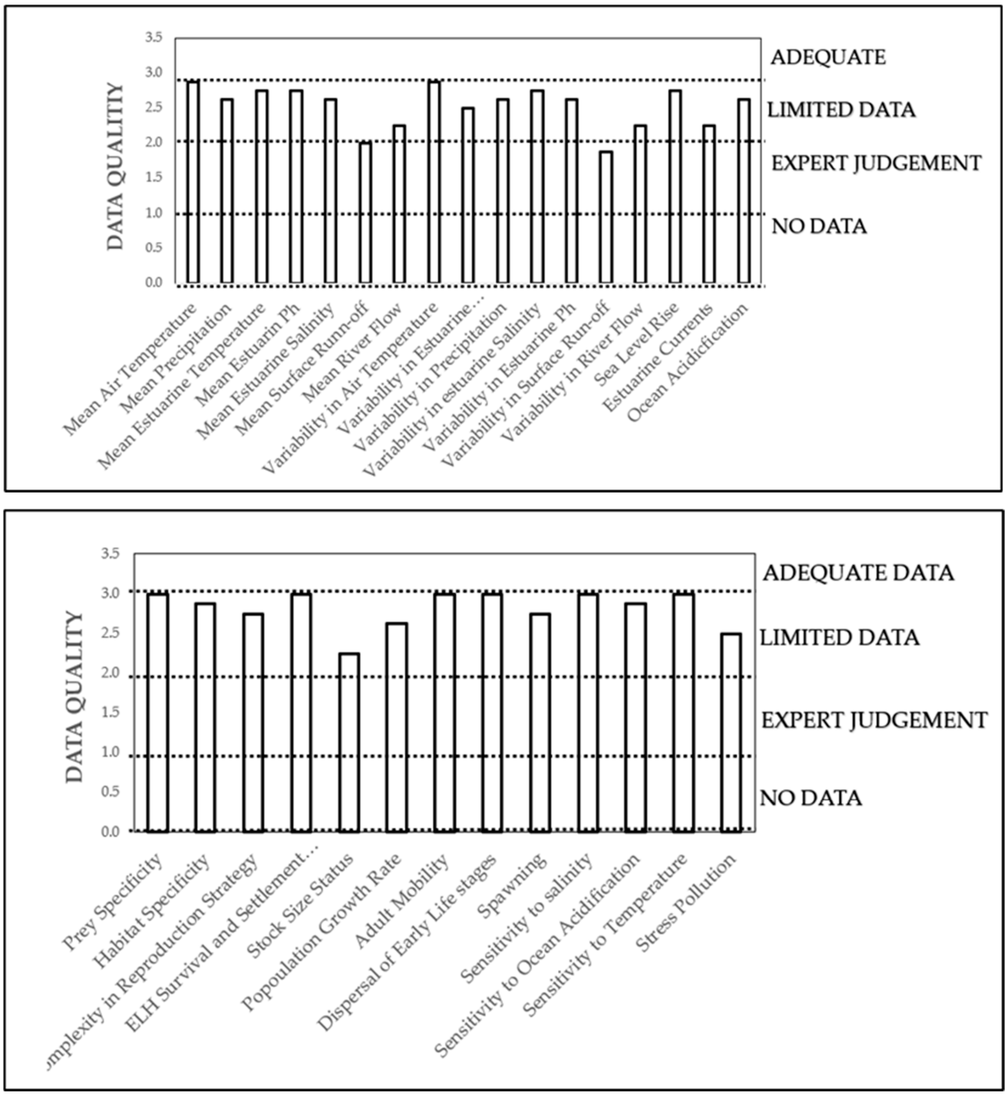

Figure 3. Quality of data used in assessing the vulnerability of *C. tulipa*. (3 depicts adequate data, 2 depicts limited data, 1 depicts data based on expert knowledge and 0 depicts no available data).

Overall Vulnerability: The overall vulnerability rank estimated from all nine exposure factors and their variabilities together and the 12 sensitivity attributes ranked *C. tulipa* as highly vulnerable to climate change with an overall vulnerability score of 12, which falls in the red region of the vulnerability matrix (Figure 4). While the overall climate exposure score in the West African coastal region remained high (Score of 3), the very high sensitivity (score of 4) of *C. tulipa* to hydrographic conditions of its habitat coupled with its biological traits pushed its overall vulnerability into the very high region of the matrix.

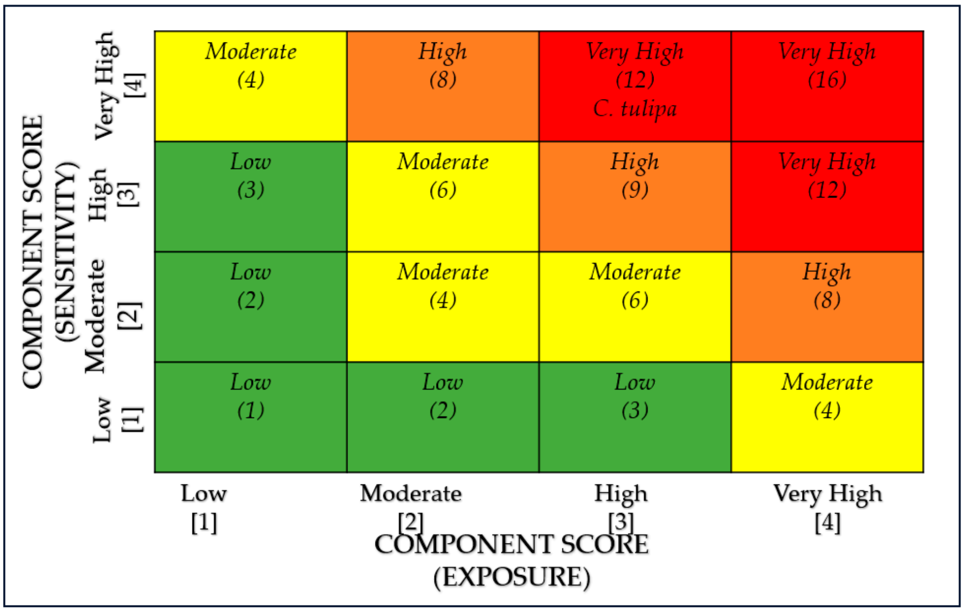

Figure 4. Vulnerability matrix showing the vulnerability region of *C. tulipa* estimated from sensitivity and exposure scores.

Temperature, salinity, and precipitation together with their variabilities, as well as sea level rise and ocean acidification, scored high (>3) in both original and bootstrapped samples while all other climatic exposure scored below 3 (Figure 5). On the sensitivity side of the assessment, early life history survival and settlement requirements, adult mobility, and sensitivity to salinity recorded very high scores (>3.5), while prey and habitat specificity, ocean acidification, and stress from other stressors such as pollution scored high (>3) (Figure 5). These exposure factors and sensitivity attributes have been identified as the most important change-driving factors in the fisheries of *C. tulipa*.

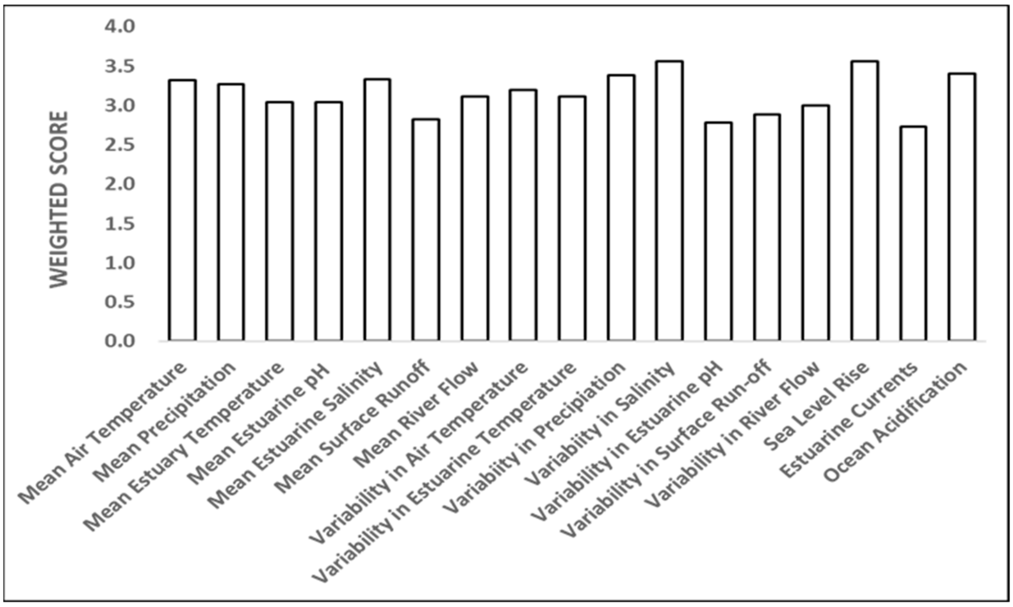

Figure 5. *Cont.*

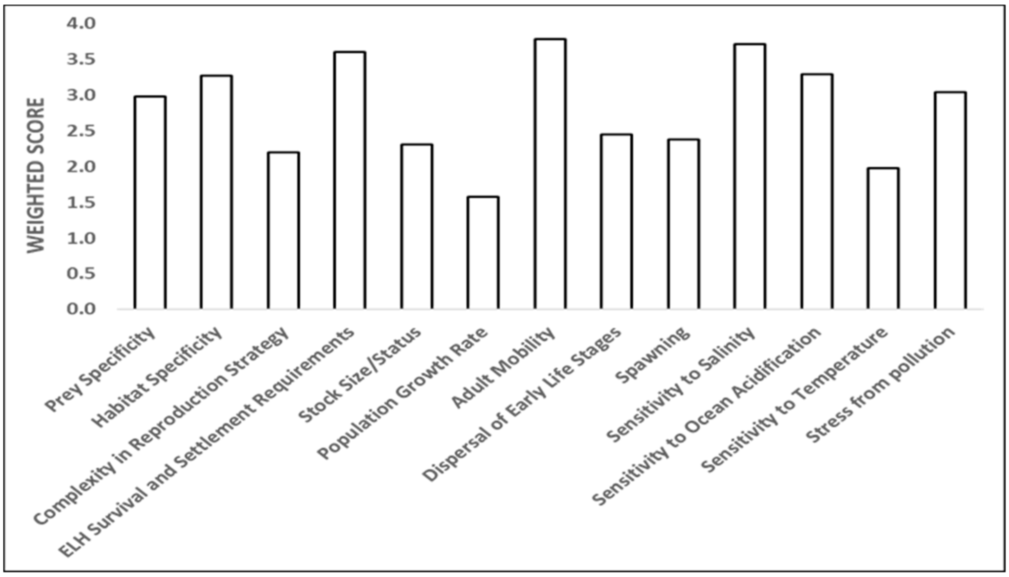

Figure 5. Average scores estimated for climatic exposures and sensitivity attributes for samples. Bootstrapped analysis of the scores indicates very high certainties in scores (>95%).

By further evaluating the importance of each factor's contribution to the overall vulnerability rank using a leave-one-out sensitivity analysis, we deduced that early life history survival and settlement requirements, adult mobility, and sensitivity of *C. tulipa* to salinity are highly important to the overall vulnerability rank. Leaving each one of these three sensitivity attributes out of the assessment reduced the vulnerability of *C. tulipa* from a rank of 12 (very high) to 9 (high) (Figure 6).

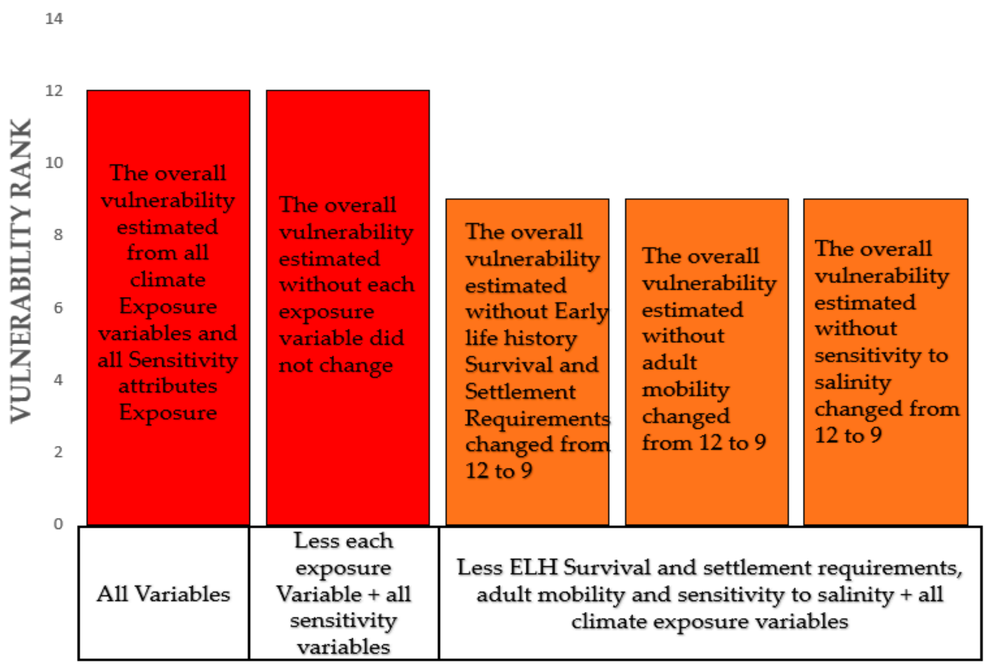

Figure 6. Importance of each factor's contribution to the overall vulnerability rank of *C. tulipa*. Red denotes very high vulnerability; orange denotes high vulnerability.

Potential for Distribution Change: A very low potential for distribution change corresponding to a score of 1 was calculated for *C. tulipa* using the weighted average scores obtained for the five sensitivity attributes (Figure 7). The sessile adult form of *C. tulipa* coupled with its high habitat specificity means it cannot move away from climate-induced changes in hydrographic conditions (temperature and salinity) of its habitat. While early larval stages are free-floating and planktonic, their ability to move in search of suitable environmental cues for settlement is at the mercy of the prevailing currents. This passive drifting does not allow the larvae to change direction away from unfavorable conditions in the environment. Depending on the direction of the current, the larvae may be pushed into fresh or marine conditions leading to delayed settlement and mortalities.

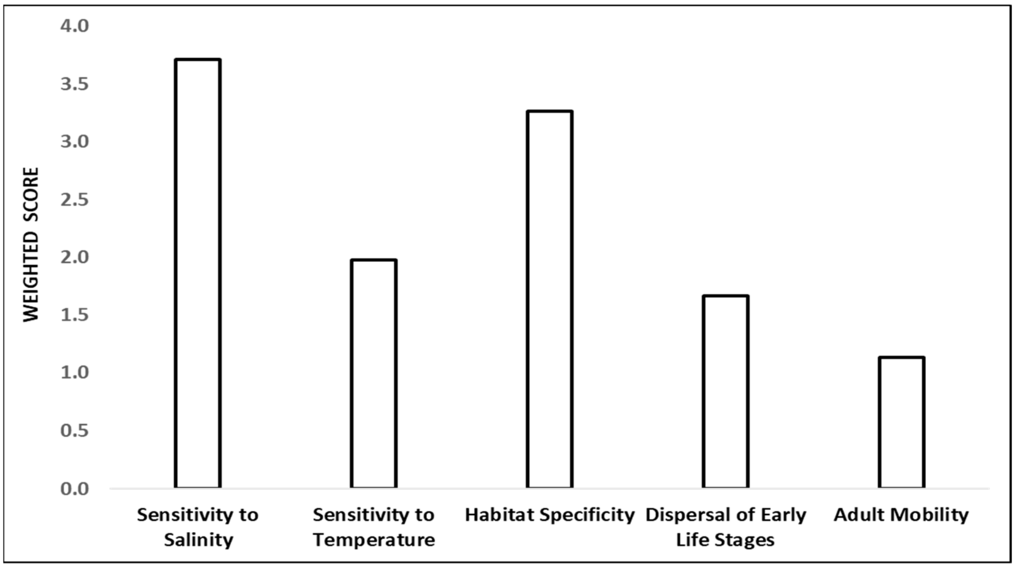

Figure 7. Average scores estimated for sensitivity attributes used in deriving potential for distribution of change of *C. tulipa*. Bootstrapped analysis of the scores indicates very high certainties in scores (>95%).

Directional Effect of Climate Change: From the analysis of the expert scores, a weighted mean score of −0.47 was obtained for the directional effect of climate change for both original and bootstrapped samples. This score implied that climate change would have a negative effect on the *C. tulipa* fisheries, and the population across the region is predicted to decrease in response to climate change. While such reductions in population have already been experienced in all *C. tulipa* countries, its causes have mostly been attributed to overharvesting, and management measures have focused on addressing overharvesting. Closed seasons have been enacted in countries such as Ghana, whereas in other countries, including Ghana, women oyster collectors are practicing low-scale wild culture to boost production. Meanwhile, a thorough understanding of prevailing conditions in the environments of oysters and long-term changes in these conditions is a prerequisite for determining suitable habitats and achieving desirable outcomes. Climate-smart oyster culture practices include the introduction of oyster hatchery systems to prioritize success in the initial stages of oyster development, as well as breeding lines of brood stock that can withstand climate-related risks.

5. Discussion

At the local, regional, and national levels, climate variability has been identified as the most significant problem in West Africa [58]. Particularly, the variability in rainfall is enormous, sometimes up to 40–80%, and increases with decreasing annual rainfall totals [58]. Although profiling of *C. tulipa* revealed its ability to thrive in exceptionally high salinities (hypersaline) in coastal areas of the East Atlantic coast of West and Central Africa, high variability in annual salinity from 0 to approximately 50‰ and heavy siltation following monsoonal rains may cause mortalities of these oysters [15,59]. This makes oyster fishery an unpredictable endeavor in the region of study. For example, in Ghana, high mortalities have been recorded in the Densu and Anyanui creeks where sporadic freshwater influx from the Densu and Volta rivers, respectively, create freshwater conditions. The unpredictable nature of the region's precipitation results in huge uncertainties that further complicate fisheries management. Despite the deleterious effects of low salinity on the species, adult *C. tulipa* could survive in freshwater for up to 10 days with the adductor muscles contracted and shell valves closed [37]. By interfering with the osmotic balance of oyster tissues, decreased salinities inhibit enzymatic activity in the heart of oysters [60]. Feeding stops at salinities below 3 ppt, and the production of healthy pseudo feet stops at approximately 5 ppt [60]. The settlement success of *C. tulipa* spat is very low below a salinity of 10 ppt, peaking at approximately 30 ppt, implying that at low salinities, spat settlement may be delayed, leading to heavy mortalities in the water column [37]. A relatively faster rate of growth of spat has been observed with an average length of 5.1 mm attained in two weeks after settlement during the dry season where salinities are high. The growth rate has been found to decrease as the salinity drops during the wet season [37].

Depending on the scenario, the temperature in most parts of Africa is projected to rise between 2.0 and 4.3 °C by 2081, compared to pre-industrial levels, with higher temperatures and more temperature extremes projected for the northern part of the Sahel. These rises in temperature present a threat to the *C. tulipa* fishery in the Region. Temperature controls the solubility of oxygen in water, which indirectly affects respiratory processes in oysters. The heart rate of oysters generally increases with increasing temperatures up to 32 °C, beyond which the heart rate begins to decline [60]. Typically, the valvular activity becomes abnormal (i.e., oysters may reduce pumping rates or close completely) beyond 30 °C. When exaggerated above 34 °C, Loosanoff [61] found that valves may remain completely closed 67% of the time at temperatures above 36 °C. Although valve closures provide protection from osmotic stress, it affects feeding and gas exchange, and long-term closure may lead to mortality, especially at high temperatures [62]. The combined effect of variability in salinity and increasing temperature may compromise key physiological processes of *C. tulipa* such as growth, fertilization, and larval yield, increasing its vulnerability. For example, high fertilization success (77% to 100%) of *C. tulipa* eggs has been observed at 25 °C to 30 °C and 30 ppt to 35 ppt, peaking at 25 °C and 35 ppt [16]. Beyond 30 °C at varying salinities, no fertilization of *C. tulipa* eggs has been achieved. High larval yields (86% to 100%) from fertilized eggs have also been observed at 25 °C to 30 °C and at 20 ppt to 30 ppt peaking at 30 °C and 20 ppt, with no larval yield beyond 30 °C at varying salinities [16].

Apart from climatic factors, the vulnerability assessment framework considers, to a lesser extent, other non-climatic stressors that have the potential to increase the vulnerability of the species. With regards to *C. tulipa*, there are other prevailing environmental stressors in its habitats whose impacts must be fully understood to build resilience and improve adaptation to climate change. Ocean acidification resulting from human emissions of carbon dioxide has already decreased and will further lower surface ocean pH in the coming decades. The consequent decrease in calcium carbonate saturation potentially threatens calcareous marine organisms [63]. The inability of the oysters to build shells or do so at an energetic cost due to ocean acidification has consequences for their growth and survival. Ocean acidification may be exacerbated by the intense seasonally upwelling that occurs along the Gulf of Guinea and the increasing flux of land-based nutrients into the region's coastal environment. Pollution stemming from human activities such as mining, textile production, farming, and industries is on the rise, putting the region's aquatic ecosystems at risk, which further increases their vulnerability to climate change [64–66]. Shifting environmental conditions such as changing currents, temperature, and salinity are known to be important triggers of oyster diseases. These shifting environmental conditions produce stress on oysters, thereby affecting their health and increasing their susceptibility to infectious pathogens [17,67,68]. Mangroves are among the few habitat types preferred by *C. tulipa* and may increase the adaptive capacities of these oysters, yet their abundance and distribution have declined significantly over the last few decades. Mangroves in the Region have been subjected to enormous pressures and threats over the last few decades. with great losses, for example over 20–30% of the mangroves in the region of *C. tulipa* [69]. The drastic decline in mangrove cover in combination with climate change, pollution, diseases, and ocean acidification presents significant threats to the *C. tulipa* fishery.

Research on the impacts of other non-climatic stressors such as diseases, pollution, mangrove degradation, and fishing pressure is relevant for managing the *C. tulipa* fishery effectively and sustainably. Future research efforts should also be directed toward assessing the stock size status and population growth rate of *C. tulipa* to provide an understanding of how these sensitivity attributes may be responding to climatic exposures.

6. Conclusions

A very high vulnerability index of 12 for *C. tulipa* places it among marine organisms that are highly vulnerable to climate change and climate variability. Temperature and salinity fluctuations driven by variabilities in precipitation, ocean acidification, and sea level rise are the most important exposure factors driving this very high vulnerability score. Early life history survival and settlement requirements, adult mobility, and sensitivity to salinity are the most important sensitivity attributes of *C. tulipa* that determine its vulnerability to climate change. The potential for *C. tulipa* to change its distribution in response to climate change was ranked very low. In combination with other non-climatic stressors such as pollution, disease outbreak, and mangrove degradation, *C. tulipa*'s adaptive capacity is compromised and its fishery could be threatened in a long-term adverse climate scenario. We recommend climate-smart adaptation practices that prioritize success in the initial stages of oyster development, as well as research into the potential of breeding lines of brood stock that can withstand climate-related risks. In addition, we recommend adaptation practices that reduce vulnerability related to non-climatic stressors such as mangrove conservation and nature-based bioremediation processes to mitigate pollution. Strong collaboration among scientists, industry, and managers is needed to attain long-term sustainability in this fishery. Future research should be directed towards developing models for predicting suitable habitats for *C. tulipa* aquaculture in the region so that adaptation planning for the sustainability of *C. tulipa* can be implemented.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fishes7040205/s1, Table S1: List of exposure factors, biological attributes, and non-climatic stressors used in assessing the vulnerability of *C. tulipa* to climate change (from [45]); Table S2: Scoring sheet for assessing the vulnerability of *C. tulipa* to climate change (from [45]); Table S3: Attributes, distribution change, and directional effect scores from the vulnerability assessment.

Author Contributions: Conceptualization, E.M.; methodology, E.M., S.S., A.K., E.O.C., E.E., Z.S., Y.Z., V.A., R.O.A., H.D.D. and R.M.; formal analysis, E.M.; investigation, E.M., S.S., A.K., E.O.C., E.E., Z.S., Y.Z., V.A., R.O.A., H.D.D. and R.M.; resources, E.M.; data curation, E.M.; writing—original draft preparation, E.M., E.E., V.A. and R.O.A.; writing—review and editing, E.M., S.S., A.K., E.O.C., E.E., Z.S., Y.Z., V.A., R.O.A., H.D.D. and R.M.; visualization, E.M. and E.O.C.; supervision, E.M. and R.M.; project administration, E.M.; funding acquisition, E.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by THE ROYAL SOCIETY through the Future Leaders African Research (FLAIR) grant number FLR\R1\201385.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are available as supplementary information as Supplementary Sheet S3.

Acknowledgments: The authors wish to thank the technical staff and research assistants at the Department of Marine and Fisheries Sciences of the University of Ghana who organized and facilitated the expert workshops.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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