HABITAT SUITABILITY MAPPING FOR DIFFERENT CULTURE SYSTEMS OF SEAWEED ALONG THE ENTIRE COASTAL AND MARINE TERRITORY OF BANGLADESH: GENERALIZED ADDITIVE MODELLING FOR SPATIAL PREDICTION

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Abstract

Seaweeds are shallow-water, photosynthetic marine macroalgae that have economic value in the food, cosmetics, pharmaceutical, and biofuel/bioplastics industries as well as play a significant ecological role in providing food and habitat for organisms. Although seaweed cultivation is well-advanced in many Asian nations, Bangladesh's seaweed sector is still in its infancy due to multi-dimensional technological, social, and environmental challenges, including a lack of a site suitability map along its entire coastal and marine territorial area. Therefore, we used the Generalized Additive Model (GAM) to develop habitat suitability mapping for different farming systems of seaweeds by using the in-situ production data and associated environmental factors of 180 culture plots of four species (*Gracilaria* sp., *Enteromorpha intestinalis*, *Ulva lactuca*, and *Hypnea musciformis*) at five culture sites. Besides in situ measurement data, satellite observations and model simulations were also used to gather the necessary data. The GAM analysis revealed that seven explanatory variables jointly explained 78%, 76%, and 79% of the variability in seaweed data from off-bottom long-line, off-bottom net, and floating long-line culture systems, respectively. The model also discovered that TSS is the primary driver for the off-bottom net culture systems and floating long-line system, while salinity is the major driver for the off-bottom long-line culture system. The predicted habitat suitability mapping displayed that the predicted suitable areas (50-100%) for floating long-line culture systems are significantly larger (1850 km^2) than off-bottom long-line and off-bottom net culture systems (380 km^2). The highly suitable areas (>75% probability) for off-bottom long-line and off-bottom net culture systems are restricted to only the southeast coast, more specifically for the sandy bottom areas of the Moheshkhali channel and surrounding areas. The floating long-line culture system is found to be the most suitable for seaweed farming along the entire coast (except Meghna and adjacent estuaries of the central region) of Bangladesh. Since Bangladesh is keen to increase the commercial cultivation of seaweed, this study may provide a crucial tool for achieving the blue economy goal by providing information on habitat suitability maps along the entire coastal and marine territory areas of the country.

Keywords: *Marine macroalgae; GAM model; Mariculture; Geo-spatial maps; Ecological drivers; Blue economy.*

CHAPTER I

INTRODUCTION

1.1 Background

Seaweeds, the ocean's most promising macroalgae for promoting global sustainability, are primarily multicellular, autotrophic creatures that can float freely or be fixed to rocks and are widely spread throughout coasts from tropical to arctic regions (Ferdouse et al., 2018; FAO, 2020). These plant-like organisms are classified into three groups based on their pigmentation (red, brown, and green), with a total number of species estimated at more than 12,000, of which 221 are currently thought to have commercial worth, including 145 species are used to make various foods and hydrocolloid production (agar-agar, carrageenan, and alginate) (Nayar and Bott, 2014; FAO, 2018). Seaweed farming is one of the fastest-growing industries in the world, producing 32.9 billion tones worth 11.8 billion USD annually and expected to reach 22.13 billion USD by 2024 (FAO, 2020). Globally, seaweed farming areas cover 48 million km22 across 132 countries, although 32 are active in aquaculture production (Froehlich et al. 2019). In these countries, diverse farming techniques for seaweed have been practiced, including line, net, floating raft, tank or pond culture, and other auxiliary or experimental methods. These methods are greatly chosen based on various factors such as cultivation facilities, productivity and availability of species, dimensional characteristics (size and depth), and ecological factors of an aquatic ecosystem (Titlyanov and Titlyanova, 2010). Line cultivation involves connecting seaweed propagules to ropes and arranging them in parallel at various depths, including off-bottom, submerged hanging, and floating lines. Net cultivation is similar but uses nets at a specific depth. Floating raft cultivation attaches seaweed to lines or nets using a floating rigid frame. Delicate species need tank or pond culture, either in tethered or free-floating conditions, while direct planting on the ocean floor, artificial substrate, and anchorless rafts are some modest or experimental methods of seaweed cultivation (Radulovich, et al., 2015).

The selection of a suitable site is critically essential for commercial-scale seaweed farming. However, determining site suitability is a complex system involving environmental factors of the culture area, biological requirements of culture species, and consideration of various human activities (Thomas et al., 2019; Sarker et al., 2021). The growth rate of seaweed is considerably influenced by several environmental parameters, including light, temperature, salinity, turbidity, and the availability of various nutrients (Murphy et al., 2017). There is a concept that seaweeds need shallow water near the surface (30 to 50 cm) that receives plenty of sunlight. Although the optimum temperature range is highly species-dependent, seaweed generally prefers low surface temperature (Werner et al., 2016; Thomas et al., 2019; Banik et al., 2023). Most seaweed species exhibit a preference for high salinity levels. Thus, identifying sites in brackish waters and estuaries that receive a substantial inflow of fresh water could impede their attainment of optimal growth levels (Thomas et al., 2019; Sarker et al., 2021). Both nutrients and heavy metals concentrations of the selected sites, which the algae absorb, are crucial considerations, mainly if the seaweed is meant for human consumption. In a selected site, the nutrient-providing capacity should match or surpass the absorption capacity of the cultivated seaweed. When selecting a suitable site, it is imperative to consider many other physical environmental factors, such as bottom composition (sandy, rocky, or clay), the seabed slope, tidal exposure, wave action, water currents, shelter from storms, and water depth (Westmeijer et al., 2019; De sousa et al., 2012) . A suitable site has been characterized by areas that are well protected from tidal waves and strong winds that come from the open seas or through monsoonal weather conditions. Wave-exposed areas are also not considered suitable for farming some seaweeds species due to the destructive effects of waves on the seaweed farm (De sousa et al., 2012). These factors play a crucial role in determining the growth of seaweed and selecting the types of culture systems and engineering design of the cultivation infrastructure.

Habitat suitability maps (HSMs) is spatial representation or model that integrates environmental parameters and species occurrence, abundance, or biomass data, to assess the relationship between species presence and ecological conditions (Elith et al., 2011). They can shed light on the ecological requirements of a species and the potential effects of environmental changes on their growth and production performances (Elith et al., 2011; Lyet et al., 2013; Rowden et al., 2017). The models have been utilized to guide the location of commercially important and endangered species, the creation of marine protected zones, and the prediction of the impact of warming temperatures on marine species (Jensen et al., 2005; Cheung et al., 2013; Derville et al., 2016). HSMs also have been used to predict the distribution of economically significant seaweed species, such as Sargassum, and to identify suitable habitats for seaweed cultivation (Li et al., 2015). Previously, a predictive model was developed to forecast appropriate culture sites of temperate seaweeds by considering a range of environmental conditions, including temperature, depth, salinity, turbidity, and nutrient concentrations (Westmeijer et al., 2019). The habitat distribution map of seaweed was also developed in the coastal waters of Australia using MAXENT and generalized linear and additive models considering climatic and non-climatic drivers (Martínez et al., 2018). In Japan, researchers used satellite data to create a map of seaweed habitats (Sagawa et al., 2012). Similarly, generalized linear models (GLMs) were used to investigate the relationship between environmental variables and the distribution of the target seaweed species (Martínez et al., 2012). Moreover, an Ecological Niche Model was also used to predict the spread of invasive seaweed species and identify high-risk regions for management and control (Marcelino and Verbruggen, 2015). The Generalized Additive Model (GAM) has also been used to predict suitable habitats for cultivating seaweed in the coastal area of Bangladesh (Sarker et al., 2021).

Bangladesh is a country with immense potential in the blue economy, which emphasizes the strategic and sustainable utilization of marine resources. The country has geographical sovereignty over 118,813 sq. km in the Bay of Bengal (MoFA. 2014b), providing ample opportunity to fully explore and harness its marine resources. These resources include fisheries, mariculture, and marine bio-resources, which can contribute to the food and nutrition security of millions of populations, increase exports, and generate employment opportunities for the growing population (Tora et. al., 2022). The country has identified 26 sectors as targets for its blue economy development, with a top priority given to marine living resources (Hossain et al., 2020; MoFA, 2014a). Among these resources, the establishment of mariculture is seen as a possible option for the sustainable expansion of the ocean-based economy in Bangladesh (Sarker et. al., 2018; Hussain et al., 2019). While land-based coastal aquaculture for tiger shrimp is prevalent in Bangladesh (Paul and Vogl, 2011), mariculture is still in its early stages due to multi-dimensional environmental, technological, and socio-economic constraints. However, despite these challenges, seaweed farming can be an immediate and good option for mariculture development as it offers the advantages of low technological and capital requirements and requires no feed and fertilizers to grow.

In Bangladesh, there are around 250 species of seaweed, 32 of which are abundant in coastal and marine habitats, and 14 of which (10 Rhodophyta and 4 Chlorophyta) are possibly cultivable (Sarker et al., 2019; Hossain et al., 2021; Chowdhury et al., 2022). Among these 14 species, four species (*Gracilaria* sp., *Enteromorpha intestinalis*, *Ulva lactuca*, and *Hypnea musciformis*) have adapted best to the brackish water along the southeast coastal areas and cultured mainly by using semi-floating off-bottom long-line and off-bottom net methods in the intertidal zones (Islam et al., 2017; Sarker et al., 2019; Hossain et al., 2021; Bokhtiar et al., 2022; Chowdhury et al., 2022). Recently, a floating long-line raft system using locally available and cheap resources has also been developed for expanding the seaweed culture system beyond the intertidal zones (Banik et al., 2023). The development of the new culture system has opened opportunities for both coastal communities and private sectors to expand their operations in the Bay of Bengal, specifically within the 10-meter depth contour. This region is renowned for its high productivity and plays a vital role in sustaining the livelihoods of fishers who rely on fishing as their primary source of income. However, the presence of additional resource users, such as seaweed growers, in these nearshore areas can potentially lead to conflicts. The lack of zoning can give rise to conflicts not only with fishers but also with various ocean users, including those involved in navigation, tourism, and other ecosystem services. To address these issues, a habitat suitability map may serve as a valuable tool for all ocean users, especially policymakers.

1.2 Justifications of the Study

Several studies have been conducted on experimental seaweed culture, indicating the site suitability based on the limited locations and without considering the roles of environmental variables (Islam et al., 2017; Sarker et al., 2019; Bokhtiar et al., 2022; Banik et al., 2023; Sobuj et al., 2023). Recently, GAM has been used to predict the potential habitats of seaweeds in Bangladesh, utilizing data on ecological conditions, seaweed occurrence (presence and absence data), and bathymetry (Sarker et al., 2021). However, none of these studies developed habitat suitability mapping for different culture systems (off-bottom long line, off-bottom net, and floating long-line) utilizing the large-scale *in-situ* production and associated ecological factors dataset.

Therefore, we used the GAM to develop habitat suitability mapping along the entire coastal and marine territorial areas of Bangladesh for different farming systems of seaweeds by using the *in-situ* production data of 180 culture plots of four species together with satellite observations and model simulations to gather other necessary data. Moreover, maximum accuracy was achieved by performing a multicollinearity test of predictor variables and using model penalties to select the best model during habitat suitability mapping.

1.3 Objectives of the Study

By taking apart the previously mentioned criteria the objectives of the study were,

1. To establish suitable sites for seaweed farming scientifically along the coastal waters of Bangladesh.
2. Providing mapping to assist the government of Bangladesh and relevant stakeholders in future planning and expansion of seaweeds farming.
3. To develop marine spatial planning of the government which is due to start soon for the implementation of various development initiatives along the coastal areas and accommodate the bio-blue economy in the major national policy plan.

CHAPTER II

REVIEW OF LITERATURE

2.1 Seaweeds and its Benefits in Environment

Seaweed is a plant-like organism linked to shallow coastal waters by a holdfast. Its growth requires sunlight and a substratum, but it lacks a root because its entire body is involved in nutrition absorption and photosynthesis. (Creed et al., 2019).Seaweeds are important to both the hydrosphere and lithosphere. It could act as a carbon sink, and then can be used as a fuel source for biofuels and other industrial processes (AftabUddin et al., 2021). Large quantities of dissolved inorganic nutrients such as nitrogen, phosphorus, and carbon are absorbed by seaweed (Islam et al., 2017). This contributes to the decrease of oceanic eutrophication (Hoq et al., 2016; Creed et al., 2019).

Seaweed contributes to "blue carbon" through carbon uptake in a global context (approximately 1,500 tons CO_2 km^2 $year^{-1}$) (Campbell et al., 2019). Globally, macroalgae might sequester approximately 173 TgC yr–1 (with a range of 61–268 TgC yr–1), according to a rough estimate (Krause-Jensen & Duarte, 2016).

In addition to the yield, the cultivation of seaweeds provides an environmental benefit through the seaweed's bioremediation potential, which can be used to offset the effect of up to 90 percent of nutrient discharge, hence reducing the danger of eutrophication (Westmeijer et al., 2019). Seaweed contributes significantly to primary production and provides refuge for a vast array of wildlife (Cotas et al., 2023). By generating lush meadows and forests, seaweeds serve as a nursery for a huge number of marine animals (e.g., fish, shellfish, sea urchins, and crabs), so contributing to the preservation of the natural environment and biodiversity. Seaweeds are part of food webs and provide ecosystem services such as homes, food, and shelter to a variety of linked creatures from different trophic levels (apex predators, fishes, and invertebrates) that are of conservation and commercial value (Cotas et al., 2023). Macroalgae are the leading primary producers in the coastal zone, with a net primary production (NPP) of 1,521 TgC yr–1 (range: 1,020–1,960 TgC yr–1) over an estimated area of 3,500,000 km^2 (Cotas et al., 2023; Duarte et al., 2013). The presence of seaweed can mitigate ocean acidification (Duarte et al., 2013) and reduce wave energy (Steneck et al., 2002). Therefore, seaweeds provide a buffer against erosion and refuge from hypoxia (Campbell et al., 2019).

Sea vegetables are rich in nutritional fiber, lipids, and proteins (Dawczynski et al., 2007; Fleurence et al., 2018). In addition, seaweeds include essential nutrients for the human diet, including vitamins (A, K, and B12), protective pigments, minerals, and trace elements. In addition, seaweeds are a fascinating source of bioactive compounds used in human and animal nutrition due to the quality of their proteins (Heo et al., 2005; Karube et al., 1990; MacArtain et al., 2007; Stengel et al., 2011). The cell membranes of seaweed are predominantly composed of polyunsaturated fatty acids (PUFAs), particularly omega-3 and omega-6.

Seaweed has anticancer, antiviral, antifungal, antidiabetic, antihypertensive, immunomodulatory, cytotoxic antibiotic, anticoagulant, anti-inflammatory, and antioxidant properties (Smit, 2004; Heo et al., 2005; Dhargalkar & Verlecar, 2009; Leandro et al., 2020; Mayer et al., 2021). Numerous varieties of seaweed contain powerful antioxidants, including phloro tannines, carotenoids, and sterols (Besednova et al., 2015). Seaweed is a potential source of neuroprotective compounds that may be useful in the treatment of Parkinson's and Alzheimer's disease (Barbosa et al., 2014; Pangestuti & Kim, 2011).

As sushi consumption increases in popularity, items are being shipped to Europe, North America, and Africa from Asia, which remains the largest consumer of edible seaweed (FAO, 2020). Seaweeds have a wide range of uses in various industries. They are used as human and animal feeds, soil conditioners, nutraceuticals, cosmetic components, and medications, as they contain bioactive compounds and photo protective factors (Cotas et al., 2023). The carbohydrate-rich biomass of seaweed can also be fermented to make alcohol (FAO, 2021) or exposed to methanogenic anaerobic digestion. Where biomass is generated for inexpensive commodities such as fuel, which aids in CO_2 abatement (Campbell et al., 2019).

2.2 Worldwide Seaweed Productions

The two main sources that contributed to the global production of seaweed are aquaculture and wild harvesting (FAO, 2021). In 1969, 2.2 million tonnes of seaweed were harvested from the wild and grown commercially. After 50 years, the amount of seaweed produced on farms has increased to 35.8 million tonnes, making about 97% of the total amount produced globally in 2019. The wild production, on the other hand, has remained constant at 1.1 million tonnes (FAO, 2021). The production of seaweed worldwide increased 1,000 fold between 1950 and 2019 (FAO, 2021) from 34.5 thousand tonnes to 34.7 million tonnes. Red seaweed output increased (from 1 million tonnes to 18.3 million tonnes) and brown seaweed production decreased (from 3.1 million tonnes to 16.4 million tonnes), while green seaweed production fell (from 31 000 tonnes to 17 000 tonnes) throughout that time. Five genera, including *Laminaria* (35.4%), *Eucheuma* (33.5%), *Gracilaria* (10.5%), *Porphyra* (8.6%), and *Undaria* (7.4%), accounted for more than 95% of the seaweed farmed globally in 2019 (FAO, 2021).

About 97% of the world's production comes from Asia, while wild collection predominates in the Americas and Europe. Just four countries—China, Indonesia, Korea, and Japan—accounted for all of Asia's production in 2019 (FAO, 2021). With a combined output of more than 30 million tonnes in 2019 and revenue from the export of seaweed and seaweed-based hydrocolloids of USD 578 million, China and Indonesia are by far the two nations that produce the most seaweed in Asia and the entire world (FAO, 2021).

2.3 Seaweed in Bangladesh

About 155 seaweed species are found in Cox's Bazar (Haque, 2013). The Shilkhali/Shamlapur coast, the Jaillapara, Shahparirdip area of Teknaf, the Nuniarchara, Nazirartek of the Bakkhali-Moheshkhali river estuary, the Moheshkhali Island, and the planted mangrove forest or Parabon region are all places in that area where seaweeds are particularly numerous (Haque, 2013). The two main species of seaweed beds are Hypnea musciformis and Enteromorpha intestinalis, and they can be found naturally in Cox's Bazar in the Nuniarchara to Nazirartek parts of the Bakkhali River and Moheshkhali Channel, as well as on Moheshkhali Island (Bhuyan and Islam, 2016).

St. Martin's Island, which is located in southeast bound of Bangladesh's, has water quality conditions that seem to be particularly favorable for seaweed abundance. Except for the north shore, all of St. Martin Island has rocky bottoms, which are essential for seaweed habitat (FAO/NACA, 1996). St. Martin's Island is home to approximately 140 seaweed species (Sarker et al., 2018). This island has four coasts (Western, Eastern, Southern, and Northern), with the northern coast being devoid of seaweeds. Along the southern beach, seaweeds such as *Sargassum coriifolium*, *Chaetomorpha moniligera*, *Gracilaria verrucosa*, *Colpomenia sinuosa*, and others can be found. Species such as *Sargassum coriifolium*, *Hypnea musciformis*, H. *pannosa*, *Hydroclathrus clathratus*, *Colpomenia sinuosa*, *Padina arborescens*, *Chaetomorpha moniligera*, and *Gracilaria verrucosa* are found on the eastern coast, while *Gracilaria textorii*, *Petalonia fascia*, *Dictyopteris divaricatum*, *Sargassum* are abundant in western coast (Sarker et al., 2018).

Seaweed cultivation along the Cox's Bazar coast has recently given seaweed mariculture in Bangladesh's Bay of Bengal a new dimension (Islam et al., 2017). A small number of researchers examined seaweed growing strategies along Bangladesh's south-eastern and south-western coasts utilizing materials that were easily accessible, like bamboo and rope (Siddiqui et al., 2019). Even However, there have only been a few trials on seaweed culture in Bangladesh, and those that have been done have all been focused on either locating viable places for seaweed culture or modifying culture methods to environmental conditions (Abdullah et al., 2020).

2.4 Environmental Factors and Seaweed

Different environmental factors influence the rate of photosynthesis, which in turn regulates seaweed growth and productivity (Radiarta et al., 2014). Each of the environmental parameters is interrelated and affected each other (Radiarta et al., 2014). To achieve the best outcomes, a synergy of all parameters is required to guarantee the growth of the seaweed at optimal conditions (Harrison and Hurd, 2001). Winter season provided the best environmental conditions for seaweed culture, resulting in good seaweed growth, whereas the wet season saw minimal seaweed production (Ali et al., 2017).

One of the key environmental factors that influence seaweed growth is temperature (Dawes, 1995). The temperature of the water affects the physiological functions of seaweeds, such as photosynthesis, respiration, metabolism, growth, and reproduction

(Dawes, 1981). According to Dawes (1981), the ideal temperature for the majority of the seaweed is between 22 and 30^{o}C. Another crucial environmental component, salinity controls the seaweed's osmoregulatory system and enables it to endure in a specific salinity range. 24-35 ppt of salinity is the ideal range for seaweed growth (WWF, 2014). According to Hoyle's (1975) research, the salinity tolerance of *Gracilaria* sp. ranges between 5 and 43 ppt.

The pH level of seawater is influenced by various factors, including biological processes such as photosynthesis and organism respiration, temperature, and the presence of ions in the water (Pescod, 1973). According to the World Wildlife Fund (WWF) in 2014, the optimal pH range for cultivating seaweed falls between 6 and 9. It's important to note that the amount of sunlight penetrating the water is determined by its turbidity, making water transparency a critical factor in the growth of seaweeds. Just like other plants, seaweeds rely on solar energy for photosynthesis (WWF, 2014).

In addition to pH and sunlight, the availability of various nutrients also plays a significant role in shaping seaweed biomass and productivity (Harrison and Hurd, 2001). Among these nutrients, nitrate stands out as a crucial chemical element for promoting seaweed growth (Brault and Queguiner, 1989). Organisms require dissolved inorganic nitrogen, including nitrate, for their development, metabolic processes, and reproduction. In aquatic environments, the availability of nitrogen nutrients can be a limiting factor for growth (Harrison and Hurd, 2001). A deficiency in nitrogen can lead to a decrease in the seaweed's ability to sustain its growth (Brault and Queguiner, 1989). Thus, it is evident that a complex interplay of factors, including pH, sunlight, and nutrient availability, influences the thriving of seaweed populations.

2.5 Worldwide Seaweed Culture

Worldwide production rates differ from place to place for different culture techniques. Inshore shallow water culture is the main method of seaweed culture but to meet the growing demand for seaweed products, the field of seaweed culture has extended to offshore deep-water culture that relies on floating rafts or long ropes to make culture rafts (Zhang et al., 2022). In Europe, seaweeds are cultivated in artificial structures in protected coastal areas where alterations in the structural design rely on the site's climatic conditions (Barbier et al., 2019). Between two types of at-sea system cultivation techniques, floating structures used mail for commercial culture. (Peteiro et al., 2012; 2013; 2016; 2018). Benthic culturing is not generally used in Europe, however it is utilized for a variety of species such as Nori (*Porphyra* spp.), Aonori (filamentous *Ulva* spp.), *Gracilaria* spp., *Eucheuma* spp., and *Kappaphycus* spp. outside of Europe. (Barbier et al., 2019). Ryther et al. (1979) and Bolton et al. (2009) discussed the land-based seaweed cultivation systems that are now present in South Africa (Five abalone farms with integrated *Ulva* production) and Canada (business Acadian SeaPlants cultivating *Chondrus crispus* - over 30 000 m2) (51). Additionally, the Portuguese company ALGAplus has also started growing *Ulva rigida*, *Codium tomentosum*, *Gracilaria gracilis*, *Porphyra dioica*, and P. *umbilicalis* in an organic certified land-based system that includes a fish farm (Barbier et al., 2019).

2.6 Seaweed Culture in Bangladesh

Seaweed cultivation has been gradually gaining momentum in Bangladesh due to an increased demand for raw seaweed and its derivatives. This growing interest is driven not only by the economic prospects of seaweed-based products but also by the need for fishing communities to explore alternative or supplemental sources of income. To ensure the success of these endeavors, it becomes crucial to determine the most effective culture systems and optimal locations for cultivating specific seaweed species. Several researchers have embarked on studies related to seaweed cultivation along the southeastern and southwestern coasts of Bangladesh (Islam et al., 2017; Khan et al., 2021). Their investigations have primarily focused on employing indigenous materials such as bamboo and rope in the cultivation methods (Hoq et al., 2016).

Noteworthy research efforts have been made by scholars like Islam et al. (2017), Sarker et al. (2018), Hossain et al. (2020), Bokhtiar et al. (2022), and Chowdhury et al. (2022). They have explored various aspects of seaweed cultivation in Bangladesh, shedding light on the most efficient techniques and materials. Among the locations earmarked for seaweed culture, the Cox’s Bazar coast, encompassing sites like St. Martin, Inani, and Bakkhali, has emerged as a focal point (Islam et al., 2017; Sarker et al., 2018). Specifically, studies have revealed that the semi-floating single-line culture system tends to outperform the semi-floating double-line system in terms of yield performance (Chowdhury et al., 2022).

One notable study by Sobuj et al. (2022) delved into the cultivation of *Gracilaria verrucosa* using the floating raft culture method in the intertidal zone of Chawfaldandi, Cox’s Bazar. This research reported satisfactory biomass production outcomes, emphasizing the potential of this method for seaweed cultivation (Sobuj et al., 2022). However, it's important to note that despite the advancements made in these studies, an integral component that is often missing is the consideration of environmental factors. While the methodologies and techniques have been investigated, the broader ecological context in which seaweed cultivation takes place remains an area requiring further exploration.

In conclusion, seaweed cultivation is gaining traction in Bangladesh due to economic prospects and the need for alternative income sources among fishing communities. Researchers have focused on regions like Cox’s Bazar coast, particularly sites such as St. Martin, Inani, and Bakkhali. Studies have indicated that certain cultivation systems, such as the semi-floating single-line approach, demonstrate superior yield performance. A study by Sobuj et al. (2022) demonstrated successful biomass production using the floating raft culture method for *Gracilaria verrucosa*. Despite these strides, it is evident that a comprehensive understanding of the ecological and environmental factors influencing seaweed cultivation is vital for its sustainable and successful implementation in Bangladesh.

2.7 Habitat Suitability Model

Habitat suitability models predict species distribution and inform conservation efforts and resource management based on environmental parameters. These models can shed light on the ecological requirements of species and the potential effects of environmental changes on their populations (Rowden et al. 2017). By using HSMs, Lyet et al. (2013) identified key habitats for endangered species and Elith et al. (2011) forecasted the effects of climate change. The models have been utilized to guide the location of commercially important and endangered species (Jensen et al. 2005 and Derville et al. 2016), the creation of marine protected zones, and the prediction of the impact of warming temperatures on marine species (Cheung et al., 2013). HSMs also have been used to predict the distribution of economically significant seaweed species, such as *Sargassum*, and to identify suitable habitats for seaweed cultivation (Kim et al., 2022). We decided to establish the habitat suitability map using the Generalized Additive Model (GAM). GAM can be used to select the optimal model for predicting the habitat of organisms by performing a multi-collinearity test of predictor variables and applying model penalties. Previously, a model was developed to predict where temperate macroalgae will grow given a range of environmental conditions (including temperature, salinity, turbidity, nutrients, and depth) (Westmeijer et al., 2019). The seaweed habitat distribution map off Australia's coast was developed using MAXENT and generalized linear and additive models to account for both climatic and non-climatic causes (Martínez et al., 2018). In Japan, researchers used satellite imagery to create a map of seaweed habitats (Sagawa et al., 2012). Martínez, B. et al utilized generalized linear models (GLMs) to investigate the relationship between environmental variables and the distribution of the target seaweed species (Martínez et al., 2012). Marcelino and Verbruggen used an Ecological Niche Model to predict the spread of invasive seaweed species and identify high-risk regions for management and control (Marcelino & Verbruggen, 2015). Sarker et al. have established a seaweed habitat suitability map for the entire coast of Bangladesh. However, none of these studies have specifically focused on suitable culture systems for seaweed. We used the Generalized Additive Model to find non-linear and complex relationships between the dependent variable and independent variables through smooth functions. It will provide a clear understanding of which culture method can be most productive in any part of the entire coast of Bangladesh while considering the drivers of the aquatic system.

CHAPTER III

METHODS AND MATERIALS

3.1 Study Area

The large Bangladesh's maritime territory, which spans 118,813 square kilometers and is located in the north-eastern part of the Bay of Bengal, is characterized by a wide range of biodiversity (MoFA, 2014b; Hossain et al., 2007). The country of Bangladesh has a coastline that is 710 km long, spans 47,201 sq km of land, or nearly one-third of its entire area, and directly or indirectly provides for the livelihood of 29% of the people (Sarkar et al., 2018; Ahmed, 2019). According to Ali (1999), Bangladesh's coastline and maritime territories can be broadly classified into the southeast, centre, and southwest zones. The southwest coastal zone of Bangladesh is a semi-active deltaic area with numerous channels and creeks, while the southeast coast of Bangladesh is distinguished by muddy flats and sandy beaches. The central coast of Bangladesh also has an estuary that is connected to the Ganges-Brahmaputra-Meghna River basins. (Ali, 1999; Anisul et al., 2016). Seaweeds are more or less present in various coastal zones depending on the environmental factors and nutrients, but the southeast zone is vital. Although the current study covers all of Bangladesh's marine territory, in-situ production data were obtained from September to April between the years 2020-2023 of three consecutive seaweeds culture method in five prospective sites (Moheshkhali, Khuruskul, Shahporir dwip, Sonapara, and Nuniachora) located at the southeast zone (Figure 1).

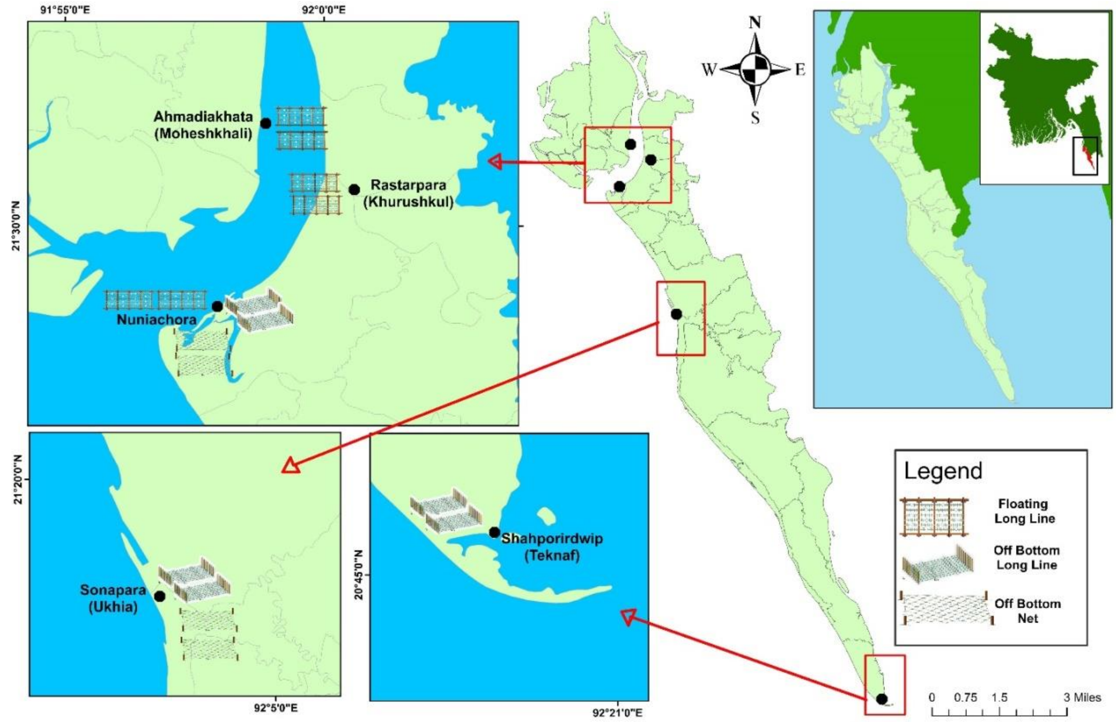

Figure 1: Map of the study area with different culture systems of seaweeds in different locations at the southeast coast of the Bay of Bengal, Bangladesh. The off-bottom long-line and off-bottom net culture systems were installed in the intertidal zone, and raft-based floating long-line systems were installed in the sub-tidal area.

According to geographical location, these areas lie near the shoreline with or without natural seaweed beds but no coral reef and seagrass vegetation. Together with muddy flats and sandy beaches like suitable substrates, these areas are appropriate for commercial seaweed production due to supporting water quality standards ((Islam et al., 2017; Sarker et al., 2018; Bokhtiar et al., 2022; Banik et al., 2023; Siddiqui et al., 2019; Hossain et al., 2020). Sometimes, a smaller natural abundance of Gracilaria, Ulva, Hypnea, and Enteromorpha are also found in these culture sites.

3.2 Design and Construction of Different Seaweed Cultivation Systems

The present research used in situ production data of gross wet biomass (kg/m^2/month) of three distinct culture systems (off-bottom long line, off-bottom net, and floating long line). For this purpose, 55 floating long-line, 70 off-bottom long line, and 55 off-bottom net culture plots (total-180 culture plots) were established (Table 1).

Table 1: The seaweed species with their culture seasons and farming systems in different locations of the southeast coast of the Bay of Bengal, Bangladesh. The field

dataset of gross wet biomass (kg/m^2/month) and ecological parameters from these seaweed species under different culture systems are used as in-situ data for this study.

Location	Geographic coordinates	Culture species	Culture systems	No culture units	Culture season
Nuniachora	21.47405556 91.96566667	*Gracilaria* sp.	Floating long-line	10	Oct-Apr
		Gracilaria sp.	Off-bottom long-line	25	Oct-Mar
		Gracilaria sp.	Off-bottom net	20	Oct-Mar
		Hypnea musciformis	Off-bottom long-line	5	Oct-Apr
		Hypnea musciformis	Off-bottom net	5	Oct-Apr
		Enteromorpha sp.	Off-bottom long-line	8	Oct-Mar
		Enteromorpha sp.	Off-bottom net	10	Oct-Mar
		Ulva lactuca	Off-bottom long-line	8	Oct-Apr
		Ulva lactuca	Off-bottom net	6	Oct-Apr
Rastarpara, Khurushkul	21.51166667 92.00972222	*Gracilaria* sp.	Floating long-line	18	Oct-Mar
		Ulva lactuca	Floating long-line	2	Nov-Mar
Sonapara, Ukhia	21.29528 92.045603	*Gracilaria* sp.	Off-bottom long-line	8	Oct-Mar
		Gracilaria sp.	Off-bottom net	10	Oct-Mar
		Ulva lactuca	Off-bottom long-line	6	Nov-Apr
		Ulva lactuca	Off-bottom net	4	Nov-Apr

Ahmadiakhata Moheshkhali	21.533007 91.98126	*Gracilaria* sp.	Floating long-line	25	Oct-Mar
Shahporirdwip Teknaf	20.75575 92.333329	*Gracilaria* sp.	Off-bottom long-line	10	Oct-Mar

Among these three culture systems, off-bottom long line and off-bottom net culture plots remained submerged under water exclusively during high tide and lie on the exposed sand flat during low tide. Therefore, these two systems are often termed as semi-floating systems. On the other hand, the floating long-line culture system remained submerged continually in water, regardless of the tide level.

In Figure 2, the layout and general overview of each of these three systems are shown. Ten bamboo poles were dug in the sandy bottom mud in a parallel series, 50 cm apart between each pole, to construct and install an off-bottom long-line cultivation plot. On the other side, at a distance of 14 meters, 10 additional bamboo poles were placed and bored in the same manner. Thus, a single off-bottom long-line culture plot was 70 m^2 (14 m 5 m) in size (Figure 2A-C). To keep floating in the water during high tide, three plastic floats were affixed to the polypropylene rope that connected each opposing bamboo pole. A nylon rope-made (1.8 m 3.5 m) net with a mesh size of 15 cm was used to set up an off-bottom net culture plot (Figure 2D-E). The bamboo poles that were placed were used to secure the netting on all four sides. To keep the net afloat in the water during high tide, three plastic floats were fastened to its core parts. Two horizontal bamboo poles measuring 10 m in length were firmly coupled with five vertical bamboo poles measuring 3 m each to create a raft with a 30 m^2 (10 m 3 m) size frame for a floating long-line culture plot (Figure 2F-H). To keep the building afloat at all times in the water, ten recycled plastic drums were affixed to the foundation. Six parallel long-line ropes, each with two plastic floats attached, were installed on a single plot.

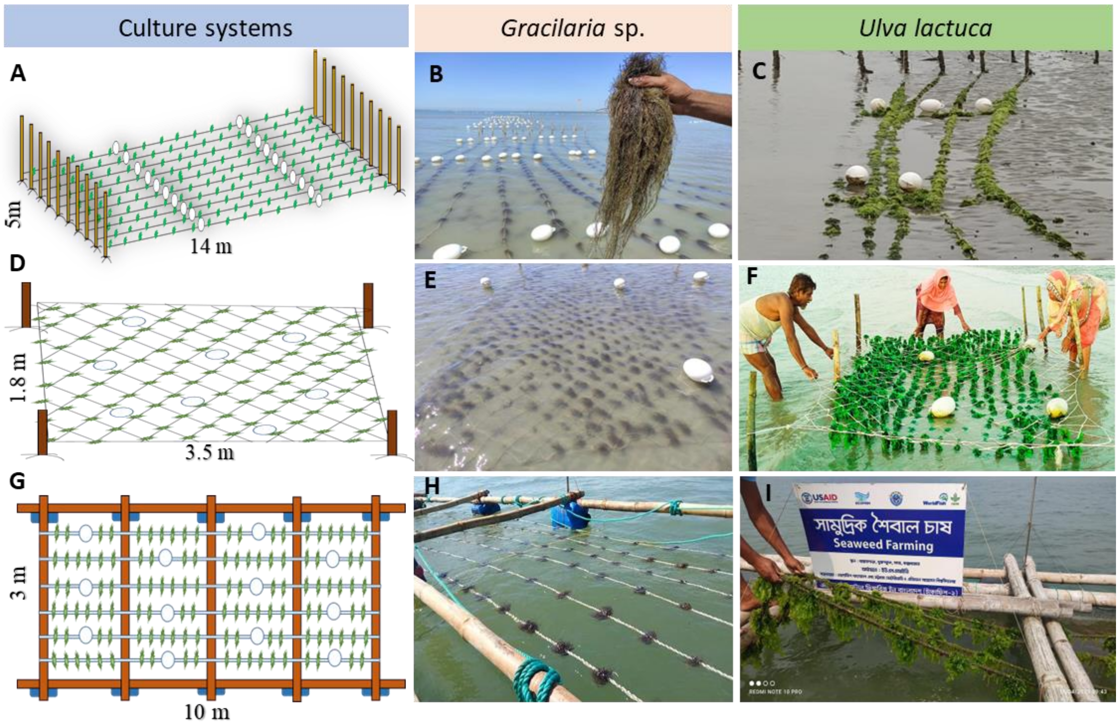

Figure 2: The diagrammatic view of different culture systems of seaweed in the southeast coast of the Bay of Bengal. The field data from three culture systems, namely off-bottom long-line (A-C), off-bottom net (D-F), and floating long-line (G-I) were used for this study. The off-bottom long-line and off-bottom net culture systems were installed in the intertidal zone and raft-based floating long-line systems were installed in the sub-tidal area.

A total of four seaweed species, namely *Gracilaria* sp., *Ulva lactuca*, *Hypnea musciformis*, and *Enteromorpha intestinalis* were cultured in these culture systems. For this study, 126 culture plots were used for *Gracilaria* sp., 10 for *Hypnea musciformis*, 18 for *Enteromorpha intestinalis*, and 26 culture plots were used for *Ulva lactuca*. After establishing the culture plots, young growing fragments of these seaweed was collected from the wild source and inoculated in between October to November depending on the culture species and locations (Table 1). For long-line systems, vegetative fragments of thalli (as the seed) were attached in the hole formed by untwisting and tugging the rope. Each rope in the long-line system was inoculated with 34 seed propagules, each weighing approximately 6 g. Similarly, seed propagules (approximately 5-6 g) were inoculated in each knot-joint for off-bottom net cultivation. The cultivation of seaweed in these systems was carried out without the application of any fertilizers, insecticides, or pesticides. All these culture plots were managed in a participatory farming approach through involving vulnerable coastal fishing communities with providing sufficient training and input-assistance as a means of alternative livelihoods approach.

3.3 Data Collection and Processing

The growth rate and production performances of seaweeds are greatly affected by various water quality parameters (Islam et al., 2019; Banik et al., 2023). Therefore, water quality parameters including temperature, salinity, pH, turbidity, nitrate, nitrite, ammonia, phosphate and total suspended solids were selected as explanatory variables considering their role in controlling the dynamics of seaweed growth and production performances (Schoellhamer, 1995; Choi et al., 2007; Roleda and Hurd, 2019; Sarker et al., 2021). These required data were obtained and compiled from the in-situ measurements, model simulations and satellite observations. Details of data collection are given in Table 2.

Table 2: Details of data used for seaweed habitat modelling in this study

Variable	**Unit**	**Abbreviation**	**Source**	**Reference**
Gross wet biomass	kg/m^2	-	*In Situ*	This study
Temperature	°C	SST	*In Situ* & satellite	This study, sentinel 3 satellite (https://www.eumetsat.int/)
Salinity	PPT	-	*In Situ* & Model simulation	This study Hossain et al. (2022)
pH	total scale	-	*In Situ* & Satellite	This study Hossain et al. (2022)
Turbidity	NTU	-	*In Situ* & Satellite	This study, sentinel 3 satellite (https://www.eumetsat.int/)
Nitrate	mg/L	NO_3	*In Situ* & Model simulation	This study Thushara et al. (2019)
Nitrite	mg/L	NO_2	*In Situ* & Model simulation	This study Thushara et al. (2019)
Ammonia	mg/L	NH_3	*In Situ* & Model simulation	This study Thushara et al. (2019)
Phosphate	mg/L	PO_4	*In Situ* & Model simulation	This study Thushara et al. (2019)
Total Suspended Solid	mg/L	TSS	*In Situ* & Satellite	This study, sentinel 3 satellite (https://www.eumetsat.int/

3.3.1 In-situ data

Throughout the study period, various water quality parameters of each seaweed culture plot in each culture site were monitored and recorded on a monthly basis. Physical parameters, including water temperature (measured with a Celsius thermometer), pH (measured using a digital pH meter, EcoSence pH10A by YSI), dissolved oxygen (measured with a digital dissolved oxygen meter, PDO-519 by Lutron), salinity (measured using a Bellinghram and Stanley E-Line refractometer by Xylen), and turbidity (measured using a digital turbidity meter, Turb430 IR by WTW) were measured on the spot from each cult-ure system. Total suspended solids (TSS) of water samples were measured using the method of APHA (American Public Health Association), (2005) by filtering 200 ml seawater with a vacuum pump using Whatman filter paper. Water samples were collected from each culture plot separately for the analysis of chemical parameters (PO4-P, NO_3-N, NO_2-N, and NH3-N). Chemical parameters were analyzed using the portable photometer (pHotoFlex STD by WTW).

Figure 3: The photographic view of different seaweeds cultured by different farming systems with participatory farming approaches involving coastal communities along the southeast coast of the Bay of Bengal, Bangladesh. (A) Off-bottom long-line system of *Gracilaria* sp., (B) Off-bottom net system of *Gracilaria* sp., (C) Floating long-line system of *Gracilaria* sp., (D) Off-bottom long-line system of *Ulva lactuca*, (E) Floating long-line system of *Ulva lactuca*, (F) Off-bottom net culture system of *Ulva lactuca*, (G) Off-bottom net culture system of *Enteromorpha intentinalis*.; (F) Off-bottom long-line culture system of *Enteromorpha intentinalis*.

Besides water quality data, gross wet biomass data (kg/m^2/month) of each culture plot of each seaweed species were recorded on monthly basis throughout the study period. The photographic view of nearly harvesting size of different seaweed species in different culture systems is given in Figure 3. To calculate the gross weight biomass, partial harvesting was carried out when farmed seaweed reached a length of 30 to 40 cm in every 15 days intervals during the peak seasons (November to February) and every 30 days intervals during the off-peak seasons (September to October and March to May). Using a knife, partial harvesting was carried out, leaving around 6 cm from the base for future growth. Each plot's freshly produced seaweed species was weighed on a digital scale (WPCS-DS758X, Walton, Bangladesh). The biomass yielded (kg/m^2/month) of each culture plot was calculated monthly after harvesting using the formula, Biomass (kg/m^2/month) = (Wt -W0)/A; where, W0 = Initial weight at the beginning, Wt = Weight at the end of the month (t), A = Area of a culture plot (m2).

3.3.2 Spatial data for the entire EEZ of Bangladesh

Spatial data on temperature, turbidity and total suspended solids for entire exclusive economic zone (EEZ) of Bangladesh was collected from the sentinel 3 satellite (https://www.eumetsat.int/). However, salinity, pH, and nutrients data are not available from the satellite sources. In addition, in-situ data of these variables for the entire EEZ of Bangladesh is not available (Sarker et al., 2021). Thus, we relied on modeled data for these variables. Nitrate, nitrite, ammonia and phosphate data were obtained from Thushara et al. (2019). Salinity and pH data were obtained from the model simulations of Hossain et al. (2020). Spatial data of these variables for the entire EEZ of Bangladesh were compiled as raster data format.

3.4 Modelling Approach

In this study, a Generalized Additive Model (GAM) was used to develop suitable habitat maps for different seaweed culture systems in the EEZ of Bangladesh. The GAM is a flexible and effective method for conducting non-linear regression analysis (Dominici et al., 2002). In addition, GAM allows the adjustments for the nonlinear effects of seasonality in data (Schwartz, 2000). Currently GAM is widely used in environmental science research and facilitates the assessment of the non-linear relation among the covariates (Barton et al., 2020). In habitat modelling of biological organisms, GAM allows the modelling of complex and nonlinear relationship between environmental conditions and habitat. The specialty of GAM in habitat modelling is to use of smooth function to capture the nonlinear relationship between habitat and environmental conditions, which may not be captured in a linear regression model (Drexler and Ainsworth, 2013). GAM is widely used for habitat prediction of biological communities i.e. spatial prediction of species abundance (Drexler and Ainsworth, 2013), suitable habitat prediction of seaweed (Sarker et al., 2021) and fish (Jiang et al., 2022), spatial distribution modelling of kelp biomass (van Son et al., 2020) and conservation area delineation (González-Andrés et al., 2021).

In this study, we used GAM to predict the suitable area for different seaweed farming techniques (i.e., floating long-line, off bottom long-line and off bottom net) along the coastal and marine territory of Bangladesh. These spatial predictions were performed in two steps. In first step, in-situ seaweed biomass data and environmental data from each of the culture systems (described in section 2.3.1) were fitted to GAMs. To do that, in-situ seaweed biomass data were considered as response variable and environmental data were considered as explanatory variables for the GAMs. At the first stage of data fitting, we tested the multi-collinearity among the explanatory variables using Variance Inflation Factor (VAF). In the regression model, multicollinearity causes when at least two of the explanatory variables shows high correlation (Vatcheva et al., 2016). A regression model with multicollinearity may result in a misleading interpretation of the system (Graham, 2003). An explanatory variable with VIF value greater than 3 indicating potential collinearity (Sarker, 2018). Thus, any variable with VIF > 3 was removed for further analysis. Along with VIF, we also tested the correlation among the explanatory variables. At the second stage of data fitting, with the explanatory variables which have no multicollinearity, we performed GAM. In the multivariate regression modelling approach, addition of high number of explanatory variables in the model causes the increase of R2 value. However, sometime addition of irrelevant explanatory variables may also increase the value of explained variance. To deal with this problem, we used Akaike Information Criterion (AIC) (Akaike, 1974). AIC is used to understand the relative information of the model using the maximum likelihood estimate method. A GAM with n number of explanatory variables will have 2^n-1 number of models (Akaike, 1974). The AIC suggests that the best model should have the lowest AIC penalty. Thus, we selected the GAMs with the lowest penalties for each culture system.

Let N_(i,t) is the seaweed biomass at time t and culture system i, and X_(i,t,j) is the value of j explanatory variable at time t and culture system i. Thus, the GAM is:

$$N_{i,t} = \alpha + \sum_{j=1}^{n} f_j\left(X_{i,t,j}\right) + \epsilon \qquad (1)$$

Where, α is the intercept, f_j is the smoothing function for the j explanatory variable, n is the total number of explanatory variables and ϵ is the unexplained variation.

All data were fitted to equation (1) in statistical software R (R Core Team, 2021) by using MGCV library. At the second step the relationship between seaweed and environmental conditions found in GAMs were then applied as predictive mode to the spatial data set of explanatory variables (as described in section 2.3.2) to develop suitable habitat maps of different culture systems of seaweed.

3.5 Model Evaluation and Validation

The area under the receiver operating characteristic curve (AUC) was calculated using the receiver operating characteristic (ROC) curve in order to comprehend the prediction error (Elith et al., 2006). To comprehend the error in prediction, Fielding and Bell (1997) also used the odds ratio (ratio of correctly assigned cases to incorrectly assigned cases), positive predictive power percentage of predicted absences that were real (PPP), negative predictive power percentage of predicted absences that were real (NPP; assess the probability that a case was not correctly predicted), and Cohen's kappa. The model was also validated by comparing *in-situ* data with the modeled data. For this, we separated 50 data points of seaweed. After modelling, modeled data for these points were compared with their *in-situ* data.

3.6 Implications of Habitat Suitability Mapping

Considering the increased pressure and competition for use of coastal areas for various purposes, a spatial mapping on habitat suitability for mariculture of seaweed is a useful tool the policymakers. This map can aid in the creation of a comprehensive ocean space strategy as well as the building of relevant regulatory frameworks and institutional arrangements for all ocean users. Therefore, key informants’ discussions were conducted with seaweed farmers, industry owners, policy makers, researchers and seafood exporters to better understand the implications of habitat suitability mapping for achieving the blue economy goal of Bangladesh.

CHAPTER IV

RESULTS

4.1 Seaweed Farming Approaches in Different Culture Systems

Seaweed aquaculture in Bangladesh is mainly confined in the southeast coastal zone, particularly in some areas of Cox's Bazar regions. Local farmers have been practicing off-bottom long line and off-bottom net culture techniques of seaweed in the sheltered intertidal zones of Cox's Bazar coastal areas with the technical and financial assistance from different NGOs and research organizations. According to the opinions of seaweed farmers, most of the sheltered intertidal coastal zones are characterized with muddy bottom, which is a major impediment for expanding off-bottom-based seaweed farming in Bangladesh.

Figure 4: Photographic views of on-going different seaweed farming activities by the coastal communities located at the southeast coastal area of Bangladesh. The participated farmers were involved in seaweed harvesting (A), washing (B),

distribution and sharing (C), drying (D-E), and packaging after sun drying.

To address these challenges, we recently developed the floating long-line raft system using locally available and cheap resources for culturing seaweed beyond intertidal zones (Banik et al., 2023). In this study, intensive technical training and input assistance were provided to the participated 400 fishermen for seaweed farming (Supp. Figure 1). They were involved in seaweed farming (Figure 3), harvesting, washing, drying, packaging and selling to generate additional income for improving their livelihood (Figure 4). Four species, namely *Enteromorpha intestinalis*, *Gracilaria* sp., *Hypnea musciformis*, and *Ulva lactuca* were adapted well in the coastal areas of Bangladesh. The seaweed culture season of these four species varied from 5-7 months depending on the effects of the southeast monsoon (Table 1). Among these four seaweed species, monthly gross wet biomass was higher for *Enteromorpha intestinalis* (0.5 to 4.2 kg/m^2/month), intermediate for *Gracilaria* sp. (0.5 to 2.1 kg/m^2/month) and *Hypnea musciformis* (0.8 to 1.9 kg/m^2/month), and the lowest for *Ulva lactuca* (0.4 to 1.4 kg/m^2/month) (Figure 5A). For all the seaweed species, the higher gross wet biomass was recorded during the month of December to February (Figure 5A). Among all, 55 culture plots were used for floating long-line, 70 were for off-bottom long line, and 55 were used for off-bottom net culture system for seaweed farming. The obtained monthly gross wet biomass data were used to calculate the influence of culture system on the production performance of seaweed (Figure 5B). The visual observation showed that harvested seaweed species from floating culture is very clean, mostly free from encrusted organisms, mud and bottom sediments, and with attractive natural coloration compared to the others two culture systems. Among the three culture systems, the monthly gross wet biomass production was found to be significantly higher in the floating long-line system (0.85 to 2.65 kg/m^2/month), followed by the off-bottom net system (0.82 to 2.14 kg/m^2/month), and the lowest was recorded from the off-bottom long-line system (0.42 to 1.652 kg/m^2/month) (Figure 5B).

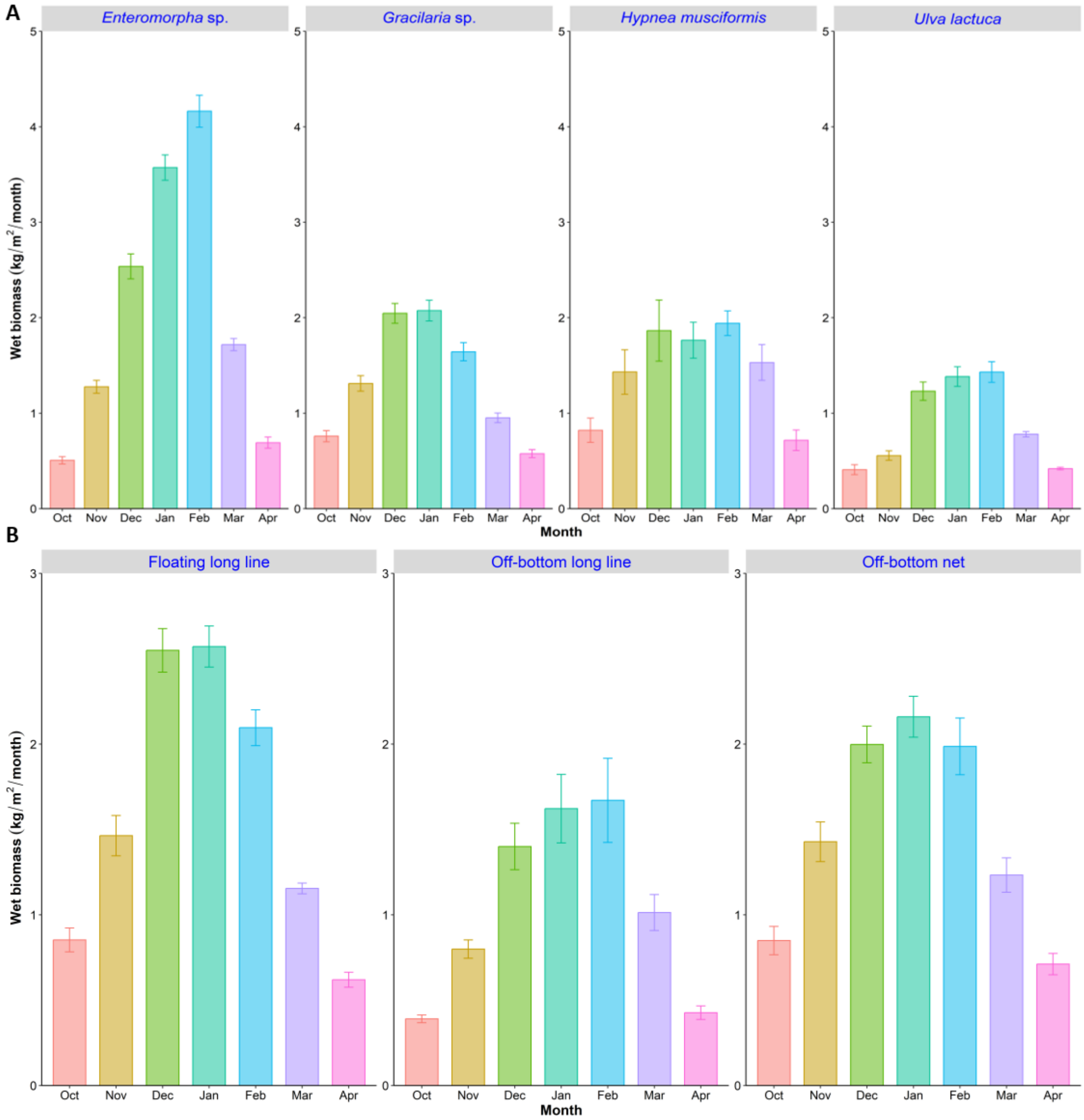

Figure 5: Monthly variation of production performance of different seaweed species and different farming systems at the southeast coast of the Bay of Bengal, Bangladesh. (A) Variation of gross wet biomass (kg/m2/month) of four different seaweed species; and (B) Variation of gross wet biomass (kg/m^2/month) of three different farming systems.

4.2 Multicollinearity Test and Model Selection

A correlation analysis was performed to understand the multicollinearity among the 9 explanatory variables (temperature, turbidity, salinity, pH, nitrate, nitrite, phosphate, ammonia and TSS) considered for this study (Figure 6).

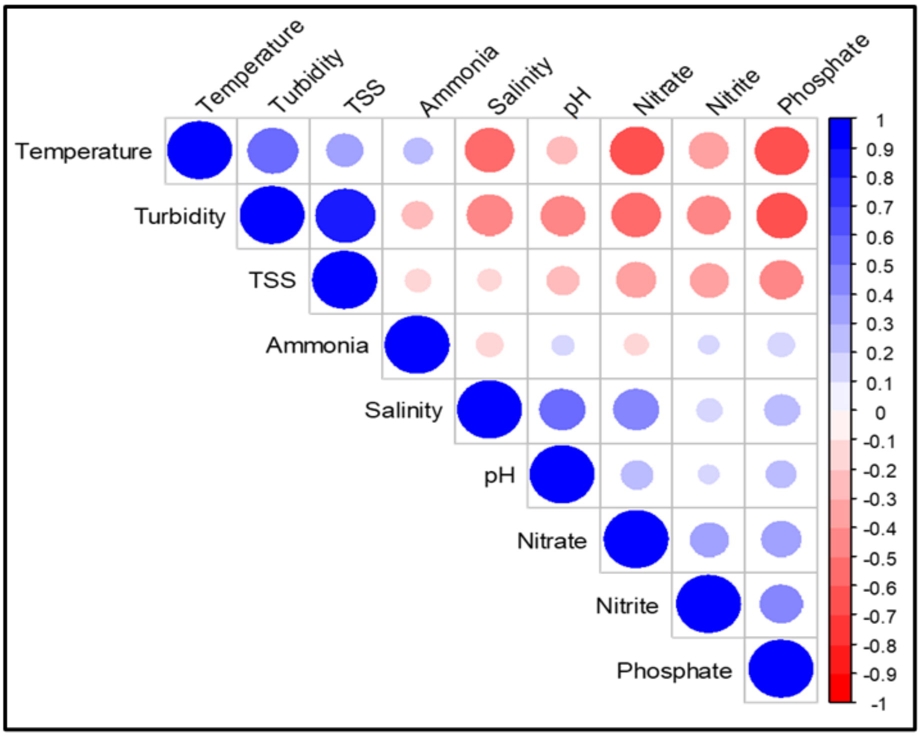

Figure 6: A Pearson correlation matrix illustrates the interdependence of nine explanatory variables. Correlation coefficient values may be negative (-1) or positive (+1). If the correlation value is less than zero, it is weak; if it is larger than zero, it is strong. TSS is an acronym for Total Suspended Solids.

The multicollinearity test found that surface temperature and turbidity have VIF values of greater than 3. In addition, both variables showed strong correlation with other variables. Thus, temperature and turbidity were removed from further analysis to estimate their contributions in habitat suitability mapping for seaweeds. About 127 models were developed using these 7 explanatory variables and the AIC values for each of these models were estimated. Our analysis found that GAM with 7 explanatory variables had the lowest AIC penalty. Thus, we used these 7 explanatory variables (i.e., salinity, pH, nitrate, nitrite, phosphate, ammonia and TSS) in GAM modelling for spatial prediction of suitable area mapping of different seaweed culture systems.

4.3 Drivers of Seaweed Dynamics

The GAM analysis found that 7 explanatory variables jointly explained 78%, 76% and 79% variability in seaweed data from off-bottom long-line, off-bottom net, and floating long-line culture systems, respectively (Figure 7).

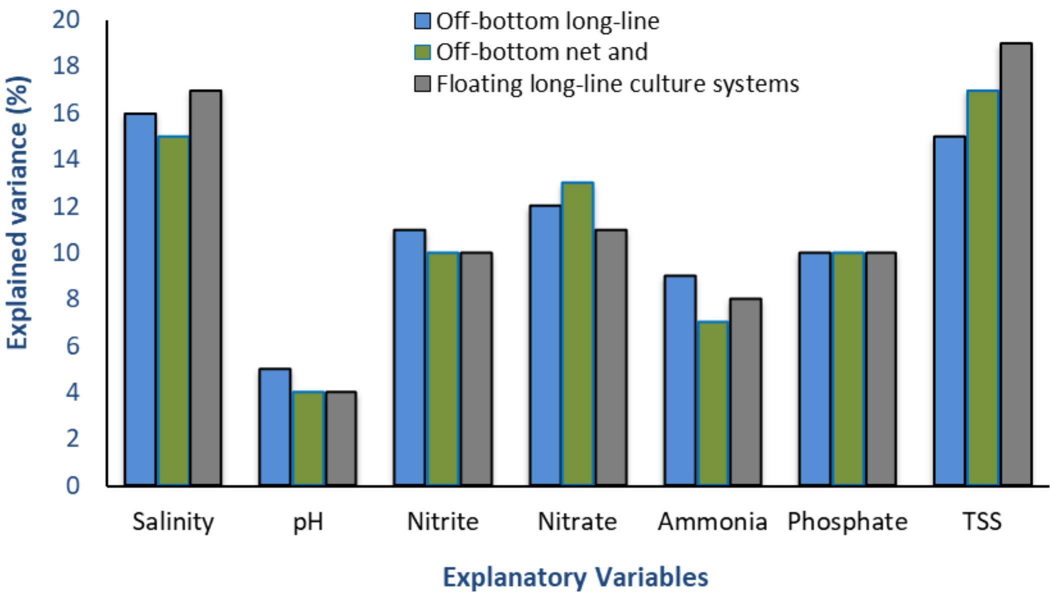

Figure 7: Role of different explanatory variables in explaining seaweed dynamics used in Generalized Additive Model (GAM) for spatial prediction of different farming system in the coastal and marine territory of Bangladesh. Here, TSS is an acronym for Total Suspended Solids.

This suggests that our model is a good predictor to explain the seaweed dynamics. In off-bottom long-line culture system, salinity was found as the major driver (explained 16% variability, $p<0.01$) followed by TSS (15%, $p<0.01$), nitrate (12%, $p<0.01$), nitrite (11%, $p<0.01$), phosphate (10%, $p<0.01$), ammonia (9%, $p<0.01$), and pH (5%, $p<0.01$). TSS was found as the major driver for off-bottom net method (17%, $p<0.01$) followed by salinity (15%, $p<0.01$), nitrate (13%, $p<0.01$), nitrite (10%, $p<0.01$), phosphate (10%, $p<0.01$), ammonia (7%, $p<0.01$) and pH (4%, $p<0.01$). TSS was also found as the major driver of seaweed production in (19%, $p<0.01$) floating long-line culture system followed by salinity (17%, $p<0.01$), nitrate (11%, $p<0.01$), nitrite (10%, $p<0.01$), phosphate (10%, $p<0.01$), ammonia (8%, $p<0.01$) and pH (4%, $p<0.01$).

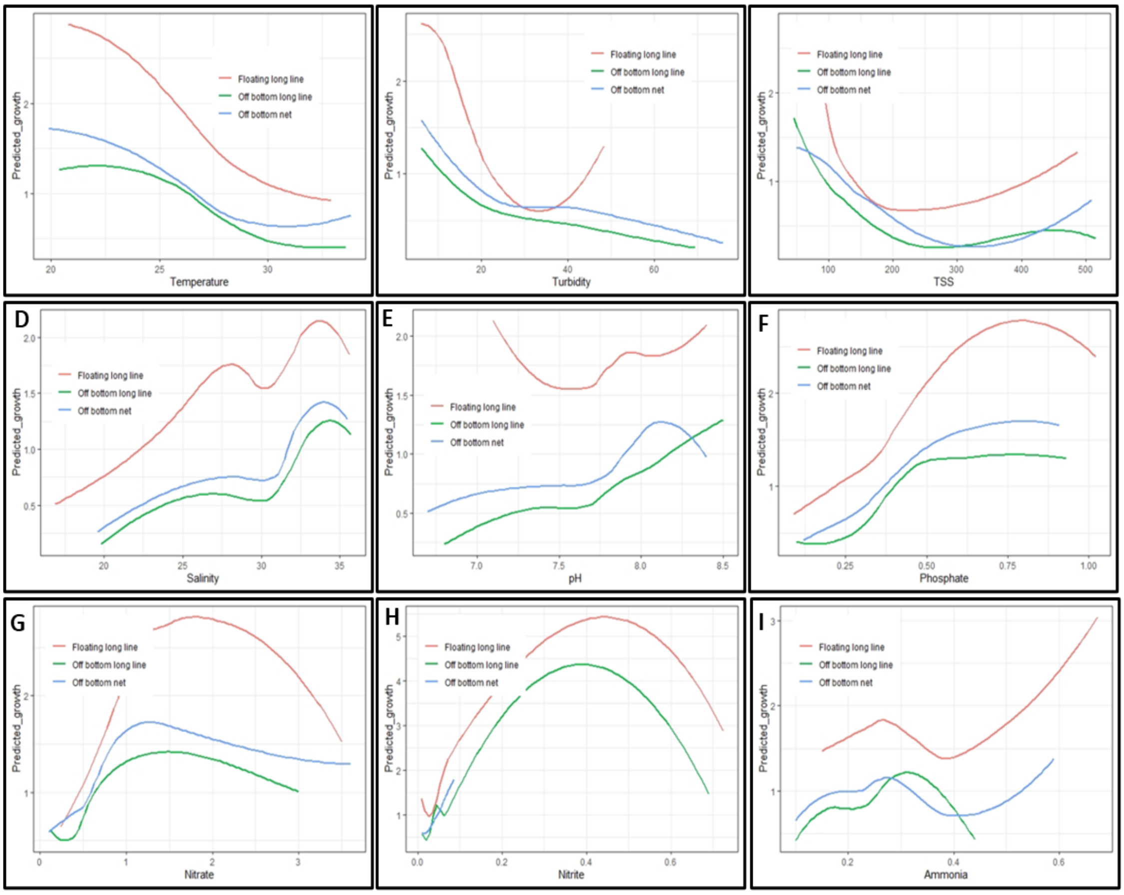

Figure 8: Estimated probability of predicted growth of seaweeds at different environmental conditions using the Generalized Additive Model (GAM) for the southeast coast of the Bay of Bengal, Bangladesh. (A) Temperature (◦C), (B) Turbidity (TSM), (C) Total Suspended Solids (mg/L), (D) Salinity (ppt), (E) pH, (F) Phosphate-phosphorus (mg/L), (G) Nitrate-nitrogen (mg/L), (H) Nitrite-nitrogen (mg/L), and (I) Ammonia-nitrogen (mg/L).

The modeled relationship of different explanatory variables and associated predicted growth in the form of gross wet biomass (kg/m^2/month) of seaweeds in different culture systems is presented in Fig. 8. In all culture systems, GAM model outputs demonstrated that higher probability of increased seaweed production was found in relatively lower temperature (18-25^{o}C), turbidity (<20 NTU), and TSS (<150 ppm), combined with higher salinity (25-35 ppt) and nutrient concentrations (nitrate > 0.5 ppm, nitrite >0.2 ppm; phosphate > 0.5 ppm, ammonia > 0.3 ppm).

4.4 Geo-spatial Habitat Map of Seaweed for Different Culture Systems Dynamics

Predicted suitability maps for different seaweed culture systems showed that suitable areas for floating long-line culture system significantly varies from off-bottom long-line and off-bottom net culture systems (Figure 9).

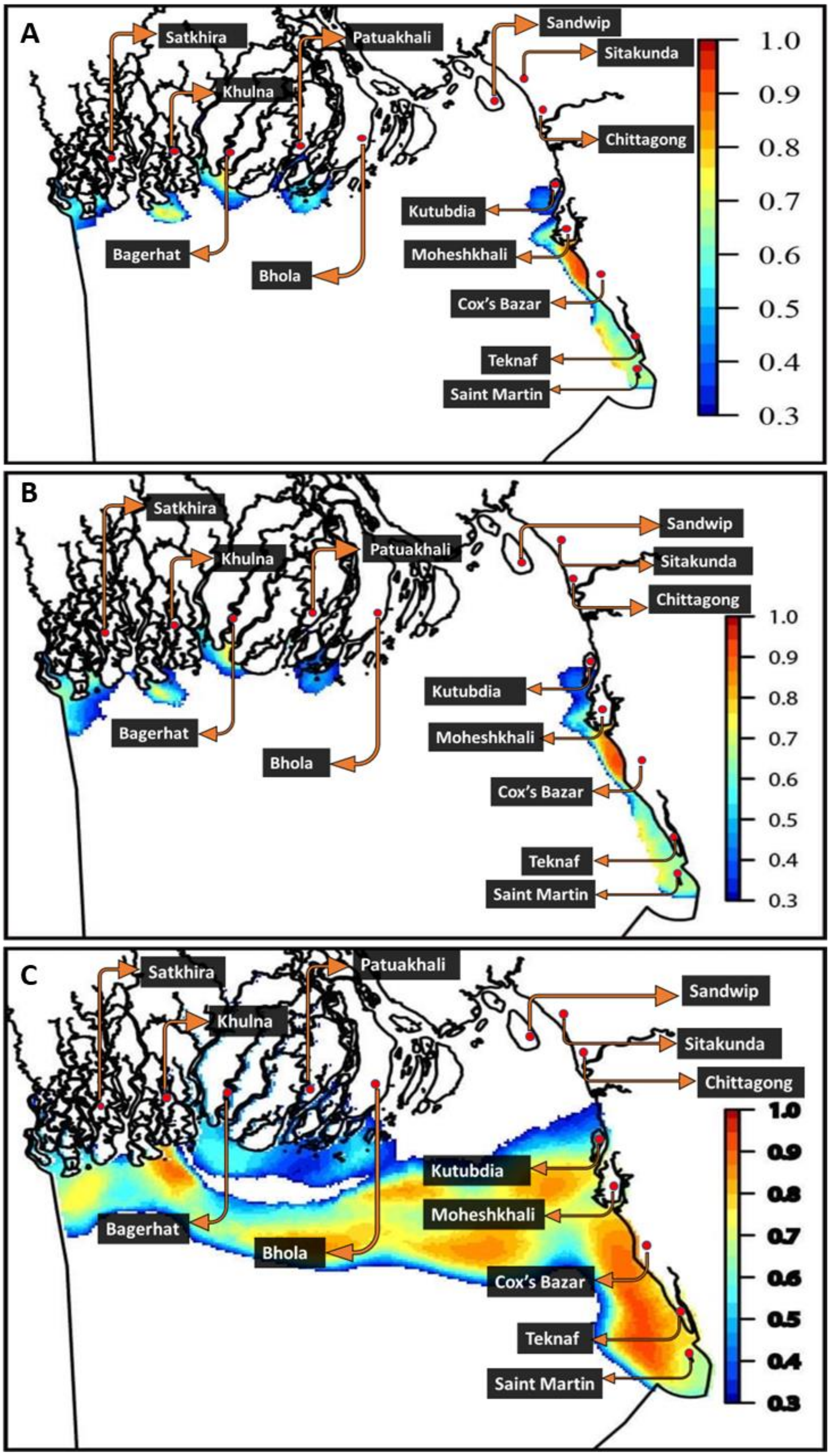

Figure 9: Habitat suitability mapping by applying the Generalized Additive Model (GAM) for spatial prediction of different culture systems of seaweed in the coastal area of Bangladesh. The spatial prediction of the feasibility of seaweed culture is shown for an off-bottom long-line culture system (A), an off-bottom net culture system (B), and a floating long-line culture system (C). Probability 1 indicates a 100% chance of seaweed cultivation. Probabilities below 0.30 are eliminated from the map.

The outcome of the habitat suitability maps is almost identical for the off-bottom long line and off-bottom net culture systems (Figure 9A-B). Both of these two systems were found to be most suitable for seaweed production in the southeast coastal zone. Maheshkhali channel and surrounding areas show a 100% probability of success for seaweed production using these two methods if the bottom mud is sandy. A very small area of the southwest coastal zone also has potential for seaweed production using these two systems, with probabilities ranging from 30 to 70%. However, the central zone is not suitable at all for seaweed production by using these two farming techniques. Interestingly, the floating long line culture system is found to be suitable for seaweed production in both the southeast and southwest coastal areas of Bangladesh (Figure 9C). The coastal regions of Maheshkhali, Cox's Bazar, Teknaf, and Saint Martin's Island in the Southeast coastal zone showed the highest production probability in this method, ranging from 90 to 100%. The southwest coast of Bangladesh and some far shore portions of central zone (Patuakhali and Bhola coast) are moderately to highly suitable for seaweed farming by floating long-line system. However, the estuaries of the central region, which are linked to the Ganges-Brahmaputra-Meghna basin, are not suitable for this culture system due to their high turbidity and low salinity levels. Moreover, there is a possibility of seaweed production using floating long-line systems towards the far shore.

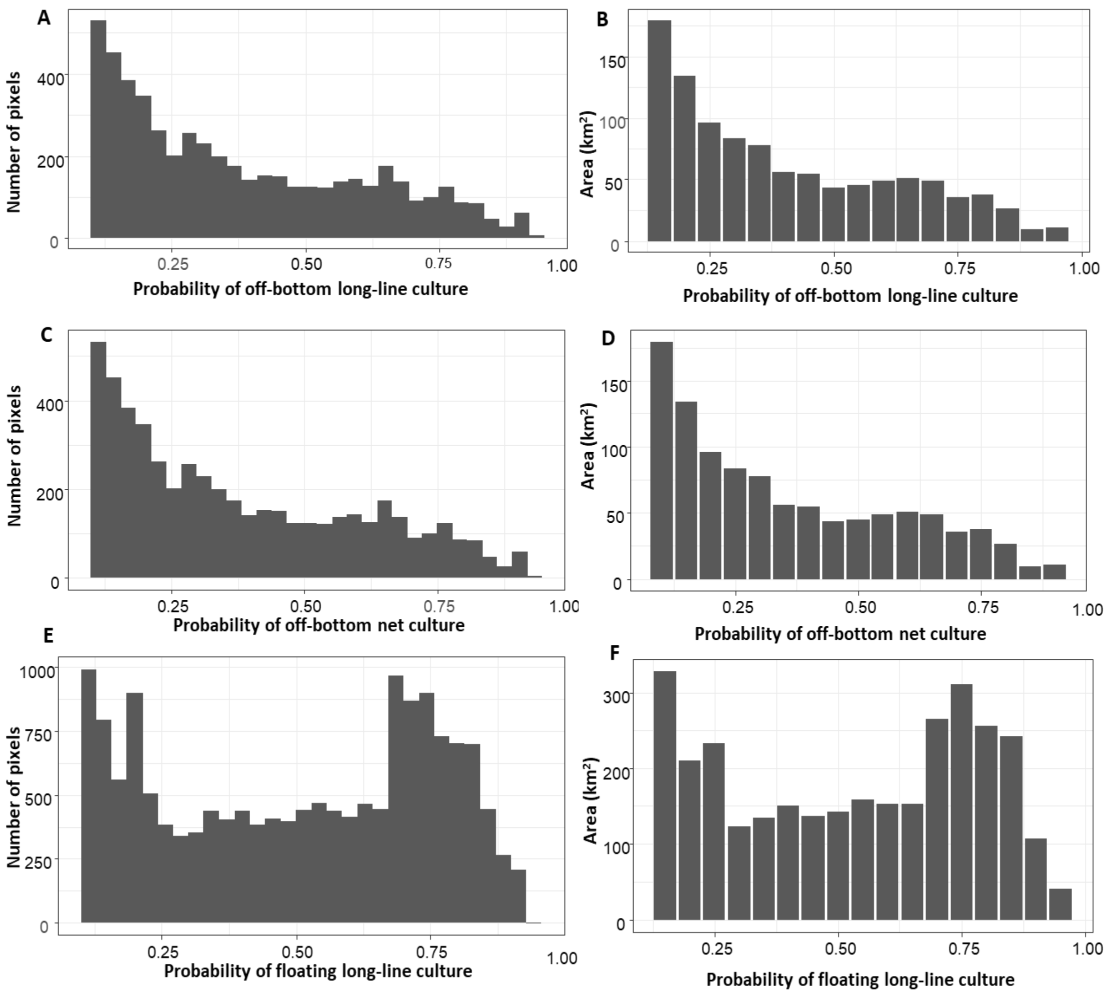

Figure 10: Probable farming area of seaweed under different culture systems in the coastal and maritime area of Bangladesh. The spatial prediction of the seaweed farming area (km^2) is shown for an off-bottom long-line culture system (A-B), an off-bottom net culture system (C-D), and a floating long-line culture system (E-F). Probability 1 indicates a 100% chance of seaweed cultivation.

We found that about 350 km^2 area has the 50-100% probability of seaweed farming by off-bottom long line and off-bottom net culture systems (Figure 10). Maximum suitable area for seaweed farming was found for floating long-line culture system. About 1850 km^2 area have the 50-100% probability of seaweed farming along the entire coastal water areas of Bangladesh by floating long-line system (Figure 10). In the total coastal waters of Bangladesh, about 120 km^2 area had the higher probability (>75%) of seaweed farming by off-bottom long-line and off-bottom net culture systems, while 950 km^2 have the higher possibility (probability >75%) of seaweed farming using floating long-line culture method (Figure 10). For better understanding, longitudinal variation of the probable farming area of seaweed under different culture systems in the coastal and maritime area of Bangladesh is also presented in Figure 11. Consistently, highly suitable areas for seaweed farming were rarely found in the central coast of Bangladesh (Figure 11).

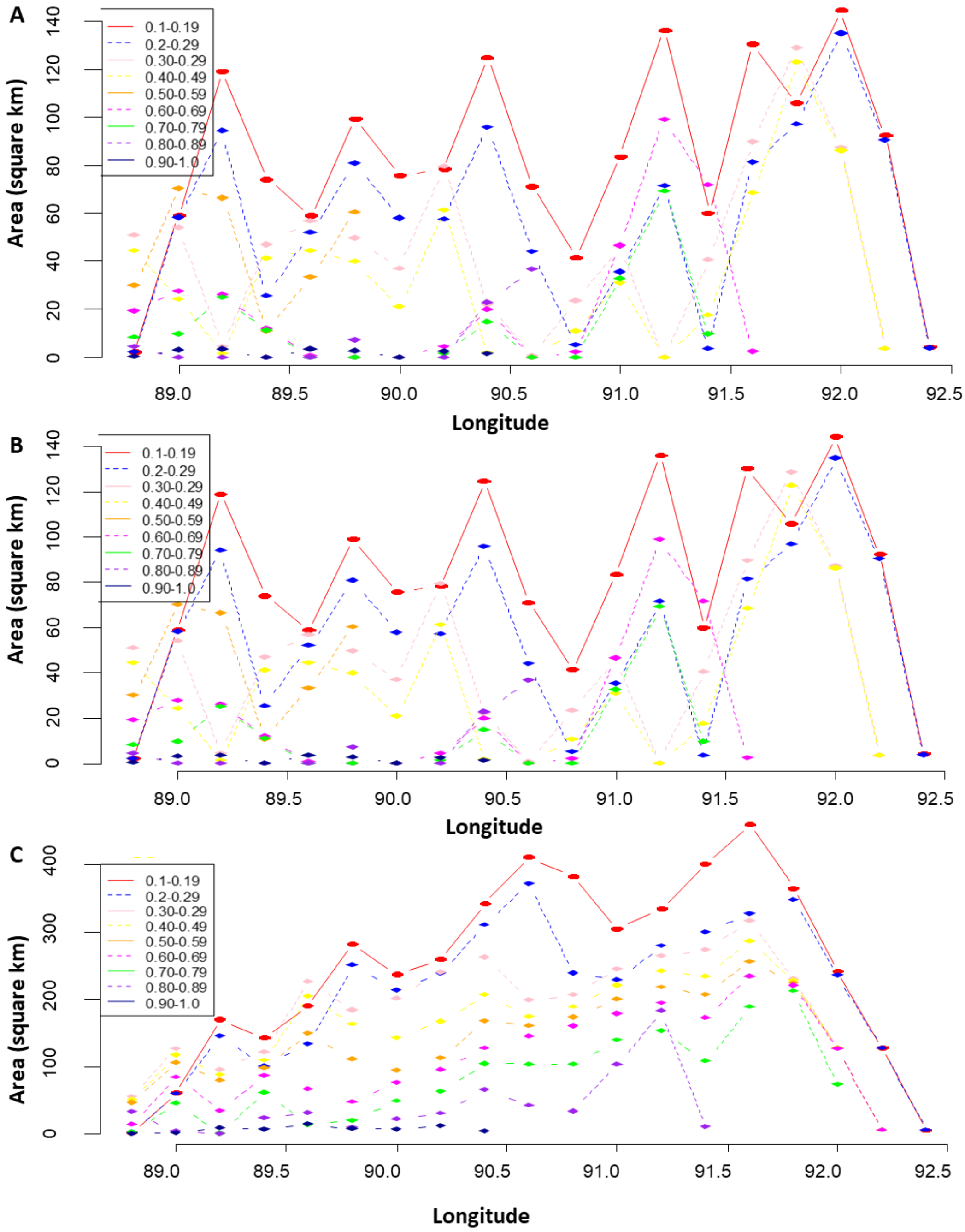

Figure 11: Longitudinal variation of the probable farming area of seaweed under different culture systems in the coastal and maritime area of Bangladesh. The spatial prediction of the longitudinal variation of seaweed farming area (km^2) is shown for an off-bottom long-line culture system (A), an off-bottom net culture system (B), and floating long-line culture system (C). Probability 1 indicates a 100% chance of seaweed.

4.5 Model Validation

When in-situ data were compared to modeled data (Figure 12), we discovered that our model is an excellent predictor of seaweed output from diverse farming methods (R^2 = 0.85, $p<0.001$). The prediction accuracy of our model was assessed using Kappa statistics and the odd ratio. We also found that predicted accuracy of our model has a good performance (Kappa = 0.82 and odd ratio = 0.12). The area under the curve (AUC) value for our research revealed that a random pick from the positive group has a higher score than a random selection from the negative group at 83% of the time. The value of PPP also confirmed that our model had good performance to predict the high probability of seaweed occurrence at a rate of 79%. In addition, NPP value (0.14) also confirmed the reliable predictability of our habitat model.

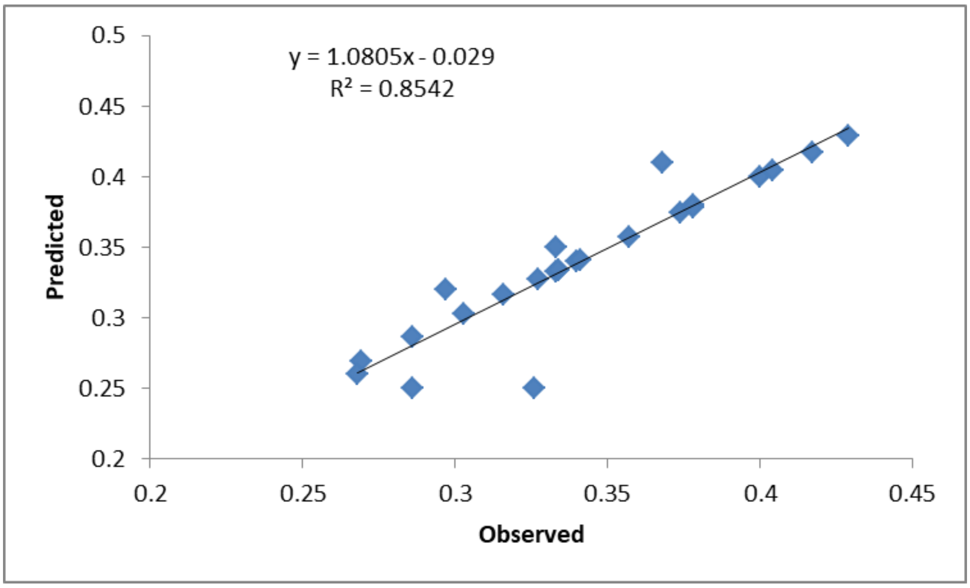

Figure 11: Comparison of observed seaweed production data (kg/m^2/month) and predicted probability for model validation using the Generalized Additive Model (GAM).

CHAPTER V

DISCUSSION

The aim of this study was to develop habitat suitability maps for different seaweed farming systems along the entire coastal and maritime territory of Bangladesh. For this purpose, we employed GAM modelling through using *in-situ* production and environmental factors data of 180 culture plots, satellite observations data, and model simulations data. In addition, we assessed the explanatory power of seven ecological driving factors that control seaweed production and forecasted the probable farming area suitable for off-bottom long line, off-bottom net, and floating long-line culture systems.

5.1 Ecological Driving Factors for Seaweed Farming in Different Culture Systems

According to our model, TSS was the key significant driving factors in spatial prediction of habitat suitability mapping of seaweed farming in the coastal and maritime areas of Bangladesh. It is important in seaweed production as seaweed farming systems are particularly vulnerable to the effects of high levels of TSS (Babuder et al. 2020; Banik et al., 2023). High levels of TSS can reduce the amount of light available for photosynthesis, which can hinder the growth and development of seaweed, leading to reduced yield and quality of the product (Banik et al., 2023). Elevated levels of TSS can also increase turbidity and decrease water clarity, which can make it difficult to absorb nutrients for seaweed and can also lead to sedimentation and reduced water flow (Babuder et al. 2020; Chapman et al. 2017). In agreement with our study, Sarker et al. (2021) also found that high level of TSS is the most important driver for the distribution of *Hypnea* spp., *Enteromorpha* spp., *Caulerpha* spp. and *Sargassum* spp. in the coastal and maritime area of Bangladesh. Similarly, we recently reported a significant negative correlation of the growth rate and biomass of seaweed with the TSS at the southeast coastal zone of Bangladesh (Banik et al., 2023). Moreover, a lower growth and absence of seaweed was reported during monsoon season as coastal areas of the Bay of Bengal experience higher level of TSS due to heavy rainfall that cause soil erosion and surface runoff (Islam et al., 2017; Sarker et al., 2021; Banik et al., 2023).

We observed that salinity is also a key driving factor in determining farming success of seaweed in the coastal waters of Bangladesh. In agreement with our study, Sarker et al. (2021) identified seawater salinity as the second most important predictor of seaweed occurrence. Seaweed can typically tolerate a wide range of salinities and grows best in the range of 17-30 ppt (Guo et al., 2015; Banik et al., 2023). However, salinities outside of this range might restrict seaweed's growth and development, resulting in decreased production performances (Choi et al., 2007). In previous studies, salinity was found as a major significant factor affecting the growth and yield of *Gracilaria changii* (Tresnati et al., 2021) and *Gracilaria vermiculophylla* in unialgal culture system (Yokoya et al., 1999), which validates the prediction of our model. Very high and low salinity cause osmotic and physiological stress, which decreases the photosynthetic rate, growth and reproduction of seaweed (Kim et al., 2016;Abreu et al., 2011).

Besides TSS and salinity, GAM model estimated that different nutrient concentrations (nitrate, nitrite, ammonia and phosphate) are the important drivers for seaweed farming. Seawater nutrients are necessary to promote seaweed development (Harrison & Hurd, 2001; Hurd et al., 2014). According to our model, nitrogenous compounds are the most significant nutrient for seaweed production because they are principal components in plant metabolism as a constituent of proteins, chlorophyll, nucleic acids, coenzymes and secondary metabolites (MacArtain et al., 2007). Dissolved inorganic nitrogen (nitrate, nitrite, ammonium) and organic nitrogen (urea, amino acids) are the main sources of nitrogen for seaweed (Roleda et al., 2019). Among the different nitrogenous compounds, studies have demonstrated that adding nitrates to the culture medium can speed up development and increase biomass in *Gracilaria edulis* (Bhushan et al., 2023). Similarly, nitrates have been discovered to be a limiting nutrient for the growth and yield of seaweed in a floating bamboo raft and hanging rope culture system (Roleda et al., 2019; Bhushan et al., 2023). Our model revealed a higher predicted biomass of seaweed can be obtained when nitrate concentration is more than 0.5 ppm. Optimal nitrate concentration of different seaweed species can increase the production in a sustainable way, e.g., nitrate concentration of 60 μM is the most suitable regime for the sustainable culture of *Ulva Fasciata* with the highest growth rate (Suthar et al., 2019). Nitrate fertilization of *Undaria pinnatifida* gametophytes also resulted in short cultivation period with high priced yield (Gao et al., 2018). However, too high nitrate levels can lead to eutrophication and reduce the quality of the seaweed, while too low levels can limit growth and productivity (Roleda et al., 2019). Like nitrate, nitrite is a liming factor for the growth of seaweed

(Roleda et al., 2019). Our model revealed that predicted biomass of seaweed is higher when nitrite concentration is in between 0.2-0.5 ppm. But high nitrite concentrations stimulates high growth of microbial contamination which could prevent seaweed from growing and even cause death (Suthar et al., 2019). Ammonium is generally preferred to all other nitrogen forms by seaweeds (except some kelp) and required for optimum growth (Kim et al., 2007). For example, *Ulva lactuca* and *Gracilaria foliifera* showed higher growth rate and consistently higher biomass yield in NH4 + -enriched cultures (DeBoer et al. 1978; Ale et al. 2011). Primary production of seaweeds based on the ammonium is termed "recycled production" because it is internally regenerated within the system by invertebrates and fish associated with the seaweeds, while nitrate-based growth is termed "new production" because NO3− is externally supplied (Boyd and Hurd, 2009). Although highly preferred by seaweeds, excessive ammonia can cause toxicity, which can lead to disease outbreaks and further reduce seaweed growth, chlorosis, and even death of seaweed (Moreno-Marín et al., 2016; Wang et al., 2020) Another essential macronutrient phosphate, which is a source of phosphorus, essential for the development of different physiological processes of seaweed. Phosphorus is needed by seaweed for a variety of processes, including photosynthesis, respiration, and energy transmission (Roleda et al., 2019; Chopin et al., 1995). The ideal phosphate content in a culture condition is important for any seaweed species' healthy production. For example *Ulva fasciata* had the maximum growth rate at a phosphate phosphate concentration of 6 μM where variation from this indicates microbial growth and thallus degradation which can lead to biomass loss (Suthar et al., 2019). In conclusion, the availability of different nutrients in the culture site plays a vital role in the growth and reproduction, thereby should carefully consider during the habitat suitability mapping for seaweed in any locations (Harrison & Hurd, 2001; Hurd et al., 2014).

5.2 Habitat Suitability Mapping of Different Seaweed Culture Systems

The feasibility of seaweed farming using different culture systems is contingent upon the environmental conditions prevalent in the coastal regions of Bangladesh. Our model predicted that the southeast coastal zone of Bangladesh is most suitable for seaweed farming through different culture techniques (off-bottom long line, off bottom net, floating long line). In agreement with our findings, various seaweed species are found to naturally occur in a number of locations in the Cox's Bazar coast (i.e. Moheshkhali channel, Nuniarchara, Nazirartek of Bakkhali-Moheshkhali river estuary, Jaillapara, Shaplapur coast, Shahparirdip area of Teknaf) due to the favorable environmental conditions (Sarker et al., 2021). Among the southeast zone, coastal regions of Maheshkhali and surrounding areas showed the 90 to 100% production probability for seaweed farming. These locations are located near the equator and sheltered bays like structure protecting this zone from strong current, pollution and heavy surface runoff during monsoon season, which ensure the optimum level of TSS and less turbidity during farming season (Hoq et al., 2016; Islam et al., 2017). Additionally, the salinity level and nutrient availability in these regions are maintained by a weak river basin and a low freshwater discharge. A number of studies already proved the suitability of seaweed farming in these regions due to less moderate turbidity combined with optimum salinity, shallow depth and nutrient availability (Hoq et al., 2016; Islam et al., 2017; Banik et al., 2023; Sobuj et al., 2023). Our findings also demonstrated that St. Martin's Island located in the very south of Bangladesh showed a high probability of seaweed farming using different culture techniques. Compared to other coastal areas, optimum temperature (21-30^{o}C), salinity (never deplete below 30 ppt), less turbidity, available nutrients brought by water currents from the southeast and rocky intertidal zone have made St. Martin's Island a unique habitat for about 240 species of seaweed (Zafar, 2007; Hoq et. al., 2016; Islam et. al. 2017).

The GAM model also predicted that the southwest coast of Bangladesh and some far shore portions of central zone (Patuakhali and Bhola coast) are moderately to highly suitable for seaweed farming (see Figure 9). Favorable environmental conditions, including warm and humid climate, moderate saline water, an ample supply of nutrients due to tidal currents and riverine flow, long coastline with many estuaries and bays which providing sheltered and protected areas, make the southwest coast of Bangladesh moderately suitable for seaweed farming (Sarker et al., 2021). Additionally, the location offers significant intertidal mudflats that may be utilized for seaweed cultivation (Bolton et. al., 2009). Largest single block of tidal halophytic mangrove forest in the world, known as the Sundarbans covering an area of approximately 10,000 km^2, is the main features of this zone (Asha et. al., 2020). The Sundarbans mangrove ecosystem is an appropriate home for seaweed due to environmental conditions and a network of interconnecting waterways. Furthermore, nutrients are brought to this area through mangrove litter falls and river discharge. Due to these favorable environment conditions, several seaweed species were found to naturally occur in the intertidal and sub tidal zones with the unique substratum of these mangroves (Islam et. al., 2019; Sarkar et al. 2016). For example, 34 species of seaweed were reported to occur by Sarker et al. (2021), while 42 species of seaweed were reported to occur by Islam et. al. (2017) in the adjacent coastal waters of the Sundarbans mangrove forest. Though the southwest coastal zone has a rich natural seaweed biome, so far, no results from experimental culture of seaweed has been reported from the southwest coastal region of Bangladesh, particularly from the Sundarbans mangrove forest area. In agreement with our findings, a very recent study demonstrated that *Gracilaria tentuistipitata* species can be farmed using the square raft technique on the central Kuakata coast of Bangladesh (Ullah et al., 2023).

Among the three types of culture systems, our model estimated that off-bottom long line and off-bottom net culture systems have the probability (50-100%) of seaweed farming in only 350 km^2 area, whereas 1850 km^2 area have the 50-100% probability of seaweed farming by floating long-line system along the entire coastal water areas of Bangladesh (see the Figure 10). This is because a large chunk of the southeast coast (from Feni to Chittagong) and the majority of the central coast (from Bhola to Feni) are not ideal for seaweed cultivation using off-bottom techniques. The Ganges-Brahmaputra-Meghna delta, one of the world's most dynamic tide-dominated deltas, is located along the central coast. The influx of substantial volumes of water and about 1 billion tons of sediments from upstream through the river tributaries renders the area turbid (Haque et al., 2013). Furthermore, a significant influx of freshwater from upstream sources results in a reduction in the salinity levels of these regions (Sarker et al., 2021). Intertidal mudflats are another characteristic of most of these zones, which makes it difficult to implement seaweed off-bottom culture methods on the muddy bottom (Islam et. al., 2019; Sarkar et al. 2016). In agreement with our findings, no seaweed species were found in these zones during the field survey along the entire coastal areas of Bangladesh (Sarker et al., 2021). In contrast, floating long-line culture systems are carried out in the subtidal zone up to 10 m depth. These far shore areas are often characterized with less turbidity and high salinity, offering the possibility of seaweed farming using floating long-line systems.

5.3 Implication in Seaweed Mariculture Development and Conservation

Habitat suitability maps are essential tools that offer critical insights into the natural distribution of seaweed and its potential for cultivation through various culture systems. The aforementioned may facilitate the stakeholders to augment their comprehension of the spatial arrangement of seaweed species, their ecological prerequisites, and their vulnerability to environmental changes. The provision of precise and comprehensive habitat suitability maps confers the ability upon interested parties to arrive at judicious conclusions, thereby promoting the preservation of marine biodiversity and the sustainable management of coastal ecosystems in the Bay of Bengal.

Although newly developed floating long-line culture systems has the potential to expand in 1850 km^2 along the entire maritime and coastal territory of Bangladesh, many of these areas are simultaneously used by a number of other government entities and large-scale private sectors for various purposes like the expansion of the international airport, naval base, power station, deep water seaport, commercial fishing, navigation, and various industrial purposes. Therefore, developing a Marine Spatial Planning (MSP) is imperative to facilitate the coexistence of multiple resource users in coastal and marine environments to avoid user conflicts (Sarker et al., 2021; Chowdhury et al., 2022). At the same time, there is a lack of area-based zoning plans demarcating suitable sites along the entire 750 km of coastal waters for offshore seaweed aquaculture with a necessary institutional arrangement to support seaweed farmers in Bangladesh, even though the farmers and private entrepreneurs have limited knowledge of site selection for seaweed farming (Sarker et al., 2018; Sarker et al., 2021; Chowdhury et al., 2022). Therefore, findings of this study on the spatial prediction of habitat suitability map can close the knowledge gap among the relevant stakeholders, aid in expanding seaweed farming, and contribute to the establishment of a marine spatial plan for mariculture in Bangladesh.

The farming advantages of seaweed and its importance in livestock feed and the human food industry have attracted many private sectors due to increasing interest to explore its potential (Chowdhury et al., 2022). But seaweed growers often confront challenges associated with the use of marine habitats due to the absence of mariculture zoning. They also need to have an extensive understanding of different farming systems and the environmental suitability of seaweed species in their respective maritime habitats (Sarker et al., 2018; Sarker et al., 2021; Chowdhury et al., 2022). In this context, our findings may play a crucial role in providing the necessary knowledge and information to the private sector. This will also enable them to optimize their cultivation efforts and effectively harness the benefits of seaweed farming for various industries. Ultimately, the habitat suitability maps for different culture system would become a valuable tool in assisting the private sector in making strategic and informed decisions to capitalize on the potential of seaweed cultivation. This map can facilitate the development of a comprehensive ocean space plan and the establishment of appropriate regulatory framework and institutional arrangements. By considering the suitability of different areas for specific activities, including seaweed farming, the map can help mitigate conflicts, ensure equitable marine resource allocation, and promote the sustainable utilization of the Bay of Bengal's resources.

Seaweed habitat suitability maps may provide valuable insights for marine conservation. They help to identify areas with high potential for seaweed growth, which are critical for supporting marine biodiversity, sustainable fisheries, and ecosystem resilience. Conservationists can use this information to prioritize protection and restoration efforts in these regions, enhancing overall ecological balance and promoting targeted conservation. They can also target their efforts, such as establishing marine protected areas (MPAs), based on areas with high seaweed habitat suitability. Currently, the government of Bangladesh is overseeing the management of these protected areas under existing legislation. Notwithstanding, the absence of distinct management plans with specific measures for each layer of management remains unresolved. This offers a prospect to incorporate suitability maps across diverse management tiers. One potential strategy for promoting the conservation of seaweed species is for governmental entities to align the boundaries of no-take zones with the distribution and abundance of these seaweed species. It is worth noting that St. Martin Island is identified as an area with high seaweed abundance (Abdullah et al., 2020). The adjacent marine ecosystem contains approximately 197 seaweed species, highlighting the importance of conserving these habitats (Sarker et al., 2021; Chowdhury et al., 2022). Therefore, the management plan for St. Martin MPA should incorporate special measures to safeguard its natural habitats and ensure the long-term conservation of seaweed species. The abundance of seaweed in the Sundarbans Reserve Forest's surrounding areas also makes it possible to include particular management practices.

This habitat suitability maps for seaweed may have a notable impact on climate change research. Seaweed plays a vital role in mitigating climate change by absorbing carbon dioxide from the atmosphere and releasing oxygen (Chung et al., 2013; Krause-Jensen et al., 2016; Duarte et al., 2017). By identifying areas with high seaweed abundance, researchers gain a better understanding of seaweed's carbon sequestration capacity and the potential for seaweed-based carbon capture and storage (CCS) technologies. Seaweed CCS shows promise in reducing greenhouse gas emissions and addressing climate change effects (Hughes et al., 2012; Krause-Jensen et al., 2016). These maps assist in identifying regions suitable for seaweed cultivation or restoration, maximizing carbon sequestration potential. Large-scale seaweed farming, also known as "blue carbon farming," contributes to climate change mitigation by offsetting CO_2 emissions and reducing ocean acidification (Duarte et al., 2017). The utilization of seaweed habitat suitability maps can guide the Bangladesh government in initiating and optimizing seaweed farming initiatives, leveraging the carbon sequestration capabilities of seaweed to address the changing dynamics of climate change.

Seaweed habitat suitability maps are essential for guiding coastal planning and development in Bangladesh, particularly in areas undergoing large-scale projects such as deep-sea ports, tourism developments and airport expansion. By integrating these maps, decision-makers can minimize conflicts and make sustainable choices that consider the conservation of seaweed habitats and their associated ecological functions. Integrating these maps supports balanced economic growth while conserving marine biodiversity and ecosystem services. This approach ensures the long-term sustainability of coastal areas and supports the well-being of communities. Seaweed habitat suitability maps also inform coastal management by identifying areas for protection and restoration, providing natural coastal protection benefits and recreational opportunities.

CHAPTER VI

CONCLUSION

The development of a habitat suitability map utilizing modelling techniques for various seaweed culture systems represents a potential avenue for the implementation of commercial-scale seaweed farming in the maritime zone of Bangladesh. According to the prediction of our model, the southeast coastal zone is highly suitable for seaweed farming through three types of culture systems (off-bottom long-line, floating long-line and off-bottom net), while the southwest zone shows a moderate to high suitability based on the sites. Interestingly, it is also possible to utilize the central zone, which may seem unsuitable due to incoming flow of Meghna large rivers, also has the potential using the floating long-line system and locating at a far-shore distance. However, there are some challenges for commercial expansion of seaweed mariculture in Bangladesh. The seasonal and monthly variation in the hydrobiological parameters and spatial gradient along the coast caused by the dynamic southwest monsoon climate makes the hydrodynamics of Bangladesh's coast the most unpredictable one, which can lead to a short annual production cycle (October to April). Moreover, being located in a subtropical region, the climatological hazards such as strong waves, currents and periodic cyclone sometimes carrying away growing seaweed and culture materials to the open sea, are making the commercial culture of seaweed more challenging. Also, the utilization of old seaweed stock for proliferation and unevaluated integrated shellfish-seaweed farming techniques, as well as lack of proper processing, value addition, and marketing of harvested seaweed are significant issues for the development of seaweed-based blue economy of Bangladesh. Therefore, after developing this habitat suitability mapping for mariculture development of seaweeds, future research and activities should be focused on the establishment of land-based seed bank, farming integration and intensification, establishing seaweed-based forward linkage industry, developing post-harvest processing technology, marketing chain, and so on.

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