Integrated Phytoremediation and Bio-Energy Solutions for Sargassum Mitigation at Punta Cana, Dominican Republic

Honors Research Thesis

The Honors Thesis is Presented in Partial Fulfillment for Graduation with Honors Research Distinction.

Student:

Juan De Dios Cuello Gálvez
Joshua I. Smith College of Business
Central State University, Wilberforce

2023

Research Advisor:

DeBonne N. Wishart, PhD., D.M.S.
Professor, Environmental Science and Environmental Studies, and Geoscience
Barry Goldwater Campus Representative
C. J. McLin International Center for Water Resources Management
Central State University, Wilberforce
Room 204
1400 Brush Row Road
Wilberforce, OH 45384-1004
Email: dwishart@centralstate.edu

CENTRAL
STATE UNIVERSITY

Innovation is in our DNA

Signatures

Juan De Dios Cuello Gálvez
Student
College of Business
Date: May 08, 2023

DeBonne N. Wishart, PhD., D.M.S.
Research Advisor
Professor, Environmental Science and Environmental Studies, and Geoscience
College of Engineering, Science, Technology, and Agriculture
Date: May 08, 2023

Dr. Paul Schlag
Executive Director of Honors College & International Affairs
Date: May 00, 2023

Table of Contents

Integrated Phytoremediation and Bio-Energy Solutions for Sargassum Mitigation at Punta Cana, Dominican Republic (DR)

Abstract

Over the last twelve years, expanding invasions of brown pelagic macroalgae (Sargassum) have continued to significantly impact tourism, economies, and fishing industries along the eastern coastal cities of Caribbean island nations, including the Punta Cana region of the Dominican Republic. Cap Cana and Cabeza de Toro are two areas in Punta Cana that have large influxes of Sargassum blooms during the months of June to October, but they reduce during November to May. An increasing problem is that algal blooms intensified by climate change and agricultural runoff are invading beaches on the eastern coasts of the Caribbean, Mexico, Florida, and the USA. Current methods for the removal of Sargassum biomass from beaches are both time-consuming and inefficient for mitigating the ever-growing seaweed invasion. An integrated mitigation approach needs to be implemented to reduce the damaging impact of Sargassum on Punta Cana's tourism and fishing industries. In this honor's thesis, an integrated approach is being proposed for mitigating invasive pelagic Sargassum blooms using (1) phytoremediation systems near golf courses along Punta Cana's coastline. (2) the deployment of floating aquatic plant booms; (3) intake suction-pumped extraction of Sargassum for conversion to biofuel; and (4) historic satellite monitoring of Sargassum.

1. Introduction

1.1. *Sargassum sp. (Gulf Weed)*

Sargassum, or gulf weed (**Figure 1a–b),** is a brown macroalga widely known for its planktonic species. It resides in warm, shallow water in temperate and tropical oceans worldwide and on coral reefs [1]. Species of Sargassum that invade the Caribbean Sea are *Sargassum natans* I (**Figure 1a**), *Sargassum natans VIII*, and *Sargassum fluitans* [2]. The prolific growth of these aquatic invasive algal mats results from nutrient runoff from anthropogenic sources such as fertilizer and metals and the coastal upwelling of deep-water nutrients to the surface, which worsens with warmer ocean water. For example, nutrient discharges from the Amazon River, upwelling off the West African coast during the boreal winter, and the fallout of dust from the Sahara Desert are all driven by circulation in the Sargasso Sea of the North Atlantic Ocean and east of the Florida Straits (**Figure 2a),** which creates the perfect conditions for spatial distribution and the migration of Sargassum blooms to the eastern coasts of the Caribbean nation islands, Mexico, and Florida, USA [3]**.** The aerial extent and density of the world's largest macroalgal bloom, the Great Atlantic Sargassum Belt (GASB), has increased to 8850 kilometers long and extend from West Africa to the Caribbean Sea and Gulf of Mexico [2] and continues to grow (**Figure 2b)** [4].

In 2015, researchers at Texas A&M University at Galveston unveiled the Sargassum Early Advisory System (SEAS), the first-of-its-kind app used by tourists, fishermen, and boaters to track the massive algal mats of seaweed in the Gulf of Mexico and provide estimated arrival times of its arrival along the Texas coastline [5]. The University of South Florida (USF) Optical Oceanography Laboratory in the College of Marine Science confirmed the approach of larger Sargassum mats separated from the 5,000-mile-wide Great Atlantic Sargassum Belt in the March 2023 edition of the "Sargassum Outlook Bulletin", started in 2018 to provide an *outlook* of the probability of *Sargassum* blooms in certain regions during the upcoming months [6].

1.2. *Efforts to Mitigate Sargassum Blooms*

Current mitigation methods employed for the removal of Sargassum are hand raking, mechanical harvesting (F**igure 3a–b)** using pumps, macerators, conveyors, earth moving equipment, and boats used to collect the algal biomass for ultimate disposal in landfills. Alternative mitigation strategies include the deployment of newly innovated invasive aquatic booms or barriers moored in selected locations to prevent Sargassum from encroaching on the beaches (**Figure 4a–e**) [7] and the burial of Sargassum for conversion to coastal fertilizer, and the valorization *of Sargassum,* which have not provided efficient, sustainable solutions for mitigation [2]. The booms allow the macroalgae to move with the wind and current either back to sea or down the coast,

An increasing problem is that algal blooms intensified by climate change and agricultural runoff are invading beaches in the Caribbean and Mexico [8]. Current methods for the removal of Sargassum seaweed from beaches are both time-consuming and inefficient to mitigate the ever-growing seaweed invasion on tourist beaches, hotels, resorts, coastal parks, marinas, boat docks, and ports. The objective of this paper is to propose integrated mitigation strategies for the efficient control and removal of invasive Sargassum mats using (1) phytoremediation of inland runoff to Punta Cana's coast and (2) the conversion of Sargassum to biofuel. The environmentally friendly and cost-effective alternative mitigation strategies for the management of invasive pelagic Sargassum could have broader impacts on the eastern coastlines of the Caribbean nations, Florida (USA), and Mexico.

1.3. *Harmful Impacts of Sargassum Blooms*

Sargassum is harmless to humans but releases hydrogen sulfide (H_2S) gas and ammonia after it washes ashore and decays [2, 8]. H_2S irritates the ear, nose, and throat [8, 9]. Sargassum absorbs carbon dioxide and serves as a critical habitat for marine organisms, e.g., turtles, birds, crabs, shrimp, and fish. However, its pungent odor also alters the pH balance of seawater and smothers coral reefs. Besides, it may contain high concentrations of arsenic and other heavy metals that are toxic and could impact groundwater by leaching [2]. The presence of the Sargassum on beaches limits beach-based tourism and eco-tourism for millions of tourists traveling to Mexico, the Caribbean, and Florida, USA. Recently, a 12.7-kilometer barrier was installed along Punta Cana's coastline to prevent Sargassum from encroaching on beaches, and manual labor was deployed to remove the Sargassum mats [9]. However, the expensive and time-consuming work is only a temporary solution to an ever-growing problem and continues to negatively impact tourism in the Punta and Cabana regions. In this paper, several integrated strategies are being proposed as an environmentally friendly approach for the mitigation of Sargassum and the coastal sustainability of the Dominican Republic's Punta Cana beaches used for tourism. The mitigation strategies proposed here may be tested and evaluated, and if proven feasible, they could be adopted by other nations impacted by Sargassum for its control and removal from beaches and other areas.

This honor's thesis is organized as follows: First, the background information on the increasing invasion of eastern coastlines by pelagic Sargassum algal mats is presented in Section 1; the geological setting of Hispaniola and the study area of Punta Cana, Dominican Republic, are briefly introduced in Section 2; proposed methods for phytoremediation remediation, invasive aquatic boom deployment, and feedstock valorization of Sargassum are provided in Section 3; the potential impact of the integrated approach is discussed in Section 4; and finally, a conclusion is proposed in Section 5.

2. Geographic and Geological Setting of the Dominican Republic

2.1. *Geographic Location of the Dominican Republic*

The Dominican Republic (18.7357° N, 70.1627° W) is the second-largest island of the Greater Antilles Archipelago. It shares the island of Hispaniola with Haiti in the Caribbean Sea (**Figure 5**) and is approximately 48,442 km2 in area. Apart from seasonal changes in temperature, the average temperature is 25°C. Its tropical climate is modified by its variation in elevation, the Northeast Trade winds, and hurricanes that occur from May to November. Tourism is the Dominican Republic's principal exchange earner, and in 2022, tourism contributed 7.6% of the nation's gross domestic product from the arrival of 8.47 million visitors. However, tourist reservations have declined, and economic growth is significantly threatened due to the prolific invasion of Sargassum biomass on its beaches, especially in the Punta Cana region.

2.2. *Geological Evolution of the Dominican Republic*

Hispaniola (19.0019° N, 71.5724° W) is located on the northern edge of the Caribbean Plate (**Figure 6)** and continues to undergo NW to WNW oblique convergence of the continental margin of the North American plate with the Cretaceous to Eocene Age (56-33.9 million years) Caribbean Volcanic Island Arc system [10, 11]. The rocks of the arc are covered by Late Eocene to Pliocene age siliciclastic and carbonate sedimentary rocks that postdate the magmatic activity of the island arc and record oblique arc-continent collision in the north, as well as active subduction on the southern margin of the arc island (**Figure 7).** To the south and east, the Eastern Cordillera ends buried under the Plio-Quaternary carbonate platform of the Caribbean Coastal Plain. Much of the crustal thickness of the Eastern Cordillera was formed by several kilometers of rocks generated in the Cretaceous by the accumulation of magma and sediments above the subduction zone in a volcanic island arc [11].

2.3. *Brief Geology of Caribbean Coastal Plain* (*Llano Costero del Caribe*)

The city of Punta Cana lies within the Caribbean Coastal Plain known as Llano Costero del Caribe (**Figure 7c),** which is uniquely characterized by a series of limestone terraces that gradually rise from 100 to 200 meters above sea level (asl). The 10- to 40-kilometer-wide Caribbean Coastal Plain lies south of the foothills of the Sierra de Yamasá and the Cordillera Oriental and extends 240 kilometers from the mouth of the Ocoa River to the extreme eastern end of the island.

2.4. *Punta Cana Region, Eastern Dominican Republic*

The city of Punta Cana lies at the easternmost tip of the Dominican Republic, abuts the Caribbean Sea and the Atlantic Ocean, and is known for its 32-kilometer stretch of beaches and clear waters **(Figures 7a–c).** Punta Cana is in the municipality of Higüey and the Juanillo section of La Altagracia Province, or Provincia de La Altagracia (**Figure 7d**). The province occupies an area of 420,000 m2 and borders the Caribbean Sea to the south and east and the Atlantic Ocean to the north. It is in the easternmost part of the country. The area's Punta Cana International Airport is located about thirty kilometers inland on the road from Higüey to La Romana. Punta Cana and the Bávaro area combine to form what is known as La Costa del Coco (the Coconut Coast), an area of lavish, all-inclusive resorts. Punta Cana's coastline extends 95 kilometers, with 37 kilometers of beach between Punta Cana and Bávaro. Bávaro has the most extensive stretch and is known for the species richness of its flora and fauna. Over the last ten years, Punta Cana has undergone vast development, including the construction of numerous tourist resorts and twelve professional golf courses. Water quality degradation and stresses on water resources have increased due to increased urbanization and rapid economic growth.

2.5. *Hydrology of Eastern Dominican Republic*

Fresh groundwater supplies from wells and springs are major sources of potable water within the Dominican Republic, and the quality of the water varies regionally. Punta Cana also relies on the Planicie Costera Oriental coastal aquifer, which consists of permeable reefal limestone, for its water supply. Reefal limestone is deposited in an open marine environment with moderate to high energy conditions [12]. Rio Yuma in the central La Altagracia Province and Rio Chavon in the east provide surface water perennially. A significant alluvial cover exists at several locations along the Yuma River. The water used for consumption in Higüey is extracted from the Sanate River.

-

3. Proposed Methodology

Google Earth satellite imagery of the Punta Cana region in eastern Dominican Republic was viewed to strategize ideal locations for the (1) phytoremediation systems near golf courses along Punta Cana's coastline, (2) deployment of floating aquatic plant booms, (3) intake suction-pumped extraction of Sargassum for biofuel production, and as an integrated approach for mitigating the invasion by pelagic Sargassum mats in this honor's thesis. **Figure 8** is a Google satellite image with areas highlighted in color as markers for the strategic implementation of (1) four phytoremediation systems for nutrient runoff (yellow bold lines) from the golf courses circled by red dashed lines; (2) the location for a 20-kilometer invasive aquatic boom (bold blue line); and (4) the location of an inland bioenergy refinery away from the coastal areas with tourist resorts (tangerine square), businesses, etc.

3.1. *Phytoremediation System Design for Nutrient Absorption*

Several golf courses and residential properties lie within 20–200 meters of the coastline and beaches. Nitrate and phosphate fertilizers are frequently used to stimulate grass growth on golf courses. Runoff from golf courses and urban areas causes eutrophication, leading to dead zones in seawater or other water bodies. Phytoremediation is one of several phytotechnologies that employ vegetation to contain, sequester, remove, or degrade inorganic and organic contaminants in surface water, groundwater, sediment, and soils. It allows the direct uptake of contaminants, e.g., nutrients such as nitrogen (N) and phosphorus (P), by the root systems (rhizosphere) of plants, while physically anchoring the soil from erosion and preventing the leaching of contaminants to groundwater resources and off-site areas. **Figure 9** is a schematic of the design suggested for the four phytoremediation systems positioned for the channelization and routing of runoff from adjoining golf courses and urban areas to reduce the impact of eutrophication on coastal waters. The total nitrogen (N) and phosphorus (P) extracted are expected to be related to the type of plant species (i.e., native or exotic) used in the phytoremediation system and the total plant biomass. Ecological adaptability rather than solely plant nutrient uptake capacity should be considered for the proper selection of potential plant species, as their phytoremediation success will be dependent on the climate, soil type, and soil conditions (e.g., pH, moisture, organic matter, etc.). Two macrophyte species potentially capable of nutrient uptake in the phytoremediation system *are Caladium* sp. and *Spinacia oleracea*. Key considerations should involve research to analyze the plant tissues for nutrient uptake and the relationship between plant survival and growth in the phytoremediation system.

3.2. *Deployment of Floating Aquatic Plant Booms*

Aquatic booms are designed to control the impact of macroalgae like Sargassum, invasive marine plants, and debris along coastlines to protect beaches, hotels, lakes, marinas, boat docks, and ports (**Figures 4a–e**). They are intended to deflect and redirect aquatic debris and the intensive invasion by Sargassum while permitting the free passage of other aquatic life beneath the barriers both seasonally and over the long term. In addition, they are not constructed with netting or materials that could potentially trap aquatic life, leading to severe injury and/or death, or cause environmental damage. A floating aquatic barrier was recently installed along the Punta Can coastlines; however, barriers are only one part of the solution to mitigating the ever-growing invasion by Sargassum. A 20-kilometer invasive aquatic boom (**Figures 8-9**) must be installed along the extent of the Punta Cana Coastline from Cap Cana to near Farallon to manage and prevent the encroachment of Sargassum on the beaches.

3.3. *Routing and Biofuel Conversion of Sargassum*

Rather than allow large Sargassum blooms barred by aquatic booms to block sunlight and kill seagrass on the ocean floor or die and decompose to deprive other marine organisms of oxygen, valorization of the macroalgae biomass into bioenergy such as methane could provide clean energy useful to the tourism industry [2, 13]. A route for the conveyance of Sargassum from behind the aquatic boom to a constructed biorefinery facility for biomass pretreatment and the conversion to fuel. A large custom-designed polyvinyl chloride (PVC) tube would need to be extended from just behind the southern end of the invasive aquatic boom to the biorefinery facility positioned inland from the coastline indicated by the tangerine dashed line in **Figure 8**. A large, well-designed suction inlet device with a high-pressure intake pump should be used to pull in pelagic Sargassum mats through the PVC tube suspended at the seawater surface.

Easy harvesting and the low breeding cost of macroalgae compared to microalgae make Sargassum species (i.e., Natans and Fluitans) considerable biomass for fuel production and byproducts [2, 13, 14]. Several options for pretreatment steps of Sargassum are microbial valorization, chemical hydrolysis, anaerobic digestion, vapor explosion, ionic liquids (IL), high-pressure technology pretreatment, and biological pretreatment (Orozco Gonzalez, 2022). The absence of the appropriate microorganisms that can decompose hydrolysis-resistant structural components (e.g., cellulose and lignin) results in low methane yields from some species. For maximum yield to be attained from macroalgal biomass, the development of a suitable pretreatment is required. Two promising processes for biofuel production from algal biomass are hydrothermal liquefaction (HL) and feedstock for methane (CH_4) fermentation. HL uses less energy to produce biofuel compared to other biofuel production techniques as an energy extractor. In addition, alginate, the main polysaccharide, is a valuable hydrocolloid in Sargassum that is biodegradable and able to generate films. Sodium alginate is used in the pharmaceutical, biomedical, textile, cosmetic, and food industries [2]. Therefore, Sargassum could be used to provide supplemental energy for the tourist industry and byproducts for several industries, showing potential as a cost-effective investment. The energy corporation of Punta Cana, Consorcio Energético Punta Cana-Macao (CEPM), has committed to reducing its environmental footprint and promoting projects that seek to protect the natural resources, with the aim of working continuously in favor of the environment. The conversion of Sargassum biomass to bioenergy could benefit the tourist industry and probably serve as a CEPM in not just the Punta Cana region but other regions of interest.

3.4. *Sargassum Monitoring from Historical Satellite Imagery*

Changing climatic conditions, Sargasso Sea circulation, and nutrient upwelling are expected to continue the intense invasion of Sargassum sp. on beaches on the eastern coasts of the Caribbean, Mexico, and Florida, USA, since the start of the invasion in 2011 [2, 3, 4]. Real-time satellite monitoring of Sargassum is available at a few websites [15, 16]. A solution to increasing invasive Sargassum cannot be limited to tourist areas but must include the eastern sides of the Caribbean, Mexico, and the USA. Sargassum monitoring using satellite imagery from several satellite sensors with different spatial resolutions to detect the migration mats of Sargassum from space allows for wide aerial coverage. Environmental data such as wind, ocean currents, and ocean chemistry combined with satellite monitoring are simpler and faster methods to raise awareness in preparation for mitigation plans to manage and reduce the impacts of invasive pelagic Sargassum. Overall, understanding the dynamics of Sargassum, the prediction of its density and size, and the potential for the biomass to encroach on coastlines will subsequently lead to improved methods for its detection, monitoring, and management by coupling ocean circulation modeling, chemistry, and satellite detection by imagery.

4. Discussion

Factors such as changing climate, ocean circulation, deep ocean upwelling of nutrients, and nutrient runoff from rivers and land continue to increase the size of invasive Sargassum mats encroaching on tropical and temperate coastlines. A cost-effective solution for the management and mitigation of pelagic macroalgae demands the application, testing, and evaluation of several technologies to identify the most efficient and cost-effective solution for mitigation that could benefit several coastal cities in the Caribbean, Mexico, and the USA. To date, several authors have proposed or used one method to address the various aspects of the Sargassum problem: manual removal (**Figure 2**); piloting, testing, and patenting a scalable, cost-effective Sargassum Ocean Sequestration (SOS) suction inlet [2]; installation of aquatic booms or barriers [7]; valorization of biomass [2]; and the development of new deep learning models specific for *Sargassum* detection based on an encoder-decoder convolutional neural network (CNN) [17], to name a few. The four integrated and environmentally friendly mitigation strategies for the monitoring and invasive pelagic Sargassum take into consideration the need to prevent nutrient transport to the beaches, Sargassum encroachment on the beaches, the recycling of matter into energy, and real-time satellite monitoring of changes in Sargassum macroalgae from space.

A pilot or bench-scale study of the mitigation strategies suggested in this honors research thesis could be tested, evaluated, and modified with emerging technologies based on the coastline of interest and the Sargassum species. Furthermore, the solution to invasive Sargassum in response to a changing climate will require collaboration between research universities, industry, the Caribbean Environment Program (CEPM), larger oil companies, UNESCO, and the IDB to solve the Sargassum problem.

5. Concluding Remarks and Recommendations

The first integrated approach of its kind is being proposed in this honor's thesis for monitoring, management, and valorization of the brown pelagic macroalgae species of Sargassum using (1) phytoremediation of inland runoff to Punta Cana's coastlines, (2) deployment of invasive aquatic booms, (3) biofuel extraction, alginate and other byproducts, and (4) historic satellite monitoring of approaching Sargassum mats. Furthermore, satellite tracking and ocean circulation modeling along the Great Atlantic Sargassum Belt (GASB) are expected to dictate and update the types methodologies used to for management and mitigation of increasing invasive biomass and on eastern coastlines of the Atlantic. Finally, the integrated strategies could be evaluated and tested by scientists and researchers in academia and industry in the Caribbean, the Gulf of Mexico, and North America as alternative mitigation methods to reduce the economic and environmental increasing aggregations of algal biomass across the broader region.

6. References

1. https://www.unep.org/cep/resources/factsheet/understanding-spread-sargassum-Caribbean
2. Gray, L. A., Bisonó León, A. G., Rojas, F. E., Veroneau, S. S., Slocum, A. H., 2021. Caribbean-Wide, Negative Emissions Solution to Sargassum spp. Low-Cost Collection Device and Sustainable Disposal Method, Phycology 1(1), 49-75, https://doi.org/10.3390/phycology1010004
3. Wang, M., Hu, C., Barnes, B., LaPointe, G.P., Montoya, J. P., 2019. The Great Atlantic Sargassum Belt, Science V. 365(6648).
4. https://www.nesdis.noaa.gov/news/sargassum-algae-amid-the-sargasso-sea
5. https://today.tamu.edu/2015/04/02/new-nasa-texas-am-galveston-app-allows-public-to-track-seaweed-hitting-texas-coast/
6. https://optics.marine.usf.edu/projects/SaWS/pdf/Sargassum_outlook_2023_bulletin2_USF.pdf
7. https://www.elastec.com/how-to-control-sargassum-seaweed/
8. https://www.npr.org/2023/03/15/1163385168/sargassum-seaweed-florida-mexico-beaches

9. https://www.traveloffpath.com/brown-smelly-seaweed-called-sargassum-invading-most-popular-caribbean-destinations/
10. Lebron, M. C. Perfitt, M. R., 1993. Stratigraphic and Petrochemical Data Support Subduction Polarity Reversal of the Cretaceous Caribbean Island Arc, Journal of Geology 101(3), pp. 389-396, The University of Chicago Press.
11. Escuder-Viruete, J., Fernández, F. J., Pérez Valera, F. J., and A. Medialdea, A., 2023. Present-Day Caribbean-North American Oblique Convergence through the Ocoa-Bonao-La Guacara Fault Zone, Southern Central Hispaniola: A Transition Zone between Oceanic Subduction and Arc-Oceanic Plateau Collision, Tectonics 42(4), 10.1029/2022TC007618.
12. https://www.sam.usace.army.mil/Portals/46/docs/military/engineering/docs/WRA/Dominican%20Republic/Dominican%20Republic%20WRA.pdf
13. https://www.jpost.com/jerusalem-report/caribbean-environmental-disaster-meets-israeli-innovation-653536
14. Guo J, Zhuang Y, Chen L, Liu J, Li D, Ye N. Process optimization for microwave-assisted direct liquefaction of Sargassum polycystum C. Agardh using response surface methodology. *Bioresour Technol*. 2012; **120:19**-25.
15. https://sargassummonitoring.com/2023/01/30/28-01-2023-sargassum-seaweed-satellite-views/
16. https://datastore.cls.fr/wp-content/uploads/sargassum/CARI/CLS_SARGA_ATL_2023-04-26.png
17. Laval, M., Abdelbadie, B., Descloitres, J., Salazaar-Garibay, A., Schamberger, L., Minghelli, A., Thiebaut, T., Dorville, R., Mazoyer, C., Zongo, P., Luc, C., Chevalier, C. 2023. Detection of *Sargassum* from Sentinel Satellite Sensors Using Deep Learning Approach, Remote Sensing 15(4), 21 p., 1104; https://doi.org/10.3390/rs15041104

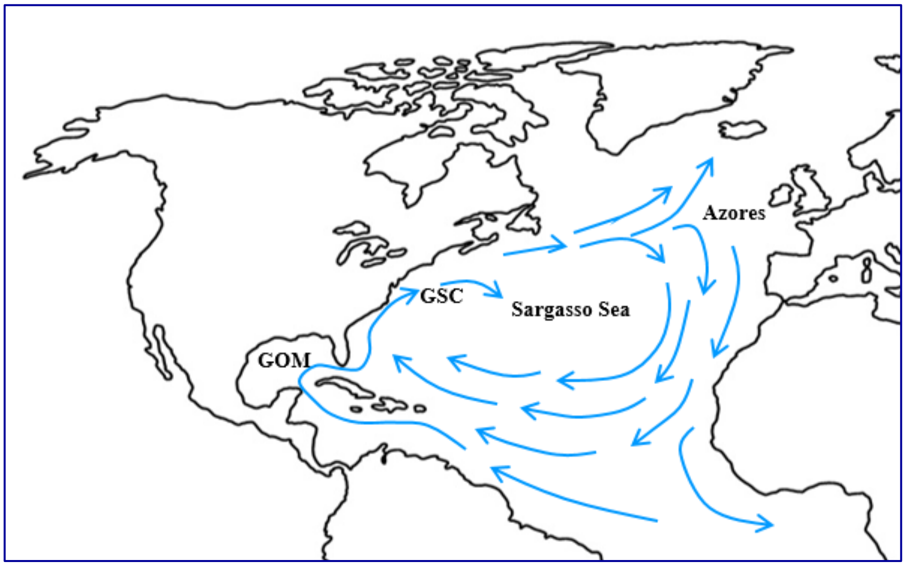
7. Figures

a.

Figure 1a. Photo of Sargassum nantans (Narrow Leaf Gulfweed), Family Sargassaceae -Brown marine algae

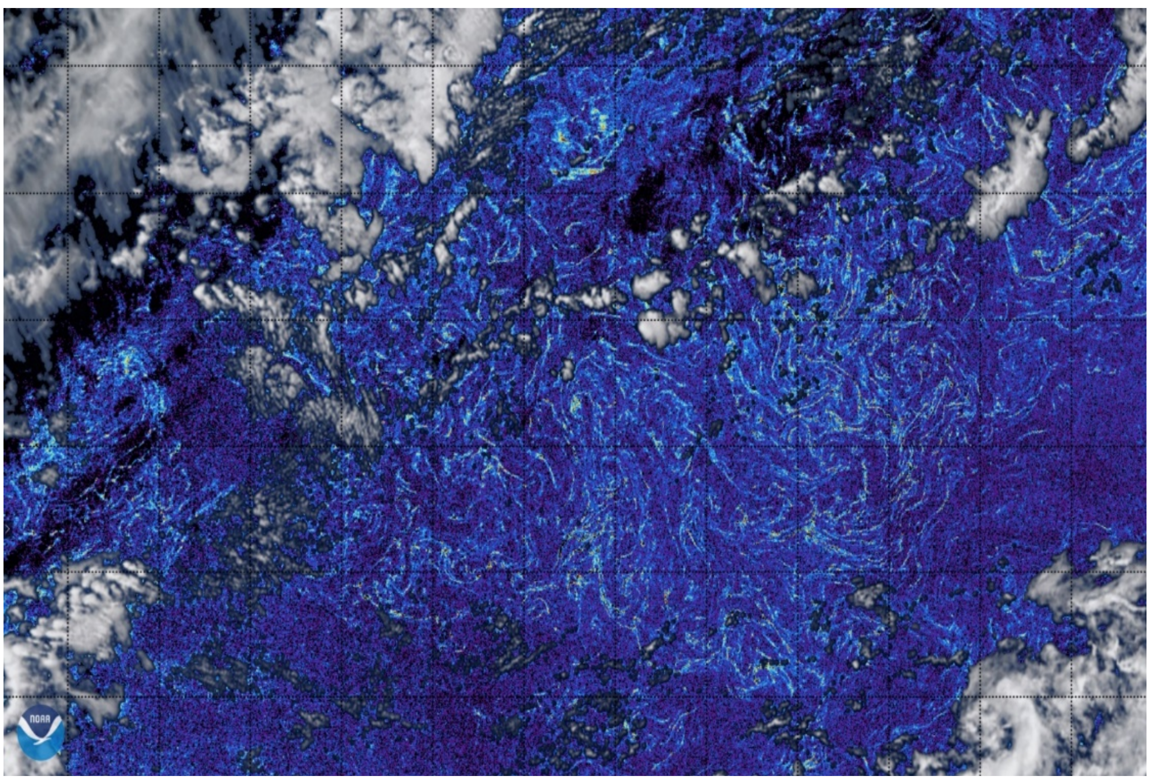
b.

Figure 1b. Photo of a Sargassum blob on a beach in Punta Cana, Dominican Republic.



a.

Figure 2a. Schematic of ocean circulation in the North Atlantic Ocean



b.

Figure 2b. Captured satellite imagery of massive amounts of *Sargassum* algae on the normally crystal blue waters of the Sargasso Sea. Courtesy of NOAA CoastWatch Atlantic Ocean Viewer. The cyan and green colored wisps and swirls indicate floating *Sargassum* patches. Indications of high chlorophyll content were calculated from the European Space Agency's Sentinel-3 Ocean and Land Color Instrument (OLCI) data. (March 3, 2021).

Figure 3. Photo of a beach worker manually raking Sargassum from a beach at Punta Cana.

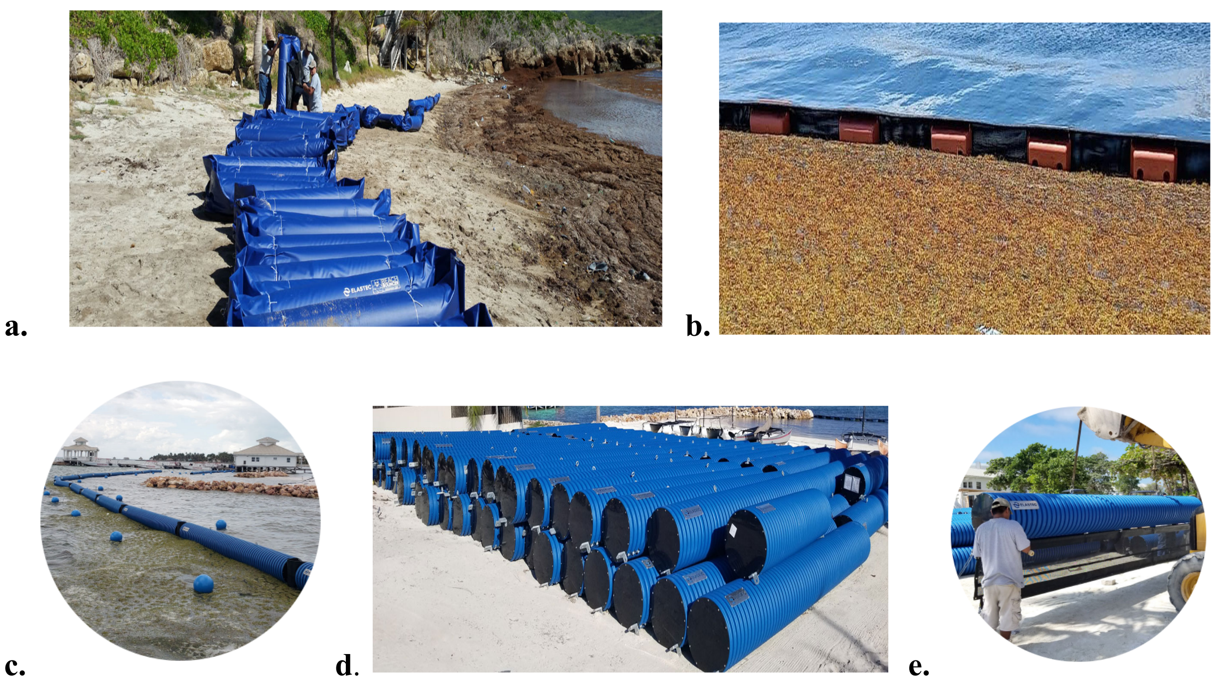
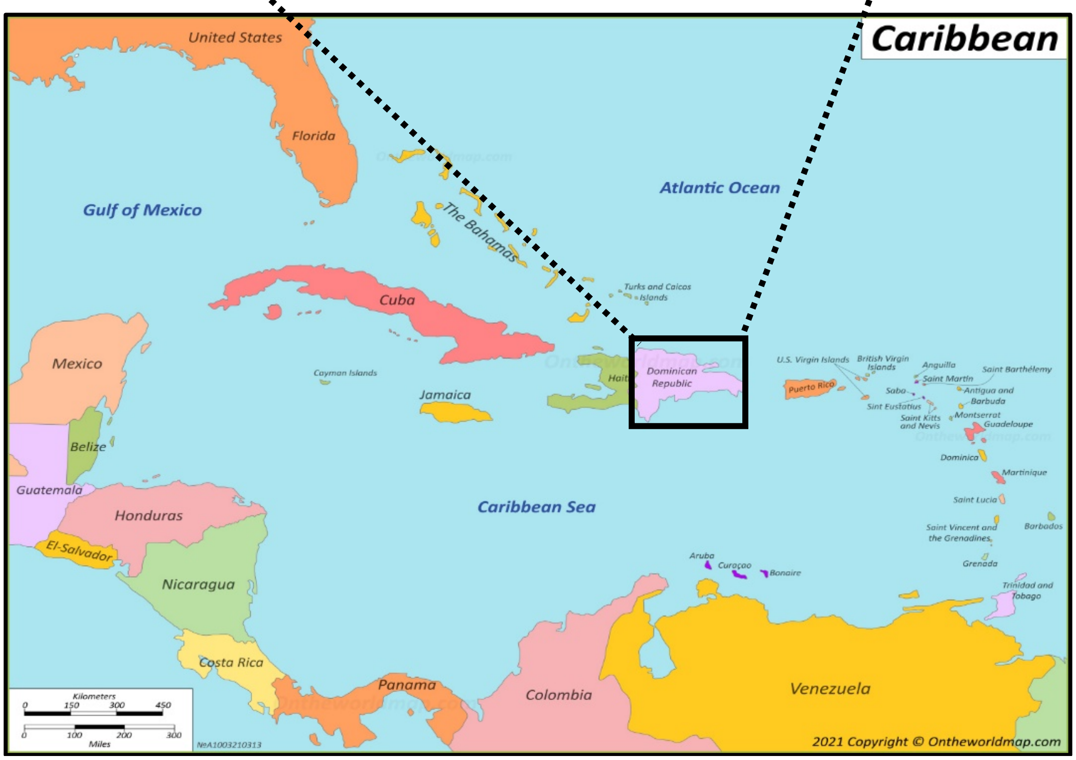


Figure 4. A variety of beach bouncer model types are used as barriers to Sargassum floats.

a.



b.

Figure 5. (a) Geographic of the Dominican Republic. b. Location of the Dominican Republic.

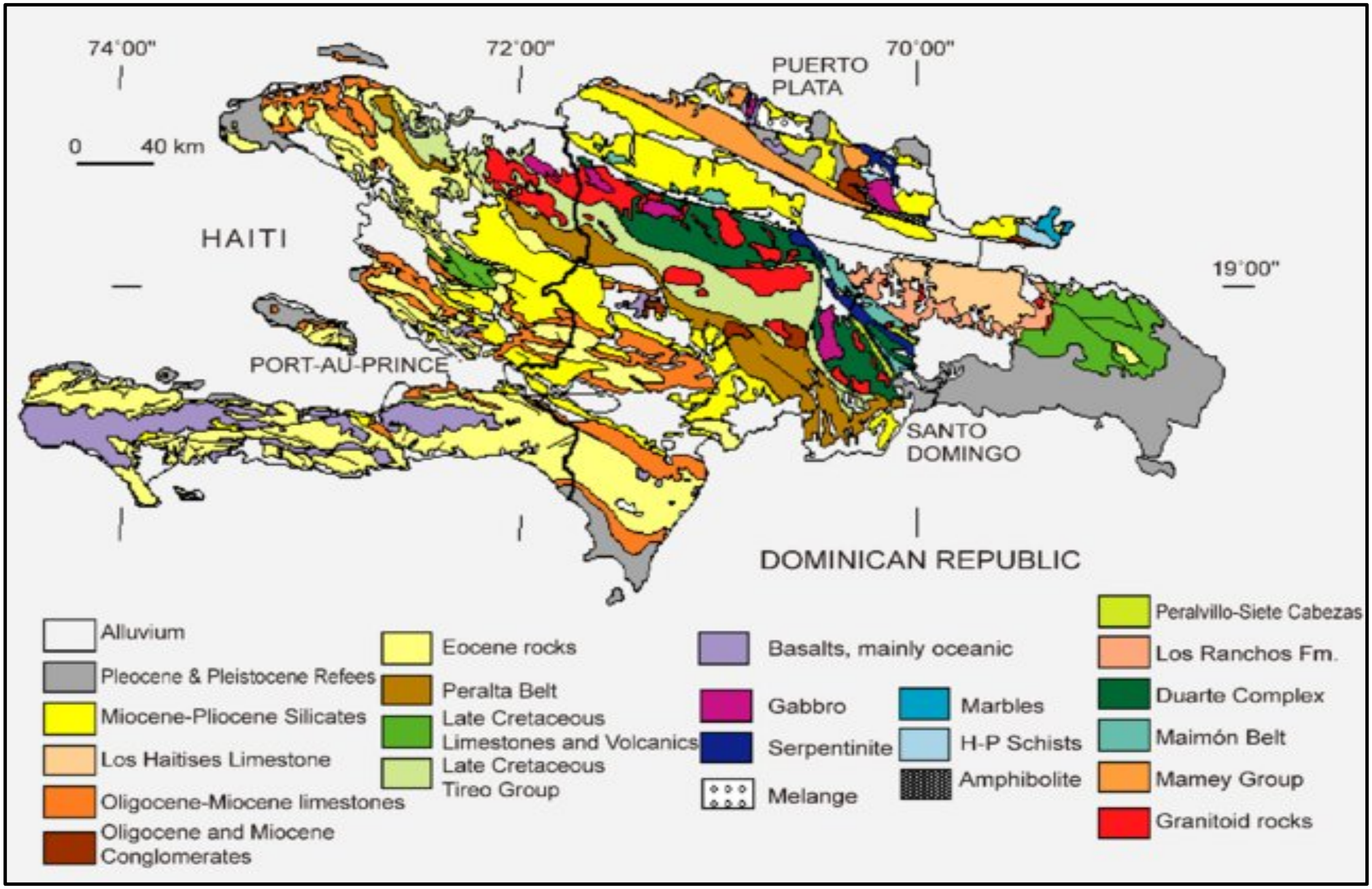
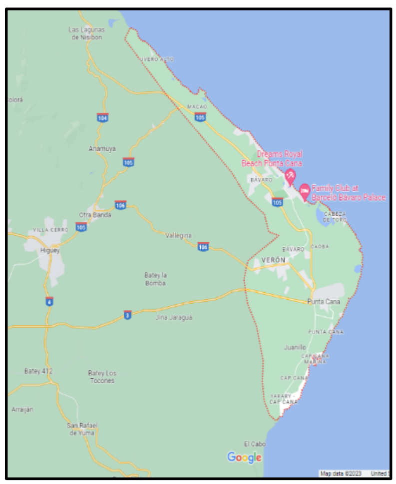


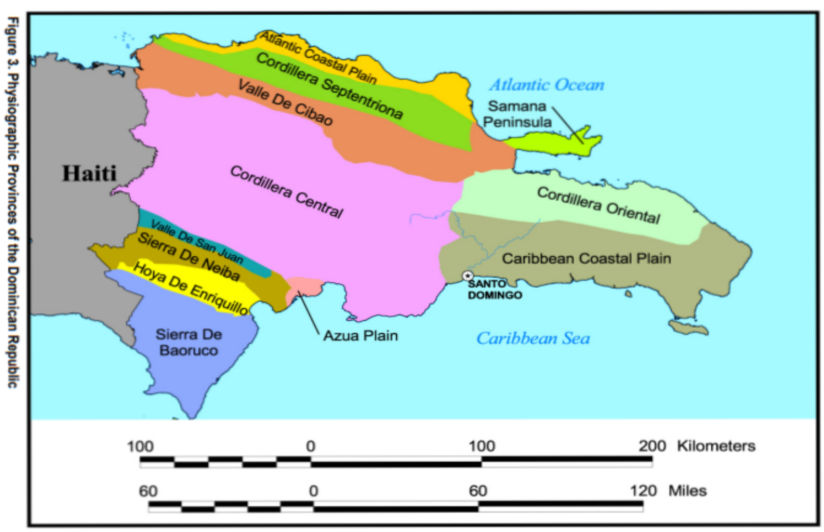
Figure 6. Geological map of the Dominican Republic (*R. Delanoy and R. Mendez-Tejeda; 2017* [9].

a.



b.

c.



d.

Figure 7. a. Location of Punta Cana, Dominican Republic. b - c. Outline of Punta Cana ton a map and satellite image. d. Physiographic provinces of the Dominican Republic.

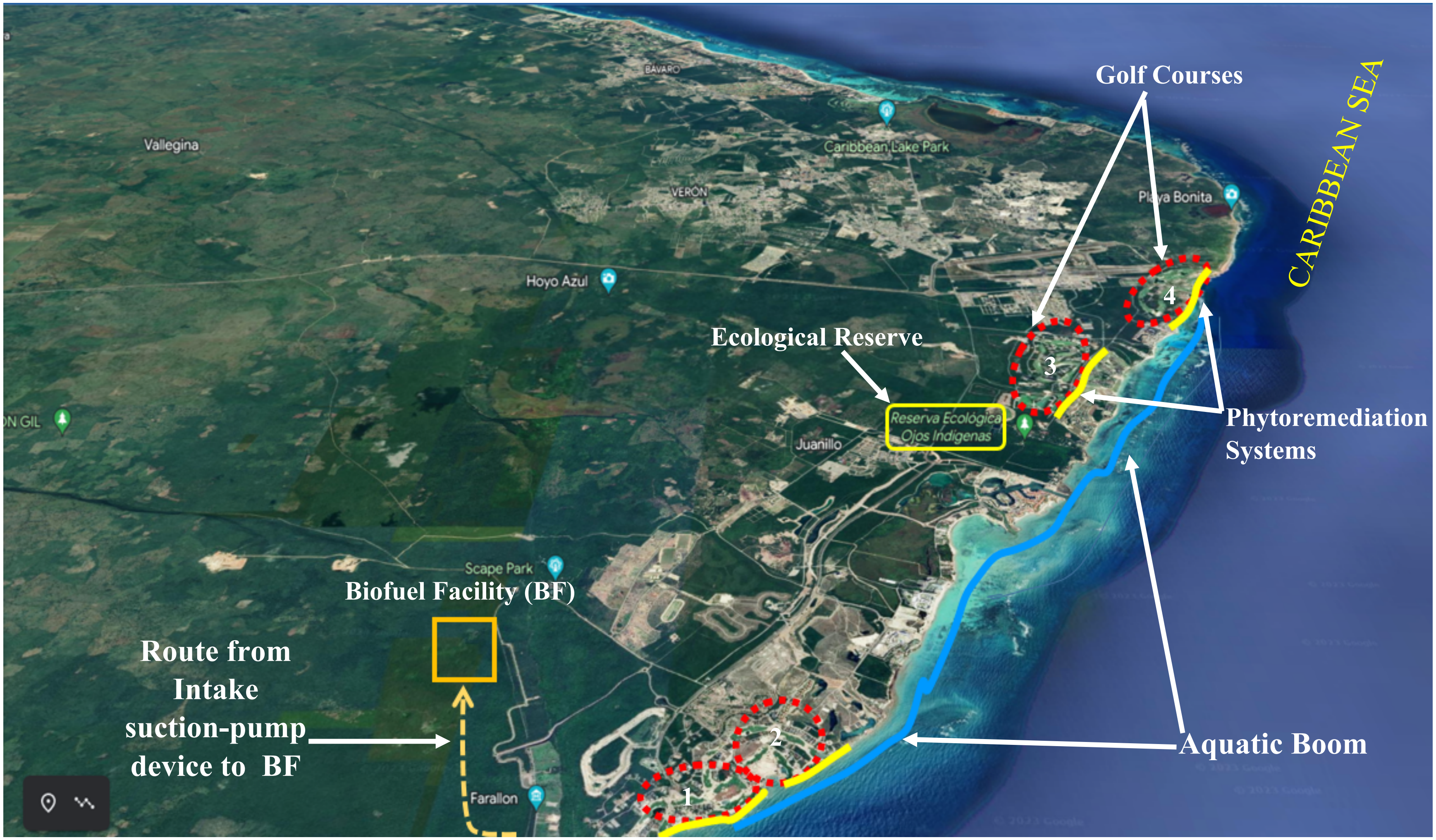


Figure 8. Google Earth Satellite Image highlighting the strategic locations for the mitigation of pelagic Sargassum along the Punta Cana coastline.

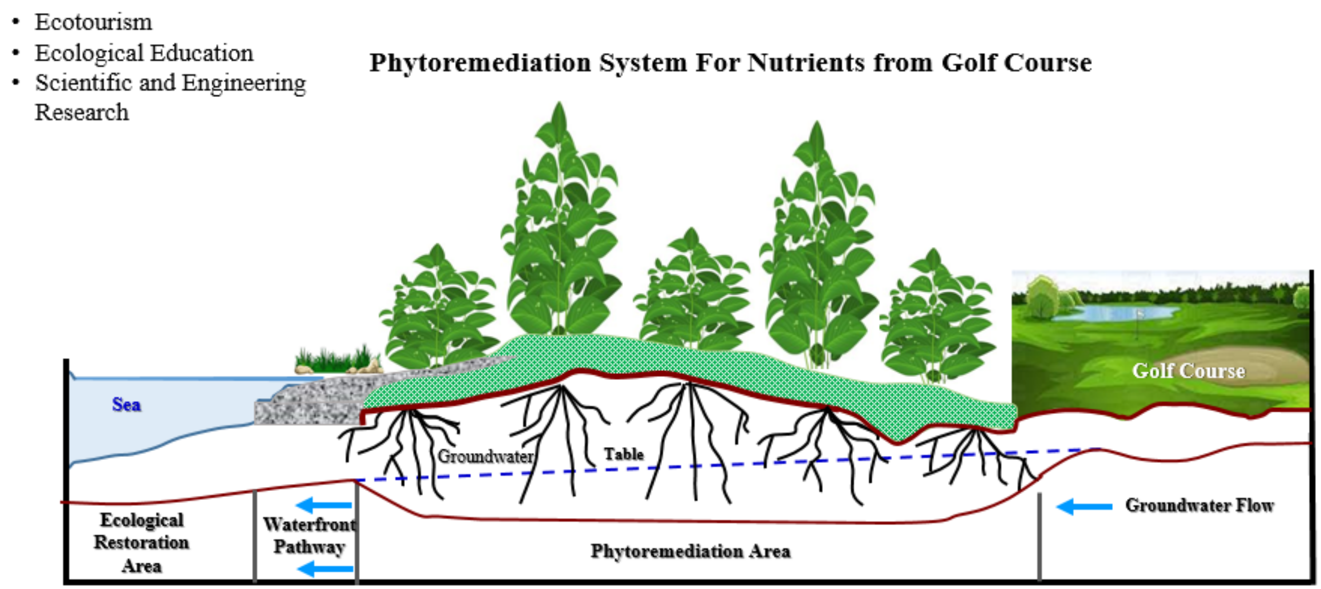


Figure 9. Proposed phytoremediation system design for the removal of nutrients by tropical plant species

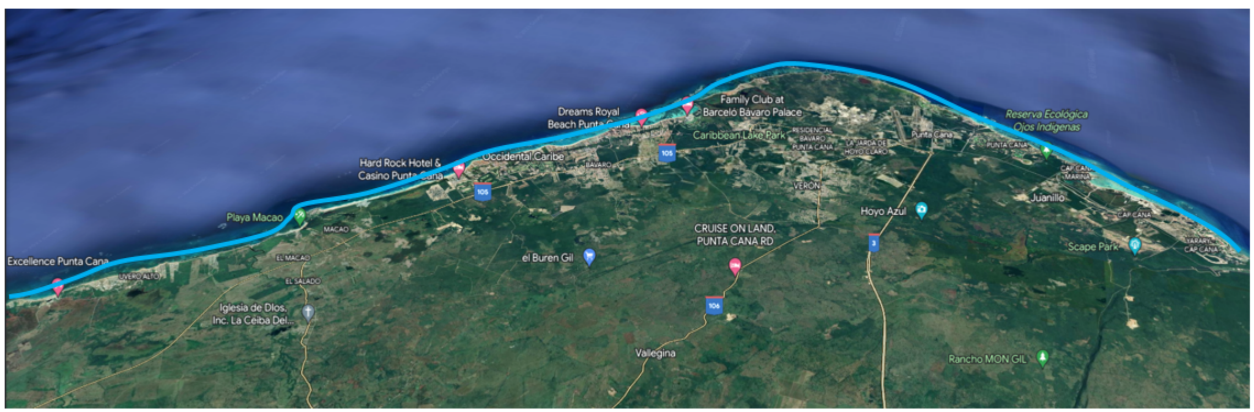


Figure 10. Proposed phytoremediation system design for the removal of nutrients by tropical plant species