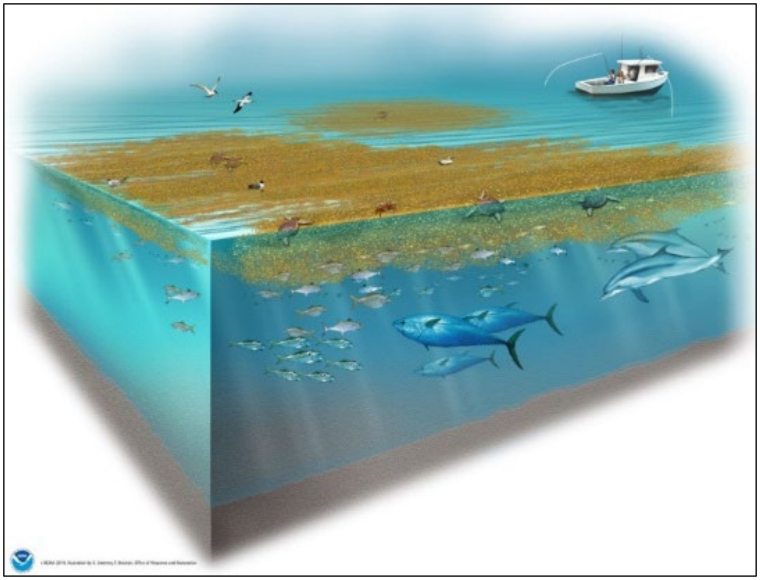
Oil Spills and Pelagic *Sargassum*

Planning and Response Considerations

July 2023



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INTRODUCTION

This report is intended to assist those who work in oil spill response and planning where pelagic *Sargassum* is at risk from or may interact with oil spills. *Sargassum* is a floating macroalgae or seaweed primarily found in the Caribbean, Gulf of Mexico, and South Atlantic regions (in U.S. waters). *Sargassum* occurs at the ocean surface and aggregates into offshore drift lines and patches that are important habitat for wildlife and fisheries resources. *Sargassum* can also be important when it strands onshore, positively influencing beach geomorphology, ecology, and wildlife. However, large *Sargassum* blooms in recent years have resulted in mass stranding events that can have negative environmental and socioeconomic impacts. Periodic large *Sargassum* blooms or influx events are linked to global climate and ecosystem change, and further heighten the need to examine oil spill preparedness and response considerations for this resource, due to increased abundance and the interaction of multiple stressors. By understanding the basics of the ecology of *Sargassum*, learning from past oil spills and responses, and incorporating other recent information on *Sargassum* blooms or influx events, we can better plan for, protect, and make appropriate decisions for how to respond to future oil spills. Those dealing with *Sargassum* influx events (without oil) may also find value in experience and methods gleaned from the oil spill response community.

This report is intended to be a technical “job-aid” for spill response planners and scientists. Our goal was to summarize as much of the scientific literature and experience from a variety of sources into a format that balances too much versus too little detail. Every spill is a unique combination of conditions–oil type and amount, location, time of year, habitats and species of concern, etc. Responders have to evaluate all of these factors and make a decision on the best course of action, under short timeframes. No one has the answer for how to respond for every spill. However, we hope that we have provided the reader with practical and useful information to help them make informed decisions.

We have organized the topics by chapter, with references provided at the end of each chapter. Chapter 1, *Sargassum Ecology*, provides an overview of the ecology of *Sargassum* and associated communities. Chapter 2, *Impacts on and from Sargassum*, provides information on what we know about how oil spills can affect *Sargassum* and associated fauna, as well as touching on impacts from *Sargassum* influx or mass stranding events (in the absence of oil). In Chapter 3, *Oil Spill Response Considerations and Sargassum*, we discuss information to support oil spill response and decision making relative to *Sargassum*, both offshore and onshore, including an introduction to information on response to large *Sargassum* influx events. Lastly, Chapter 4, *Sargassum Case Studies*, includes three response case histories involving *Sargassum*.

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Chapter 1. *Sargassum* Ecology

Key Points

- Pelagic *Sargassum* consists of two species of floating algae that are transported and aggregated into patches, clumps, or windrows according to oceanic processes.
- *Sargassum* plays important ecological functions (e.g., primary productivity, nutrient transport, habitat facilitation) both in the water and on shorelines.
- Floating *Sargassum* aggregations harbor a complex community of organisms and are critical habitat for sea turtles and essential habitat for commercially and recreationally important fish.
- *Sargassum* abundance and distribution varies annually, according to factors that are not fully understood.
- Large influxes of *Sargassum* have occurred periodically in the Caribbean, Gulf of Mexico, and Atlantic coast of Florida beginning in 2011, causing ecological, economic, and health concerns.

What is *Sargassum*?

Sargassum is a floating macroalgae, or seaweed, which occurs at the ocean surface and aggregates into patches of varying size based on winds, currents, and waves. *Sargassum* is a genus of brown macroalgae consisting of over 300 species worldwide. Most species of *Sargassum* have a benthic phase; however, this guide is focused on "holopelagic" *Sargassum* species, which spend their entire lifecycle floating at sea. Two species of holopelagic *Sargassum* are found in U.S waters, *S. natans* and *S. fluitans*. For the purpose of this document, they are collectively referred to as *Sargassum*.

Sargassum patches function as islands of concentrated biological activity in offshore surface waters which are otherwise low in productivity. As such, *Sargassum* supports a unique, dense community of small, cryptic marine organisms, as well as juvenile sea turtles, sport fish (e.g., dolphinfish, billfish, tuna), and pelagic seabirds. *Sargassum* is present in U.S. waters in the Caribbean, Gulf of Mexico, and South Atlantic regions. Further north, *Sargassum* can be present offshore in association with the Gulf Stream and Sargasso Sea. Abundance is typically higher in summer months.

Sargassum Life History

Pelagic *Sargassum* populations in the Atlantic Ocean are comprised primarily of three morphotypes of two different species, which vary physically in blade morphology, branching patterns, and complexity (Figure 1-1). Individual *Sargassum* plants are typically 20-80 cm in diameter, gold-brown in color, and exhibit complex branching patterns. Interspersed in the foliage are small berry-like structures called pneumatocysts, that are filled mainly with oxygen and keep the plant afloat. *Sargassum* propagates by vegetative fragmentation and does not have a means of sexual reproduction. *Sargassum* aggregates into concentration areas in the ocean based on wind, current, and wave movements, forming long ‘weed lines’ or ‘windrows’ in areas with downwelling currents due to Langmuir circulation, internal waves, or convergence zones along fronts. Outside of convergence zones, *Sargassum* can aggregate into large patches or clumps that can be tens to hundreds of meters or more across.

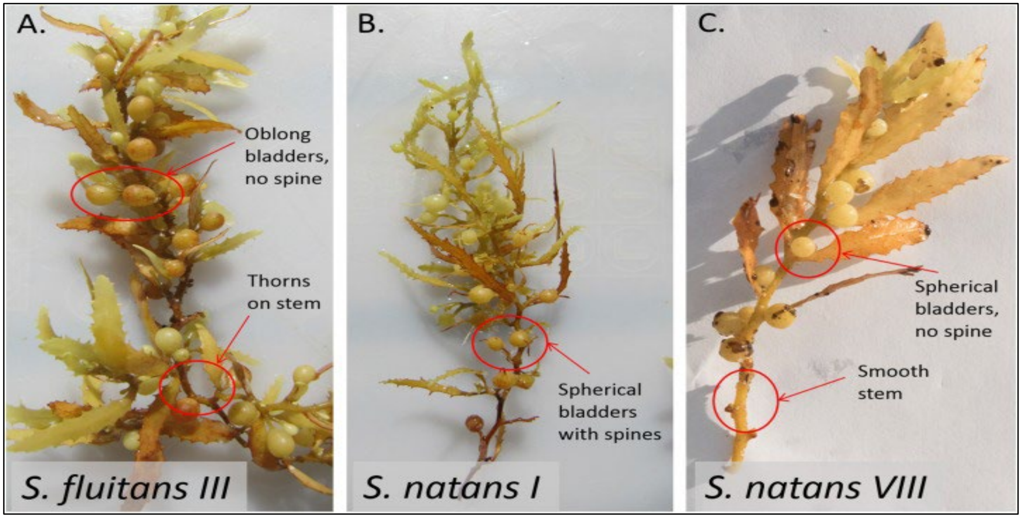

Figure 1-1. Morphological differences between the three dominant *Sargassum* morphotypes. Source: Govindarajan et al. 2019.

Sargassum growth is dependent on many factors including insolation (sunlight intensity), temperature, and available nutrients. The exact factors that determine *Sargassum* growth are complex and vary by location and morphotype (e.g., Magaña-Gallegos et al. 2023a). *Sargassum* has been observed to grow readily at temperatures and salinities normally found throughout its range, with some evidence of growth limitation at higher temperatures (>31°C; Magaña-Gallegos et al. 2023b; Corbin and Oxenford 2023) and lower salinities (Wang et al. 2019).

Pelagic environments are generally nutrient poor, and the limiting factor to *Sargassum* growth is typically nutrient availability. *Sargassum* plants are thought to experience both nitrogen and phosphorus limitation on a broad scale, and early field studies showed that both growth and productivity could be enhanced by the addition of both nitrate and phosphorus (Lapointe et al. 2021). *Sargassum* has adaptations which allow it to take advantage of scarce nutrients; for example, the presence of enzymes that allow sequestration of alternate forms of phosphorus, and mutualistic relationships with nitrogen-fixing cyanobacteria (Lapointe 1995). Additionally, the high concentrations of fish and invertebrates associated with *Sargassum* patches create environments that have elevated ammonium and soluble reactive phosphorus (SRP) concentrations from metabolic excretion, resulting in a readily available source of nitrogen and phosphorus for *Sargassum* uptake (Lapointe et al. 2014).

Differences in nutrient limitation and resulting growth rates vary by geography. *Sargassum* can double in biomass in as little as 10-11 days in nutrient-rich neritic environments (from the shoreline to the offshore edge of the continental shelf), whereas doubling rates are on the order of 40-50 days in nutrient-poor environments, such as the Sargasso Sea (Lapointe et al. 2014). Higher *Sargassum* areal cover has been observed near major river plumes concurrent with nitrogen and phosphorus enrichment of these waters (Lapointe et al. 2021). Long-term increases in nitrogen content in marine waters have been correlated to decreasing nitrogen limitation in *Sargassum* (Lapointe et al. 2021) and may be contributing to increased blooms of *Sargassum*.

Sargassum mortality can occur through a number of methods. Some biomass is lost to incidental consumption by associated fauna (e.g., sea turtles, fish) while foraging; however, the consumption of *Sargassum* itself by herbivorous species is relatively low compared to consumption of associated epifauna, zooplankton and phytoplankton (e.g., Rooker et al. 2006). *Sargassum* mortality due to sinking is caused by fragmentation of weed clumps and successive sinking of less buoyant fragments, excessive growth of fouling organisms, disease, and/or entrainment of clumps in downwelling currents (Baker et al. 2018). *Sargassum* is sensitive to desiccation and will experience tissue damage if exposed to dry air for as little as 7-10 minutes. Plants will die rapidly after washing ashore and can even experience tissue damage due to desiccation in very calm seas (SAFMC 2002). It has also been theorized that *Sargassum* growth follows an intrinsic annual growth cycle that is inherent to the plant, which has been shown to occur in other species of brown algae but not for *Sargassum* (Wang et al. 2019). The relative contribution of these sources to the overall population dynamics of *Sargassum* is not known.

Distribution and Abundance

Large-scale *Sargassum* distribution and biomass are determined by currents and wind. Entrainment in gyres with favorable habitat for growth during the winter months, such as the North Equatorial Recirculation Region, can lead to larger standing stocks of *Sargassum*. As currents weaken seasonally, *Sargassum* leaves these systems and is advected to other geographies. As *Sargassum* travels with the currents, it can be exposed to conditions that can accelerate growth such as nutrient-rich river plumes or upwelling areas. Currents then bring *Sargassum* to Caribbean island nations, the southeastern United States, Mexico, Central America, northeastern South America, and parts of West Africa.

The seasonality of these patterns leads to annual *Sargassum* blooms from Spring-Fall occurring in the Caribbean Sea, Gulf of Mexico, and South Atlantic U.S. (Gower et al. 2013; Wang et al. 2019). Fluctuations in sources of natural mortality, such as cyclones and seasonal overgrowth of fouling organisms, may also play a role in the seasonality of *Sargassum* populations (Putman and Hu 2022; Sosa-Gutierrez et al. 2022). The abundance of *Sargassum* in the North Atlantic fluctuates annually, according to climactic conditions, the standing stock of *Sargassum* biomass, and inherent variations in source populations of *Sargassum*.

Recent (2011-present) Influx Events and the Great Atlantic Sargassum Belt

Historically, most *Sargassum* production was thought to occur in the Sargasso Sea (Figure 1-2). However, since 2011, unusually large (in some cases, ‘massive’) amounts of pelagic *Sargassum* have periodically inundated shorelines in the Caribbean, Gulf of Mexico, Atlantic coast of Florida, and west coast of Africa. The origin of these blooms was unknown at the time, and current patterns precluded the Sargasso Sea from being the source.

As these occurrences have become more common, researchers have identified a second area of *Sargassum* proliferation, the North Equatorial Recirculation Region, which gives rise to the ‘Great Atlantic *Sargassum* belt’ (Franks et al. 2016; Wang et al. 2019). *Sargassum* likely expanded into this area from the Sargasso Sea as a result of the extreme North Atlantic Oscillation (NAO) that occurred in Winter 2009-2010 (Johns et al. 2020). Massive bloom events originating from this region are attributed to seed populations that persist through the winter. These populations begin growing in the spring due to increases in nutrients that are brought to the surface by seasonal wind-driven changes in open-ocean upwelling and vertical mixing. *Sargassum* populations then move north and west where they are influenced by nutrient input from the Amazon River (Wang et al. 2019; Johns et al. 2020).

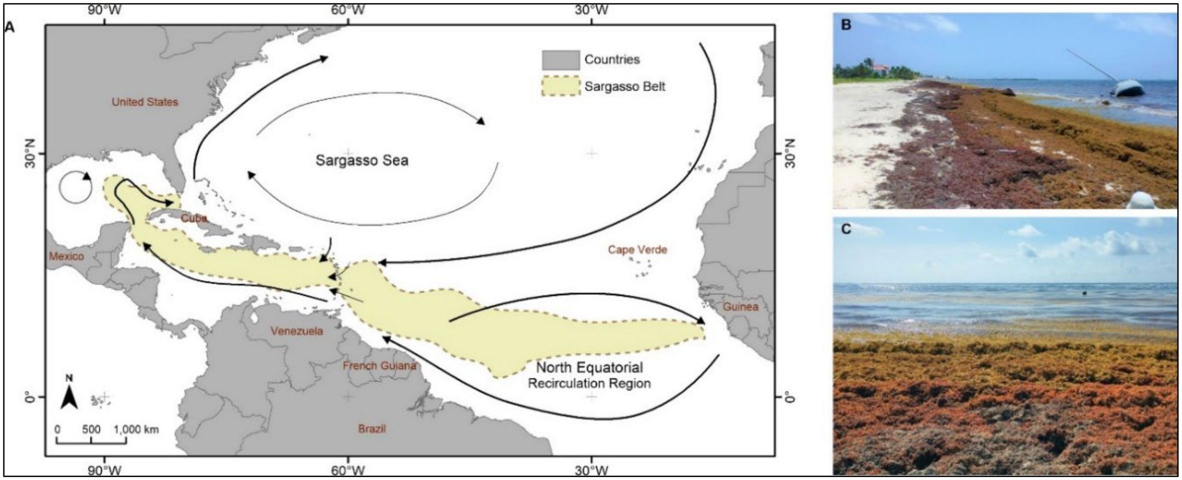

Figure 1-2. (A) Schematic representation of main ocean current patterns and areas of *Sargassum* accumulation in the Atlantic Ocean (The Great Atlantic Sargasso Belt; July 2011–2018 configuration; based on information from Wang et al. 2019). (B,C) Accumulation of beach-cast *Sargassum* at Puerto Morelos, in the Mexican Caribbean in June 2021. Source: Uribe-Martínez et al. 2022; photo credit: L. Ribas.

Influx events, or 'blooms', vary interannually in composition of *Sargassum* species and can also include other species of detached benthic *Sargassum* (Vázquez-Delfín et al. 2021). Beaches impacted by these blooms have received up to 100 metric tons of *Sargassum* per kilometer of beach per day during influx events[1]. The continuing persistence of these blooms is debated. Many scientists attribute the blooms to favorable growth conditions that will likely persist in the future (e.g., Wang et al. 2019). However other researchers speculate that it is possible that climatic conditions could eventually lead to periodic nutrient limitation in the tropical Atlantic that will limit population expansion and could eventually lead to its extirpation (Johns et al. 2020). Large influxes can have detrimental ecological and economic impacts to coastal communities where massive amounts of *Sargassum* come ashore (see Chapter 2).

[1] https://www.cavehill.uwi.edu/cermes/projects/*Sargassum*/home.aspx

Pelagic Sargassum Communities

The structure and productivity of *Sargassum* habitats attract a variety of sea turtles, fish, invertebrates, birds, and dolphins (Figure 1-3). *Sargassum* concentrations are a hotspot of biological activity in offshore surface waters which are otherwise generally low in productivity. *Sargassum* production can account for a large proportion of the primary production in the upper meter of the water column in pelagic habitats (SAFMC 2002 and references therein). Additionally, *Sargassum* provides complex structure in an otherwise featureless environment, which is exploited by juveniles and early life stages of marine organisms. Known *Sargassum* assemblages include fungi, micro- and macro-epiphytes, over 145 species of invertebrates, 658 bacterial and archaeal families, over 100 species of fish, numerous marine birds, and sea turtles (Coston-Clements et al. 1991; SAFMC 2002).

Pelagic *Sargassum* harbors a unique community of abundant, small, cryptic organisms many of which are camouflaged to mimic *Sargassum*, including sessile species such as hydroids, bryozoans, tube-worms, barnacles, anemones, tunicates, and other algae; and small motile epifauna, such as flatworms, polychaete worms, snails, nudibranchs, amphipods, isopods, shrimp, crabs, and resident fish (Morris and Mogelberg 1973; Butler et al. 1983; Coston-Clements et al. 1991; Martin et al. 2021; Figure 1-4). At least 10-12 of these species are endemic, occurring only in pelagic *Sargassum* habitats (Coston-Clements et al. 1991; Martin et al. 2021). Recent surveys have examined epiphyte communities associated with pelagic *Sargassum* and found that they are relatively consistent across geographies, but can vary by morphotype of *Sargassum*, likely due to differences in plant morphology (Hunn 2019; Alleyne et al. 2023a). Motile epifauna species also vary across *Sargassum* morphotypes (Martin et al. 2021).

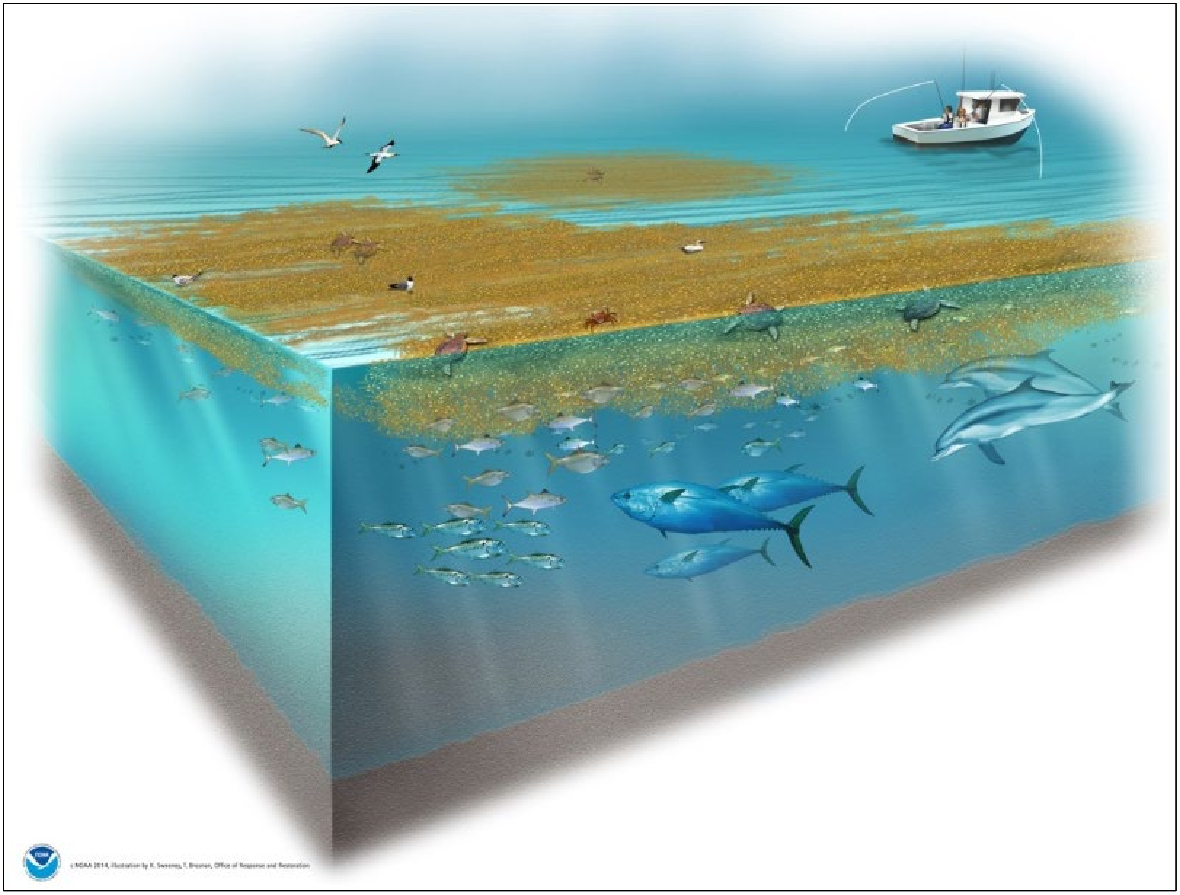

Figure 1-3. Illustration of *Sargassum* and associated fauna, including fish, sea turtles, birds, and dolphins. Human fisheries also target fish species that aggregate near *Sargassum* habitat. Source: DWH NRDA Trustees (2016), graphic by Kate Sweeney for NOAA.

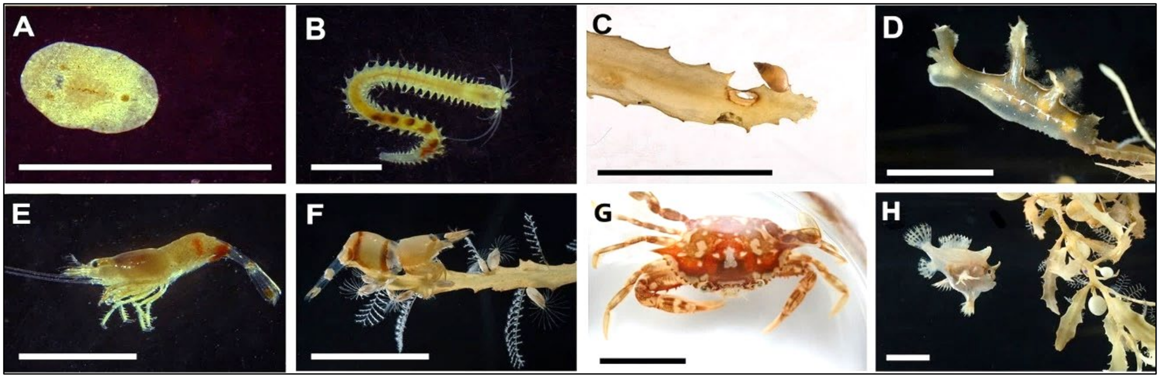

Figure 1-4. Examples of *Sargassum*-associated cryptic, motile epifauna, including endemic species: (A) flatworm, (B) nereid worm, (C) snail, (D) *Sargassum* nudibranch, (E) slender *Sargassum* shrimp, (F) brown grass shrimp, (G) *Sargassum* crab, and (H) *Sargassum* anglerfish. Scale bars ~1 cm. Source: adapted from Martin et al. 2021; photo credits: J. Schell, S. Zankl, J. Bering; used with permission from L. Martin.

Sea Turtles[2]

Pelagic life stages of sea turtles are strongly associated with *Sargassum* habitat. Upon leaving natal beaches, post-hatchling and juvenile sea turtles associate with floating *Sargassum* during developmental years spent in pelagic environments of the Atlantic and Gulf of Mexico (Figure 1-5). Post-hatchling loggerhead and green turtles preferentially orient towards *Sargassum* when they encounter it in the marine environment (Smith and Salmon 2009). In an extensive survey of sea turtles and pelagic *Sargassum* habitats, 89% of the animals sighted were within 1 m of floating *Sargassum*. This association is best described for loggerhead and green sea turtles; however, Kemp's ridley and hawksbill sea turtles were also observed using *Sargassum* habitats (Witherington et al. 2012).

Post-hatchlings are found at or near the surface while in *Sargassum* habitats, primarily drifting with or foraging in *Sargassum* mats (Witherington et al. 2012; Mansfield et al. 2014; de Boer and Saulino 2020). The structural complexity of these mats provides protection from predation for small turtles, along with a concentrated source of food. While turtles cannot digest *Sargassum* itself, they feed on *Sargassum*-

[2] For more information on sea turtle biology and life-history, see the following NOAA oil spill guidelines: Stacy et al. 2019 and Shigenaka et al. 2021.

associated organisms, including attached epifauna, other algae, and small invertebrates. *Sargassum* mats disrupt surface flow and trap waters warmed by insolation, providing a thermal refuge for post-hatchling and juvenile sea turtles. Mesocosm experiments documented a 6°C temperature difference between waters with *Sargassum* and without. Increased temperatures can lead to faster growth and favorable digestion in sea turtles, further enhancing the value of *Sargassum* as turtle nursery habitat (Mansfield et al. 2014).

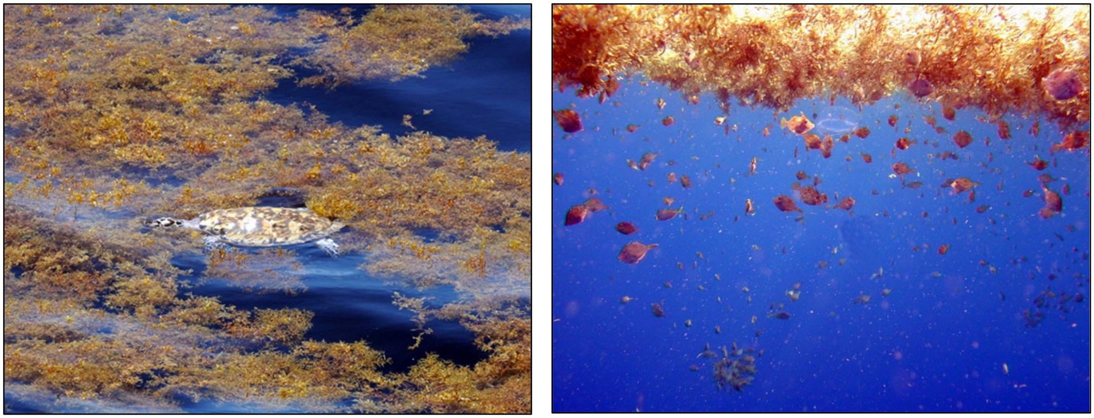

Figure 1-5. A young loggerhead sea turtle resting among *Sargassum* (left) and smaller fishes, such as filefishes and triggerfishes in and among the *Sargassum* (right). Source: NOAA, https://blog.response.restoration.noaa.gov/sea-turtles-seaweed-and-oil-spills.

Due to the value of *Sargassum* habitat to loggerhead sea turtles, areas where sea turtles associate with *Sargassum* are designated as Critical Habitat for the Northwest Atlantic Distinct Population Segment (DPS) of loggerheads under the U.S. Endangered Species Act (Figure 1-6; 79 FR 39855). The following primary constituent elements of loggerhead Critical Habitat are associated with *Sargassum* (NMFS 2013):

1) Convergence zones, surface-water downwelling areas, and other locations where there are concentrated components of the *Sargassum* community in water temperatures suitable for the optimal growth of *Sargassum* and inhabitance of loggerheads.
2) *Sargassum* in concentrations that support adequate prey abundance and cover.

3) Available prey and other material associated with *Sargassum* habitat such as, but not limited to, plants and cyanobacteria and animals endemic to the *Sargassum* community such as hydroids and copepods.
4) Sufficient water depth and proximity to available currents to ensure offshore transport and foraging and cover requirements by *Sargassum* for post-hatchling loggerheads, i.e., >10 m depth to ensure not in surf zone.

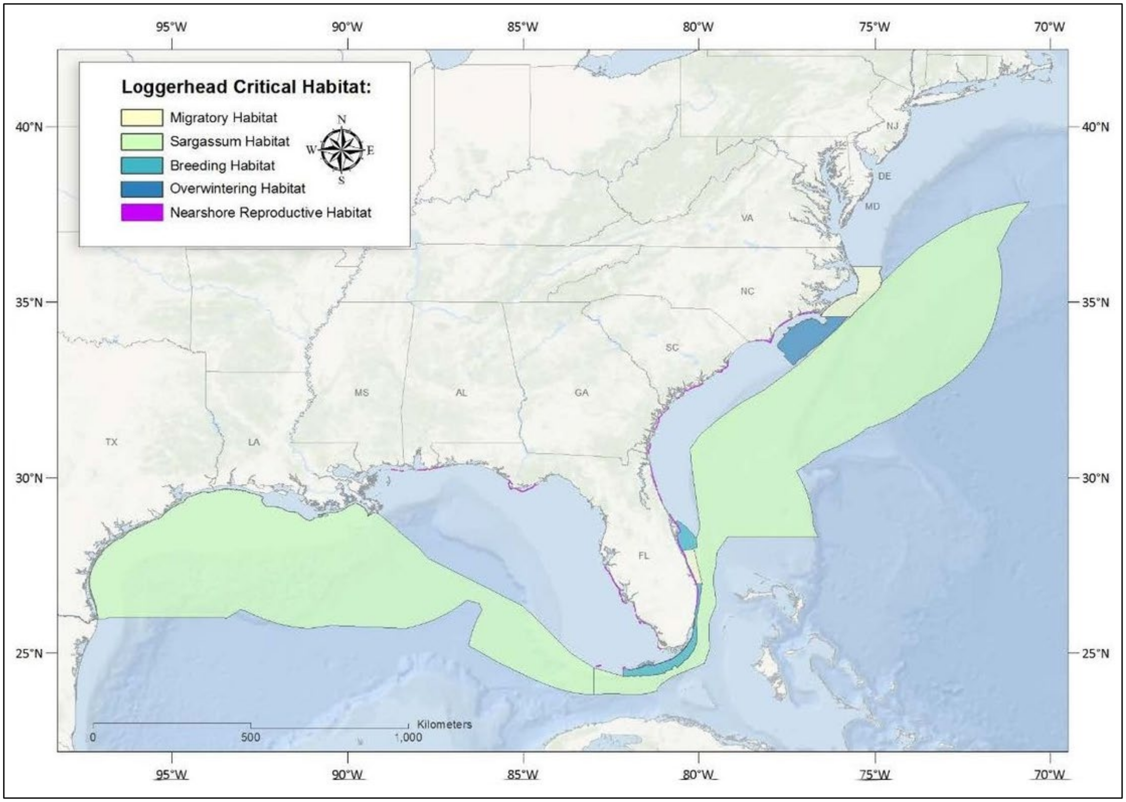

Figure 1-6. Loggerhead Critical Habitat (Northwest Atlantic DPS) in the Gulf of Mexico and Atlantic. Source: https://www.fisheries.noaa.gov/resource/map/loggerhead-turtle-northwest-atlantic-ocean-dps-critical-habitat-map.

Fish

Sargassum provides an important habitat for pelagic fishes, serving as a refuge from predation and a source of food for fish in the open ocean (Figure 1-5). Studies quantifying fish communities in *Sargassum* habitat consistently find higher abundance and diversity compared to nearshore open-water habitats (e.g., Casazza and Ross 2008). *Sargassum* itself comprises approximately 50% of the diet of primary consumers associated with *Sargassum* mats (Rooker et al. 2006; Wells and Rooker 2009). *Sargassum*-associated fish communities often have a high proportion of juveniles; for example, 95% of the catch reported in Wells and Rooker (2004) represented early life history stages of fish. Based on video observations, Casazza and Ross (2008) observed that smaller fish stayed closer to *Sargassum* mats and swam into the algal mat when predators approached from below. *Sargassum* is also spawning habitat for some species (e.g., flying fish). Studies have indicated that larger rafts have greater species richness (Alleyne et al. 2023b), likely because diversity increases with the amount of time a raft has been drifting as well as with its overall area, volume, and variation in microhabitats.

The rich community of invertebrates and small fish hosted by the *Sargassum* forms the prey of many large species of fish, many of which are economically valuable or of conservation interest. Fishery species commonly found in or under the *Sargassum* canopy include juvenile swordfish, juvenile and subadult jacks, juvenile and subadult dolphinfish, filefish, triggerfish, flyingfish, and driftfish. These communities attract larger predatory species, including adult jacks, amberjacks, dolphinfish, barracudas, mackerels, wahoo, tunas, billfishes, and sharks (e.g., SAFMC 2002; Casazza and Ross 2008). The association between certain commercially and recreationally sought species (e.g., dolphinfish) and *Sargassum* is well known, and commercial and recreational fishers commonly seek out *Sargassum* patches or weed lines in order to catch these species.

Due to the importance of *Sargassum* habitat to commercially and recreationally important species, it is designated as essential fish habitat (EFH), defined as “those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity”, by several fishery management councils (Table 1-1). In some cases, this includes EFH Habitat Areas of Particular Concern (HAPCs), which are defined as “subsets of EFH that exhibit one or more of the following traits: rare, stressed by development, provide important ecological functions for federally managed species, or are especially vulnerable to anthropogenic (or human impact) degradation".[3]

Table 1-1. Fisheries for which *Sargassum* is defined as essential fish habitat (EFH).

Fishery Management Council	Species/Group	Designation
Caribbean	Gray triggerfish	EFH
	Reef fish	EFH
Gulf of Mexico	Reef fish (Greater amberjack, lesser amberjack, almaco jack, banded rudderfish, gray triggerfish)	EFH
South Atlantic	Dolphin/wahoo	EFH-HAPC
	Snapper/grouper	EFH-HAPC
	Coastal migratory pelagics	EFH-HAPC

Birds and Marine Mammals

Seabirds use pelagic *Sargassum* habitat primarily for foraging, but also for roosting. Marine predators drive prey items up into *Sargassum* mats, concentrating prey items and making them easier targets for birds, who forage in and around *Sargassum* mats using a variety of techniques including aerial dipping, plunge feeding in and around mats, pursuit diving, and standing on mats and picking prey from the *Sargassum* (Moser and Lee 2012). Studies from the South Atlantic Bight have documented 20-25 species of birds using pelagic *Sargassum* habitat, with a higher abundance and density of seabirds in waters with *Sargassum* compared to waters without *Sargassum* (Haney 1986). *Sargassum* or *Sargassum*-associated prey were found in gut contents of 21 species of seabirds and shorebirds and formed a substantial portion of the diet for four '*Sargassum* specialist' species: Audubon's shearwater, royal tern, bridled tern, and red-necked phalarope (Moser and Lee 2012). In an earlier study, Haney (1986) considered five species to be '*Sargassum*-affiliated' because they had a high frequency of occurrence near *Sargassum* mats: white-tailed tropicbird, red-billed tropicbird, masked booby, brown booby, and bridled tern. Additionally, Haney (1986) observed terns roosting on *Sargassum* mats at sea, suggesting that these habitats provide a valuable resting place for pelagic species.

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[3] https://www.fisheries.noaa.gov/southeast/habitat-conservation/habitat-areas-particular-concern-within-essential-fish-habitat.

Several species of dolphins have been observed near *Sargassum*. Typical behaviors include playing with clumps of *Sargassum* and also rubbing themselves with it (e.g., de Boer and Saulino 2020). It is also highly likely that dolphins are attracted to *Sargassum* habitats to feed on associated fish communities.

Role of Sargassum in Oceanic Nutrient Cycling

In the open ocean, *Sargassum* plays an important role in nutrient cycling, as a route for incorporation of atmospheric carbon into the marine system, and also a means of nitrogen and phosphorus transfer between marine habitats and geographic regions as *Sargassum* strands or sinks. Nitrogen fixation by *Sargassum*-associated cyanobacteria can represent an important route of nitrogen incorporation into the marine environment. Estimates of carbon sequestration by *Sargassum* are low compared to total phytoplankton; however, it can be locally important (Hu et al. 2021; Putman and Hu 2022 and references therein). In oligotrophic waters, primary productivity of *Sargassum* can account for up to 60% of the total primary production in the top 1 m of water (Rooker et al. 2006 and references therein). During bloom seasons, *Sargassum* carbon can account for ~18% of the phytoplankton total particulate organic carbon in the upper water column in the Caribbean Sea and central West Atlantic (Wang et al. 2018). Modelling studies indicate that it is possible that the global carbon stock is similar to amounts stored by other key marine ecosystems (Gouvêa et al. 2020).

Sargassum sedimentation (sinking) represents an important pathway of nutrient transfer from pelagic to benthic environments. Sedimentation occurs when *Sargassum* dies and loses its buoyancy, or when healthy *Sargassum* is submerged due to weather or circulation patterns and/or entrainment of clumps in downwelling currents (Baker et al. 2018; Sosa-Gutierrez et al. 2022). As *Sargassum* sinks, it transports nutrients to the deep sea, where it can occur in relatively high abundance, serving as an important carbon source for these environments (Figure 1-7; Baker et al. 2018). The sedimentation rate of *Sargassum* is fast enough that substantial degradation or predation does not take place as it sinks to the seafloor.

Sargassum and epifauna communities are a food source for a variety of deep-sea benthic invertebrates, including isopods and ophiuroids, and also attract benthic polychaetes and amphipods (Fleury and Drazen 2013). Baker et al. (2018) observed large and relatively well-preserved accumulations on the sea floor in association with elevated densities of macrofauna compared to areas without *Sargassum*, demonstrating the importance of these resources. It is possible that *Sargassum* sedimentation could be large enough to be an important carbon sink on the global scale (Gouvêa et al. 2020).

Figure 1-7. *Sargassum* seen on the deep seafloor (between 407-611 m) near St. Croix, U.S. Virgin Islands. Source: https://oceanexplorer.noaa.gov/okeanos/explorations/22voyage-to-the-ridge/gallery/gallery.html. Image courtesy of NOAA Ocean Exploration, Voyage to the Ridge 2022.

Ecological Functions of Sargassum Wrack

The periodic stranding of moderate amounts of *Sargassum* serves important ecological functions in shoreline environments with respect to nutrient transfer, habitat enhancement, food/prey provisioning, and the maintenance of beach structure (Hyndes et al. 2022) (Figure 1-8). In the surf zone, *Sargassum* also provides nursery habitat for some species of fish and foraging habitat for birds (e.g., Spotte 2013).

Beach-cast *Sargassum* quickly begins to decompose, providing a food source for beach fauna. Wrack-associated invertebrate communities including amphipods (beach hoppers), isopods, and insects quickly recruit to decomposing wrack, which, in turn provides foraging opportunities for higher trophic level species. On beaches, shorebirds and shoreline-associated seabirds (terns, gulls, etc.) use *Sargassum* for foraging, roosting, and/or protection (Figure 1-9). A study done in Pensacola, Florida, documented 11 species of shorebirds interacting with wrack, comprising up to 50% of the birds observed in a day (Schultz Schiro et al. 2017). Species observed using *Sargassum* were both migrant and resident birds and included nesting populations of snowy plover and least tern, both species of conservation concern. Least terns and black skimmers (another species of conservation concern) were also observed using *Sargassum* as camouflage for nests and chicks (Schultz Schiro et al. 2017). In addition to shorebirds and seabirds, wading birds (herons, egrets) and insectivorous passerines (e.g., martins, swallows) forage in and around beach wrack.

Figure 1-8. Examples of light (left) and moderate accumulations (right) of older *Sargassum* wrack (without oil) from Ormond Beach, Florida. Source and photo credit: J. Weaver/Research Planning, Inc.

Figure 1-9. Shorebirds foraging in and around *Sargassum* wrack in Barbados (left) and Texas (right). Sources: https://100barbadosbirds.blogspot.com/2022/08/birds-of-sargassum-images.html; photo credit: J. Moore (left); https://www.crystalbeach.com/sargassumbirds.htm; photo credit: J. Stevenson (right); used with permission.

Sargassum wrack can strand within areas proposed or designated as critical habitat for red knot and piping plover, both of which are migratory shorebirds listed as threatened under the U.S. Endangered Species Act. Surf-cast wrack (including *Sargassum*) is recognized as a physical or biological feature (PBF) essential to the conservation of red knot, because it contains important food sources for red knots (USFWS 2021; 2023). Critical habitat for red knot is proposed in 13 states along the Atlantic Coast and Gulf of Mexico but had not been finalized as of June 1, 2023. In areas likely to have *Sargassum* wrack, critical habitat represents wintering habitat for these species. Piping plover will opportunistically use *Sargassum* wrack as a refuge from predation and will forage around wrack lines. Critical habitat units for wintering piping plover occur in all Gulf States and along the South Atlantic coast (USFWS 2001; 2009).

As it decomposes, *Sargassum* provides nutrients to sand beach and dune environments, which are otherwise nutrient-poor. Wave action transports some of these nutrients to nearshore environments, supplementing their availability in shallow nearshore habitats such as seagrass beds and algal communities (reviewed by Hyndes et al. 2022). The stranding of moderate amounts of *Sargassum* and associated nutrients can provide nutrients to these communities, enhancing growth. However, too much *Sargassum* can have the opposite effect (see Chapter 2).

Wrack deposits have important benefits to the physical structure of sand beaches and dunes. Beach wrack traps wind-blown sand to form hummocks and small dunes and facilitates recruitment of dune vegetation by trapping propagules. Experiments have shown that *Sargassum* wrack attenuated wave energy, decreased scouring velocity, and reduced dune erosion, even at the lightest covering of *Sargassum* tested (Innocenti et al. 2018). Decomposing beach wrack can further facilitate vegetation development in embryonic dunes by adding nutrients to the soil (Chávez et al. 2020).

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Chapter 2. Impacts on and from *Sargassum*

Key points

- Oil concentrates in *Sargassum* patches, exposing the plants and associated fauna to oiling effects. This includes severe effects to young sea turtles and other species.
- *Sargassum* can accumulate oil and transport it to otherwise unoiled environments, including shorelines and the deep sea.
- Oil impacts to *Sargassum* are not well quantified.
- Mass *Sargassum* influx events, including in the absence of oil, can have negative environmental and economic effects.

Oil Impacts on *Sargassum* and Associated Fauna

Oil spills in the pelagic environment have the potential to cause detrimental impacts to *Sargassum* and *Sargassum*-associated species. *Sargassum* is transported and concentrated by the same mechanisms as oil, putting it at high risk of being impacted by marine oil spills. The physical structure of *Sargassum* traps oil and tar, resulting in higher oil concentrations in *Sargassum* clumps relative to surrounding waters (Figure 2-1). Oiled *Sargassum* has often been observed during oil spills, and polycyclic aromatic hydrocarbons (PAH) have been detected in *Sargassum* following oil exposure (Stout et al. 2018); however, the toxicity of oil to *Sargassum* has not been quantified. Oiled *Sargassum* that dies as a result of oiling would then sink, complicating efforts to estimate mortality based on field observations. Studies conducted on similar species of brown algae have shown that direct exposure to oil caused tissue necrosis, reproductive impairment, and other nonlethal impacts, with a greater sensitivity in younger stages of growth (Powers 2012). These impacts occurred across a variety of exposure levels, even in cases where macroalgae was not visibly coated by oil (Powers 2012). Based on these results, Powers (2012) concluded that “the overall consensus from the literature would support a model that physical coating of *Sargassum* with oil would cause substantial, acute injury to *Sargassum* and that lower levels of oil could reasonably be expected to cause inhibition of photosynthesis, respiration and growth.”

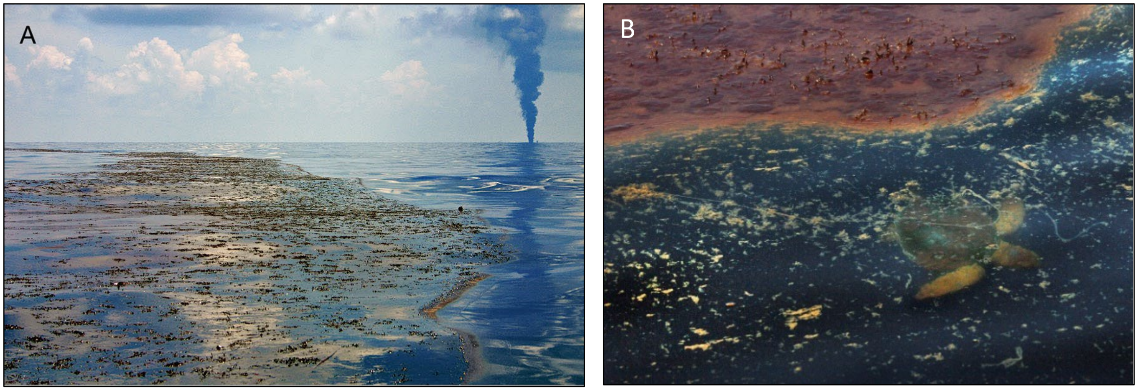

Figure 2-1. Examples of oiled pelagic *Sargassum*: (A) A typical convergence line of oil and pelagic *Sargassum* during the *Deepwater Horizon* oil spill. The column of smoke on the upper right is from a similar convergence area where oiled *Sargassum* was collected in an oil boom and burned. Source: McDonald et al. 2017; photo credit: B. Witherington; (B) A sea turtle swimming through oil along the edge of an oiled *Sargassum* patch during the *Deepwater Horizon* oil spill. Source: NOAA, https://blog.response.restoration.noaa.gov/sea-turtles-seaweed-and-oil-spills.

Oil becomes trapped and concentrated within *Sargassum*, coating the vegetation and accumulating in and on the water among algal fronds and clumps. Oil trapped within and under the floating vegetation may weather and break down more slowly than oil slicks on open water due to the shelter provided by the plant's structure. As *Sargassum* drifts with the currents, it can transport spilled oil with it, expanding the geographic impact of a spill and lengthening the temporal exposure of *Sargassum* and associated organisms to oil. In some cases, oil in *Sargassum* can be transported and detected far away from the spill source. During *Deepwater Horizon*, pelagic *Sargassum* collected 80 and 170 km from the wellhead contained weathered Macondo oil (Stout et al. 2018). However, oiled *Sargassum* may not persist for long after a spill in any specific place; *Sargassum* collected 3 to 4 months after *Deepwater Horizon* in previously oiled areas showed no chemical evidence of exposure (Stout et al. 2018), likely because contaminated *Sargassum* had either drifted away with the currents or sank. The sinking of contaminated *Sargassum* can transport oil to deeper environments as it sinks, creating an additional pathway for exposure in open ocean environments (Powers et al. 2013), the effects of which are not fully understood. The sinking of oiled *Sargassum* would also result in immediate habitat loss for many associated species.

Oil impacts can cause substantial losses of *Sargassum* habitat. It was estimated that heavy oil exposure during the *Deepwater Horizon* spill may have caused the loss of up to 23% of *Sargassum* habitat in the northern Gulf of Mexico (DWH NRDA Trustees 2016; Hu et al. 2016; see Chapter 4 for more information). Loss of *Sargassum* habitat would also result in direct losses of closely associated fauna, including sessile and epifaunal species, as well as loss of habitat for larger free-swimming species. In addition to habitat loss, oil in *Sargassum* can directly impact associated species through a variety of mechanisms. Floating oil accumulated and trapped within *Sargassum* drift lines and mats would expose associated animals to direct coating and fouling, inhalation of oil vapors, aspiration of oil, ingestion of oil, including weathered oil such as tarballs, thermal stress, and low dissolved oxygen (Figure 2-2). These impacts can be especially harmful because many of these animals seek out *Sargassum* habitat as larvae or juveniles and have limited mobility, factors that make them more susceptible to oil impacts.

Oil spills have the potential to impact all *Sargassum*-associated fauna; however, the most severe effects have been documented for sea turtles (see Chapter 4: Case Histories). Following *Deepwater Horizon*, wildlife rescue operations primarily recovered oiled sea turtles from convergence zones containing *Sargassum*. Juveniles from four species were captured (Kemp's ridleys, greens, loggerheads, and hawksbills). Impacts to these populations were substantial; it was estimated that roughly half of the population of 1- and 2-year-old Kemp's ridley sea turtles were exposed to oil following the *Deepwater Horizon* oil spill, and 10-20% of the population died as a result (DWH NRDA Trustees 2016; McDonald et al. 2017). Turtle injuries associated with oiling include impaired mobility, exhaustion, dehydration, hyperthermia (temperatures above the lethal maximum for those species), ingestion of oil, and inhalation/aspiration of oil (see Shigenaka et al. 2021 and Stacy et al. 2019 for thorough discussions of oil impacts to sea turtles). While injury estimates were not reported specifically for turtles in *Sargassum* habitat, most of the sampling occurred in convergence zones containing *Sargassum* mixed with oil. In total, it was estimated that between 55,000 and as many as 160,000 small juvenile sea turtles were killed as a result of the *Deepwater Horizon* oil spill; many of these turtles would have been using *Sargassum* habitat (DWH NRDA Trustees 2016). Most of this mortality was likely due to oil exposure, although it is possible that some animals were injured during mechanical skimming and *in-situ* burning of oil in and near *Sargassum* habitats.

Impacts to fish and invertebrates in oiled *Sargassum* habitats were also quantified following the *Deepwater Horizon* oil spill (see Chapter 4: Case Histories). Estimates were based on densities of fish and decapods (shrimp and crabs) documented in unoiled *Sargassum* habitats and the area of heavily oiled *Sargassum* directly impacted by the spill. Preliminary findings estimated that oiling impacts to fish associated with *Sargassum* ranged from 341 million to 1.2 billion kg of lost biomass of larval, juvenile, subadult, and adult fish (Ruder et al. 2017).[4] Counts of individuals lost ranged from 1.3 to 5.2 trillion decapods and fish. Harvested fisheries species accounted for much of the biomass loss, including amberjack, blue runner, dolphinfish, sea chubs, almaco jack, and triggerfish.

Impacts from direct oiling and oil-related habitat loss to birds and marine mammals associated with or using *Sargassum* habitats have undoubtedly occurred but have not been specifically quantified.

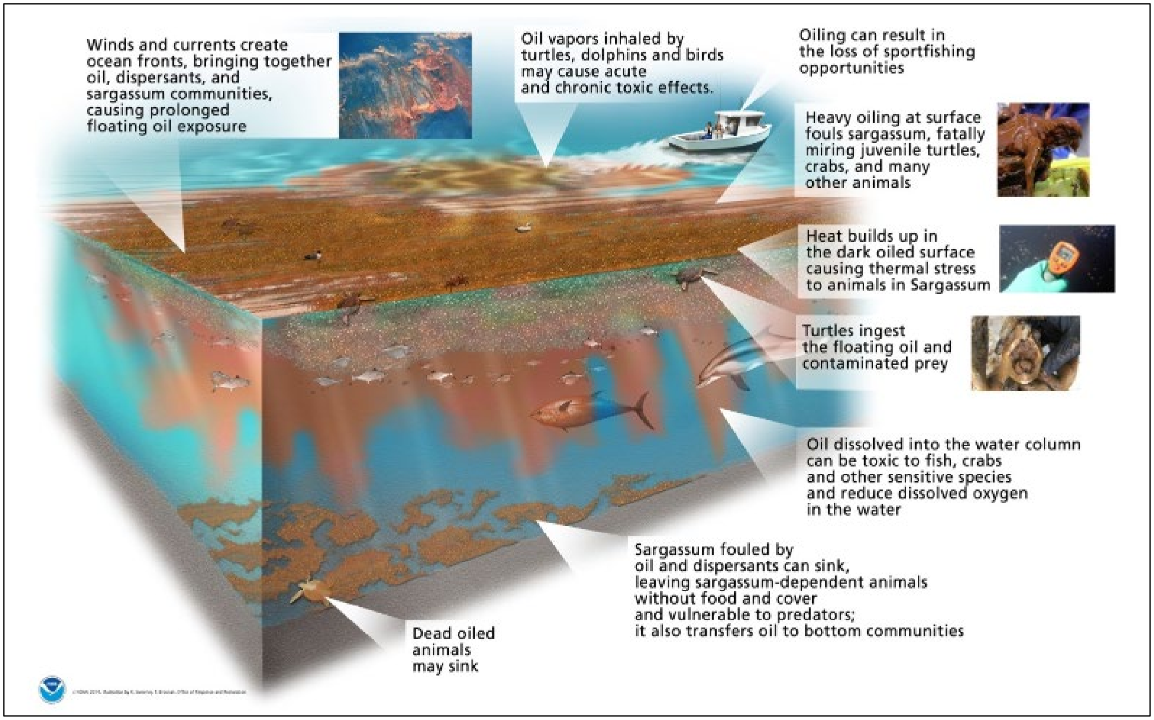

Figure 2-2. Illustration of the potential impacts of oiled *Sargassum* and associated biota in the water column. Source: DWH NRDA Trustees (2016), graphic by Kate Sweeney for NOAA.

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[4] These estimates were only preliminary and were not included in the injury calculations presented in the PDARP.

Chemical dispersant use can alter the impacts of oil on *Sargassum* and *Sargassum* communities. Dispersants break oil into smaller molecules that then disperse into the water column and can be more rapidly degraded by biological activity. However, smaller oil molecules are more bioavailable to many organisms. Additionally, dispersed oil is more abundant in the water column compared to undispersed oil, which floats on the surface of water. Therefore, if oiled *Sargassum* were treated with dispersants or if dispersed oil plumes come into contact with nearby *Sargassum* patches, dispersant use could potentially cause a temporary increase in oil exposure levels for water column organisms, such as fish and invertebrates, which are concentrated in and around *Sargassum* habitat, as well as for less mobile species that are closely associated with *Sargassum*. The effects of dispersed oil or dispersants themselves on *Sargassum* has not been quantified; however, Powers et al. (2013) observed in a mesocosm experiment that *Sargassum* exposed to dispersed oil or dispersants alone sank more rapidly than unoiled or oiled *Sargassum* in the absence of dispersants. As described above, sinking of *Sargassum* would result in immediate habitat loss. Powers et al. (2013) also observed that water surrounding *Sargassum* habitats exposed to dispersants (with and without oil) showed a rapid depletion of oxygen, likely due to increased biological activity associated with oil and/or dispersant degradation. Localized anoxia can cause mortality in *Sargassum* communities. This has not been measured in situ following an oil spill; however, localized anoxia due to degradation of *Sargassum* in nearshore environments has been observed during mass *Sargassum* stranding incidents and can contribute to mortality of *Sargassum*-associated fish and invertebrate communities (Rodríguez-Martínez et al. 2019).

Oil and Response Impacts on Human Use of *Sargassum*

Little to no information is available on this topic; however, oiling of *Sargassum* and associated spill response activities, including fisheries closures, would impact or impede fisheries that target *Sargassum* habitats and associated species, such as recreational, guided charter, and small-scale commercial fisheries for dolphinfish, jacks, tuna, and other species. From 1976 to 1997, a small *Sargassum* harvest existed in the U.S. South Atlantic (SAFMC 2002); however, there is currently no commercial harvest of *Sargassum*. If direct harvest operations develop in the future, perhaps in response to increasing *Sargassum* levels and influx events, they could be impacted by oil spills and response activities.

Oil Impacts on *Sargassum* Wrack and Associated Biota

Oiled *Sargassum* wrack can be a source of contamination for shoreline communities and compromise the ecosystem services *Sargassum* wrack provides to sand beach and dune ecosystems. *Sargassum* that is stranded before oil comes ashore has the potential to trap and concentrate stranded oil and increase the persistence of oil on shorelines. Oiled *Sargassum* that washes ashore can exacerbate impacts to shoreline environments and can even contaminate unoiled beaches (Bejarano and Michel 2016). Wrack that deposits on top of oiled shorelines can extend the persistence of oil in these habitats, especially if these deposits trap sediment and facilitate burial. Oiled wrack may also be a source of oil deposition in shallow subtidal habitats, such as nearshore troughs between the beach and sand bars, especially when oiled wrack is mixed with sediments on the shore or in the wave swash or surf zones.

Oiling of wrack results in reduced diversity of wrack-associated invertebrate and microbial communities and can increase mortality to and decrease the abundance of wrack-associated invertebrate communities beyond what would be experienced by shoreline oiling (Michel et al. 2017). Impacts can also occur to shoreline animals, such as shorebirds that forage or shelter in and around oiled wrack, including threatened species such as red knot and piping plover. These impacts include mortality due to ingestion or coating with oil, and sublethal effects, such as decreased fitness or reproductive success due to oiling and lowered prey availability (e.g., Donlan et al. 2003). For species that nest in the region, adults can transfer oil to eggs and chicks, causing additional mortality. Sea turtle hatchlings can also become oiled after emerging if they encounter oiled wrack on the beach.

Impacts of *Sargassum* Mass Stranding or Influx Events

While moderate amounts of *Sargassum* can provide benefits to nearshore and shoreline environments, massive influxes of *Sargassum* can be detrimental to nearshore and shoreline environments, human health, and the economies of affected communities.

Environmental Impacts

When large accumulations of *Sargassum* come ashore, some of the first impacts can be to biological communities in shallow nearshore waters. The physical presence of *Sargassum* thickly covering the top of the water reduces light attenuation, causing negative impacts to photosynthetic communities such as algae, corals, and seagrass. *Sargassum* also traps heat and large accumulations can cause substantial increases in nearshore water temperature (van Tussenbroek et al. 2017). As *Sargassum* degrades, increased bacterial activity leads to increased oxygen consumption in shallow nearshore waters, creating localized hypoxia and anoxia, resulting in fish and invertebrate kills (Rodríguez-Martínez et al. 2019). Breakdown of *Sargassum* and leachates can also lead to '*Sargassum* brown tides' or SBTs, characterized by nearshore dark murky waters (van Tussenbroek et al. 2017; Rodríguez-Martínez et al. 2019; Figure 2-3). *Sargassum* brown tides can result in a number of water quality changes that can impact benthic and water column biota, such as increased water turbidity and color, reduced light penetration, reduced oxygen levels, reduced pH, increased hydrogen sulfide and ammonia, increased water temperature, increased particulate organic matter, and increased nutrient loads. In small amounts, degrading *Sargassum* can enhance seagrass productivity in adjacent waters. However, nutrients leaching from mass influxes can lead to eutrophication of these habitats, leading to algal blooms. The sum of these effects can

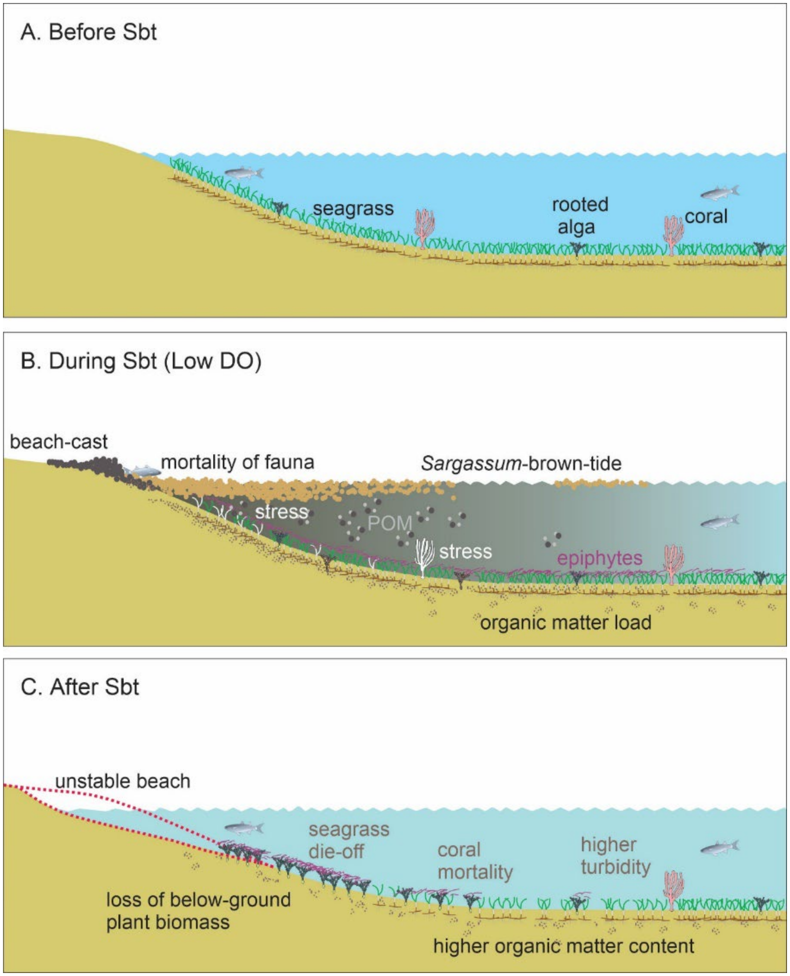

Figure 2-3. Schematic representation of the impacts of *Sargassum* brown tides (Sbt) to coastal environments: (A) before the impact, seagrass is plentiful and algae and corals are present; (B) decomposing *Sargassum* causes low dissolved oxygen, increased turbidity, and other impacts stressing coastal fauna; and (C) following Sbt, the beach has eroded and macroalgae have become more dominant as seagrass and coral have died. Source: adapted from van Tussenbroek et al. (2017).

lead to stress and mortality to important benthic resources, such as corals and seagrass, and overgrowth of undesirable benthic algal forms. The result of this shift in communities can lead to ongoing increased turbidity with impacts lasting more than a year following an influx event (Maurer et al. 2015; Ricardo and Martin 2016; Gavio and Santos-Martinez 2018). In parts of the Caribbean, loss of nearshore native seagrasses and increased turbidity can also lead to colonization and spread of the non-native seagrass *Halophila stipulacea*.

Once stranded on the beach, massive influxes of *Sargassum* can cause substantial impacts to shoreline habitats and species. Mass stranding events can have negative impacts on the physical structure of beaches. While moderate amounts of *Sargassum* can promote accretion, extreme *Sargassum* accumulations can cause erosion of affected beaches, due to loss of nearshore seagrass habitat and undertow caused by *Sargassum* accumulations (Chávez et al. 2020). Increased erosion leads to a loss of beach habitat. Additionally, decaying *Sargassum* mats trap heat, raising the temperature of beach environments and affecting resident species. The physical presence of *Sargassum* can cause a barrier to species that are not highly mobile and prevent access to sandy habitat used for foraging. The influx of decaying *Sargassum* can cause a surge of nutrients into beach environments, potentially affecting community composition of beach invertebrates.

Sea turtles can be heavily impacted if *Sargassum* stranding events occur in areas with substantial nesting habitat during the nesting season. Female sea turtles will not dig nests in areas with substantial *Sargassum* accumulations, leading to decreased nesting densities on affected beaches and increased densities in less affected areas (Maurer et al. 2015; 2021). Nesting females may spend more energy searching for a site when large amounts of beach-cast *Sargassum* are present, leading to an overall reduction in their potential reproductive output (Ricardo and Martin 2016).

Sargassum that washes ashore on top of existing sea turtle nests has the potential to alter the physical characteristics of beaches, with implications for nesting outcomes. Sex determination in sea turtles is dependent on incubation temperature, so increases in beach temperatures due to *Sargassum* influxes can alter sex ratios in hatchling populations, potentially leading to population effects. If heat trapping is extreme it can lead to mortality of eggs. In addition, following emergence from the nest, hatchlings have to crawl past or across *Sargassum* wrack to get to the ocean. The presence of substantial *Sargassum* accumulations on the beach in front of nests can impede the migration of hatchlings to the ocean (Maurer et al. 2015; Ricardo and Martin 2016; Gavio and Santos-Martinez 2018). In a study of loggerhead sea turtle hatchlings conducted in Southeast Florida, researchers documented hatchling avoidance of large *Sargassum* wrack accumulations on the beach, with a marked decrease in hatchling emigration if wrack lines were greater than 20 cm in height. Additional time spent crawling to the ocean also put hatchlings at greater risk of predation and increased the likelihood of a landward crawl. The net result of this study was an estimated 22% decrease in number of hatchlings that reached the ocean due to *Sargassum* interference (Schiariti and Salmon 2022). The population implications of these effects are not known.

Impacts to sea turtles can be species- and location-specific. Larger turtles may not be as affected by *Sargassum* influxes on the coast. Loggerheads tend to be more impacted than other species, and the presence of additional *Sargassum* habitat in nearshore waters can increase the survival of hatchlings. In some places, green sea turtles have shown historically high nesting success following *Sargassum* influxes in some locations (Ricardo and Martin 2016), and in Jamaica scientists have observed an increase in survival rate and population growth of juvenile hawksbill turtles during times of *Sargassum* influx (UNEP 2021). Many studies have not quantified the amount of *Sargassum* present on impacted beaches, so the threshold for negative impacts to sea turtles is not well understood; however, it is generally accepted that the negative impacts to nesting habitat outweigh the positive benefits of having additional pelagic habitat for juvenile turtles, though this likely needs further study.

Human Health and Safety Concerns

Potential impacts to human health and safety from *Sargassum* influx events include emissions of potentially harmful gases, leaching of heavy metals, and exposure to potentially harmful bacteria and stinging organisms that co-occur with *Sargassum*. This section is not comprehensive but is meant to give an overview of health and safety concerns. Consult local, state/territorial, and federal health and safety agencies for more information on this topic.

Decaying *Sargassum* emits hydrogen sulfide and ammonia gases, both of which have negative consequences to human health. Populations in close proximity to decaying *Sargassum* influxes, such as residents living near the shore or workers removing large *Sargassum* accumulations on the shoreline, can be exposed to concentrations exceeding recommended exposure levels for these chemicals. Health problems, including neurological, digestive, respiratory, and reproductive symptoms, have been documented in populations exposed to moderate levels of hydrogen sulfide emissions (≤5 ppm) consistently over the span of days-weeks, resulting from the decomposition of extreme *Sargassum* influxes (Resiere et al. 2018; 2021). Effects of chronic sub-acute exposures such as these are not well understood.

Heavy metals accumulate in *Sargassum* tissues while it is in the open ocean. In particular, *Sargassum* often contains high levels of arsenic. Other metals are present in lower concentrations but can bioaccumulate, including copper, molybdenum, manganese, and lead (Rodríguez-Martínez et al. 2020). Concentrations vary by time, year, and geography. Decaying *Sargassum* leaches these metals, potentially contaminating habitats where *Sargassum* is left to decay. Leachates from *Sargassum* influxes can contaminate sediment, nearshore waters, and potentially groundwater if stranded *Sargassum* is not disposed of properly. Humans can be exposed to these metals by eating contaminated seafood or drinking contaminated groundwater.

Some bacterial species of the genus *Vibrio* can be present in pelagic *Sargassum*. While some species of *Vibrio* can cause severe infections or gastrointestinal distress in humans (e.g., cholera), it is uncertain if *Vibrio* species associated with *Sargassum* represents an increased health risk in nearshore waters or in shoreline wrack (Theirlynck et al. 2023; Mincer et al. 2023).

Stinging organisms associated or co-occurring with *Sargassum*, such as various hydroids and jellyfish, may also be present in *Sargassum* wrack on the shoreline, which could be a hazard for beach users and cleanup workers, resulting in stings or rashes, some of which can be serious (e.g., for certain species of jellyfish).

Socioeconomic Impacts

Sargassum influxes can have various socioeconomic effects on coastal communities, including disruption of tourism, interference with fisheries, and impacts to infrastructure. While it is possible to reuse *Sargassum* for various purposes and products, efforts to scale up the beneficial reuse of *Sargassum* are underway but thus far limited in scale. The effects of massive influx events are mostly negative to coastal communities.

Impacts to tourism from *Sargassum* accumulations are primarily negative. Decaying *Sargassum* causes odiferous smells, increases the number of flies and other pests on the beach, and decreases the visual appeal of beaches and nearshore waters. These impacts can be substantial; following the 2018 *Sargassum* influx in Mexico, tourism was reduced by 35% (UNEP 2018). *Sargassum* cleanup incurs additional costs for tourism businesses and local governments; however, cleanup operations can also provide jobs for displaced workers (Rodríguez-Martínez et al. 2016).

Sargassum influxes have complex effects on fisheries in affected areas. Physical impacts include fouling of gear (e.g., propellers and nets), which results in increased time and cost to fishermen, and necessitates adoption of modified gear to minimize these impacts. Fishing boat launches, harbors, and anchorages can also become clogged or fouled with *Sargassum*, hindering access and requiring increased time and maintenance. Fish cleaning, processing, and market locations can also be affected directly or indirectly by *Sargassum* influx via fouling, clogging, odors, etc. Ecological impacts to fisheries from *Sargassum* influx include shifts in distribution and behavior of targeted species, which may have varying effects on small-scale fisheries.

Sargassum influxes and SBTs can impact seagrass habitats, which serve as nurseries for many targeted species; however, *Sargassum* influxes can also result in a net gain of juvenile habitat for other coastal species and also make pelagic species more accessible (Ofori and Rouleau 2021). As a result, increased presence of *Sargassum* in the Caribbean has caused shifts in small-scale fisheries as the availability of target species changes. An interesting case study is the Barbados flyingfish fishery, which has traditionally relied on fish aggregating devices (FADs) to aggregate flyingfish. The influx of *Sargassum* rendered traditional FADs ineffective, as flyingfish preferred to use natural *Sargassum* habitat, and showed other behavioral changes that made them difficult to catch. Concurrently, *Sargassum* influx brought a pelagic species, almaco jack, closer to shore, making them more accessible to these fishers, who increased their catch of jacks to compensate for the lack of flyingfish (Oxenford et al. 2019). Shifts in availability of different life stages can also have implications for fishers and fisheries managers. In Barbados, *Sargassum* influxes bring juvenile dolphinfish closer to shore, making them more accessible to fishers, who would typically be targeting adult fish. As a result, catches of dolphinfish have increased; however, the population effects of targeting juveniles that have not reproduced yet are not fully understood and could be detrimental (Oxenford et al. 2019).

Sargassum influx events can also affect infrastructure and marine transportation beyond the fisheries sector. For instance, large accumulations of *Sargassum* can clog water intakes, affecting critical infrastructure, such as desalination plants, power plants, and industrial facilities (see Chapter 4 for an example from the U.S. Virgin Islands). Ports, harbors, marinas, and boat ramps can also be affected by *Sargassum* influx events. Commercial ships can be affected when water intakes are clogged or propellers fouled. Local governments are often tasked with collecting and properly disposing of large amounts of *Sargassum*, which needs to be properly contained to avoid groundwater contamination, requiring lined landfills and taking up limited landfill space, an important concern for local communities and small island nations. (Chávez et al. 2020).

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Chapter 3. Oil Spill Response Considerations and *Sargassum*

This chapter is organized into sections regarding the following topics:

- Incorporating *Sargassum* into spill planning
- Monitoring *Sargassum* during a response
- Considerations for on-water oil spill response
- Considerations for shoreline oil spill response
- Human health and safety concerns regarding *Sargassum* collection and disposal
- Response to *Sargassum* influx events
- *Sargassum* disposal methods

Key recommendations are provided as bullet points or tables within each topic.

Incorporating *Sargassum* into Oil Spill Planning

In areas where *Sargassum* is likely to occur, the following steps can be taken to prepare for *Sargassum* involvement before an oil spill.

- Compile and maintain list of available resources for *Sargassum* awareness.
- Develop protocols for *Sargassum* detection and monitoring in the event of a spill.
- Develop protocols for documentation of oil spill impacts to *Sargassum* and associated species.
- Incorporate the potential for removal of *Sargassum* (including potential large amounts) into response plans (e.g., additional staging and equipment needs).

Resources for *Sargassum* Detection, Monitoring, and Forecasting

This section summarizes remote sensing methods used to detect *Sargassum* from satellite imagery and then provides recommendations on their use for spill responders. Detection, forecasting, and monitoring of *Sargassum* abundance and distribution is an area of emerging research, and new methods are under development. The following section is not a comprehensive list of resources but is meant to give an overview of tools available at the time of publication that can be used in the event of a spill that may involve *Sargassum*.

Remote Sensing in Pelagic Environments

Many methods have been developed to detect *Sargassum* from satellite imagery data. Traditional methods infer the presence of *Sargassum* by creating indices based on reflectance wavelengths collected by common observing platforms. These indices are ratios of different reflectance values to the range of values observed across specific wavelengths. The three most commonly used indices are summarized in Table 3-1 and are available under the '*Sargassum*' tab in the AOML OceanViewer (https://cwcgom.aoml.noaa.gov/cgom/OceanViewer/).

Table 3-1. Summary of indices commonly used to detect *Sargassum* accumulations from routinely collected satellite imagery data.

Index name and source reference	Calculation description	Use notes
Maximum Chlorophyll Index (MCI) (Gower et al. 2006)	The chlorophyll fluorescence peak (709 nanometers [nm]) is quantified against a baseline between (681 nm and 754 nm). These values are for the Ocean Land and Color Instrument (OLCI) sensor and may vary slightly from those used to generate MCI from other sensors.	Good at detecting extreme blooms but not as sensitive as other products (e.g., will appear low/negative even in waters experiencing blooms and "normal" levels of floating *Sargassum*).
Floating Algae Index (FAI) (Hu 2009)	The red-edge reflectance, part of the near-infrared reflectance (NIR) at 859 nm is quantified and a linear baseline between the red band (645 nm) and short-wave infrared band (1240 or 1640 nm).	Accurately detects floating vegetation at a resolution of 250 m, but also returns high values for clouds, making interpretation difficult to the untrained eye.
Alternative Floating Algae Index (AFAI) (Wang and Hu 2016)	Improves upon the methods in the FAI by adjusting for sources of error (clouds).	Interpretation is simpler than the FAI; however, it has a lower spatial resolution (1 km) than the FAI.

Recently, more sophisticated machine learning models have been applied to satellite imagery data to detect *Sargassum*. These models can improve coverage of predictions and merge multi-sensor observations to improve detection capabilities. In particular, Hu et al. (2023) developed a deep learning model with an accuracy of 92.5%, an improvement over the AFAI model (86.2%). Other examples can be found in Wang and Hu (2021) and Laval et al. (2023). These methods are promising, but they have not yet been incorporated into commonly issued forecasts, so they are not discussed in further detail.

Nearshore and Shoreline Detection

The ability of remote sensing products to forecast *Sargassum* accumulations in nearshore areas has historically been limited. Most frequently acquired satellite imagery is of coarse resolution and can only detect very large patches. Finer-resolution imagery is acquired less frequently, resulting in less coverage for nearshore areas. Additionally, increased biological activity and cloud cover nearshore make satellite observations difficult to use. Automated detection methods using machine learning techniques have been applied to different sources of aerial imagery ranging from satellites to unmanned aerial systems (UAS, or "drones") (Table 3-2). These techniques could also be applied to imagery collected from other platforms, for example, fixed wing aircraft, and applied to spill response (see 'Monitoring' section below).

Table 3-2. Examples of methods used to delineate nearshore *Sargassum* accumulations from imagery.

Method and source	Analytical approach	Use notes
Satellite imagery (MultiSpectral Instrument [MSI]) (Wang and Hu 2021)	Neural networks trained from MSI imagery.	This approach requires less manual processing than some index approaches and can be adapted to different areas.
Satellite imagery (Google Earth Engine) (León-Pérez et al. 2023)	Used supervised classification in Google Earth Engine to identify nearshore and shoreline *Sargassum* accumulations and decomposition stage (fresh, brown, decaying) with good accuracy.	These methods could be adapted for use with newly collected imagery following a spill.
UAS imagery (Weekes et al. 2019)	Supervised classification using Maximum Likelihood Classification (MLC) in ESRI ArcMAP, along with ground-truthing of observations.	Real-time imagery can be collected fast, and methods are able to be repeated in the future; however, processing methods require advanced GIS skills.

Sargassum Inundation Forecasts

Several derived products are available that cover U.S. waters and are discussed below. The two main sources at present are the NOAA/USF *Sargassum* Inundation Report (SIR) and the USF Satellite-based *Sargassum* Watch System (SaWS). A Caribbean Coastal Ocean Observing System (CARICOOS) *Sargassum* web site provides information specific to Puerto Rico and the U.S. Virgin Islands. Additional products are available for the Caribbean outside of U.S. waters but are not discussed in this report.

***Sargassum* Inundation Report (SIR)** – This gives a weekly report showing the potential for shoreline inundation based on proximal observations of *Sargassum* density derived (using AFAI) from satellites. Shorelines are classified into low (blue), medium (orange), and high (red) risk categories. See Figure 3-1 for an example. Available at: https://www.aoml.noaa.gov/phod/*Sargassum*_inundation_report/

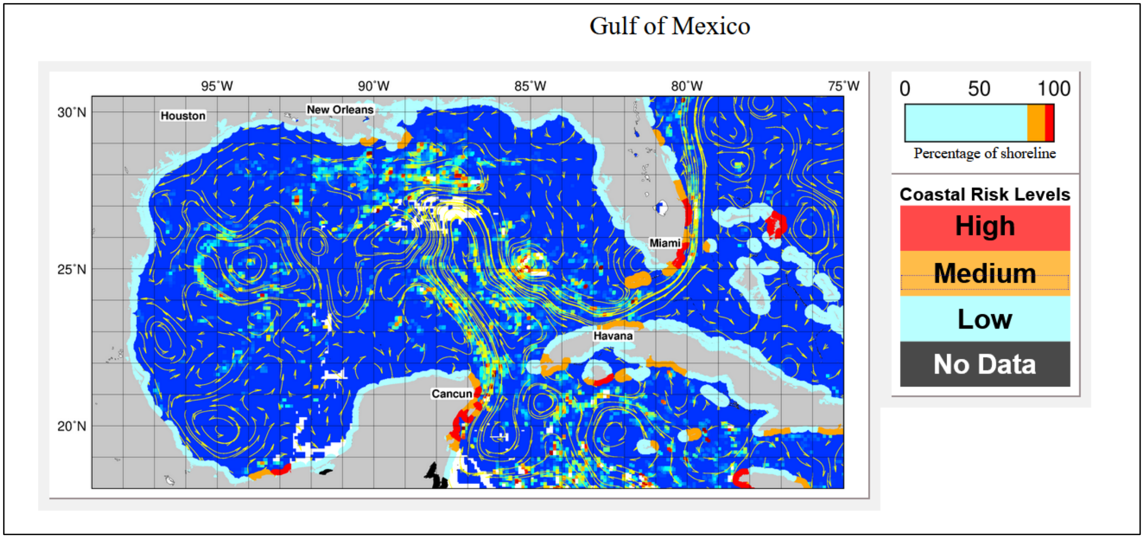

Figure 3-1. Example *Sargassum* Inundation Report (SIR) output for Apr 25 – May 1, 2023.

Satellite-based *Sargassum* Watch System (SaWS) – This site produces a monthly bulletin showing *Sargassum* abundance and giving outlook for abundance and distribution, including areas likely to experience buildups. It also has a map that shows a variety of satellite imagery data and data products available at finer time scales (e.g., AFAI, FA density, Chlorophyll CHL, SST) from different satellite observing platforms. See Figure 3-2 for an example. Available at: https://optics.marine.usf.edu/projects/saws.html

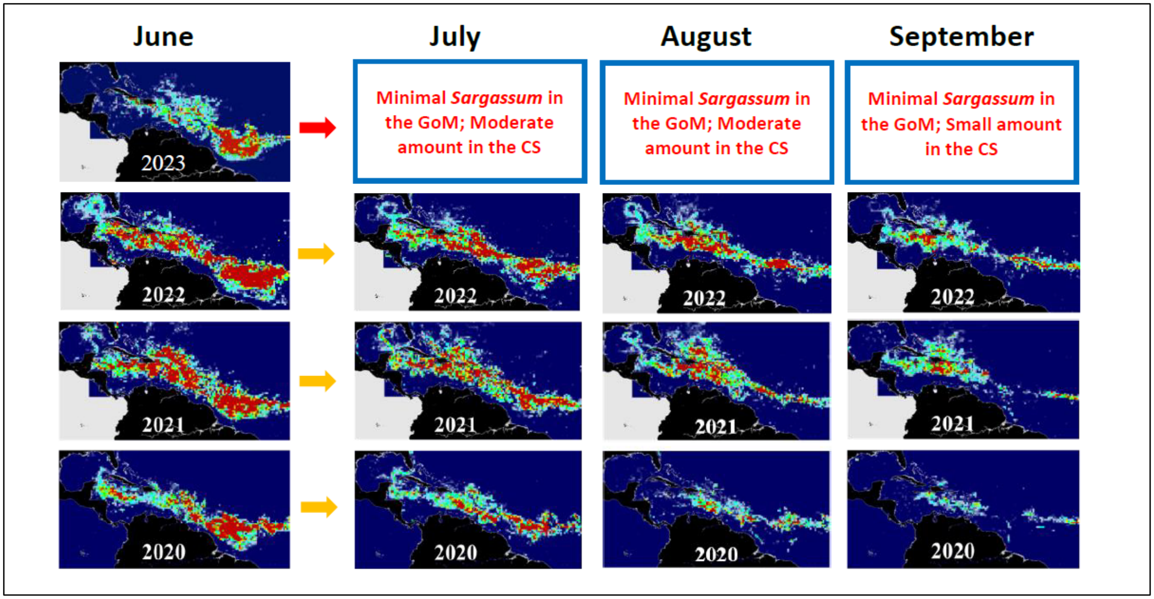

Figure 3-2. Example of monthly output from *Sargassum* Watch System bulletin for June 2023.

Caribbean Coastal Ocean Observing System (CARICOOS) – This site contains oceanographic data, such as wind and current data, for coastal areas around Puerto Rico and the U.S. Virgin Islands. This information can help determine where *Sargassum* accumulations might be moving. The *Sargassum* tracker (https://www.caricoos.org/sargassum?locale=en) contains information on past and present *Sargassum* distribution, along with forecasts and outlooks for Puerto Rico and the U.S. Virgin Islands.

Other resources may be available to determine *Sargassum* accumulation levels depending on the location, including:

- *Sargassum* Monitoring – This website has a summary of webcams with a map colored by detection of *Sargassum*. https://Sargassummonitoring.com/; and
- *Sargassum* Watch – This site summarizes a citizen science data collection project, used to report shoreline *Sargassum* observations. https://five.epicollect.net/project/Sargassum-watch.

Monitoring *Sargassum* During a Response

If *Sargassum* accumulations are likely to occur in the response area, *Sargassum* distribution and abundance should be monitored in the area of potential impact. Offshore *Sargassum* accumulations can be identified and monitored using satellite modelling techniques, such as those described above. Once concentration areas are identified, trajectory models supported by overflight or shipboard observations may be able to assist in forecasting their movement. Other remote sensing methods can also be used to detect and monitor oil spills, and in some cases methods for detecting and monitoring oil slicks versus *Sargassum* can be integrated. Following the *Deepwater Horizon* oil spill in 2010, methods were developed to differentiate between oil slicks and *Sargassum* using the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) instrument mounted to a fixed wing aircraft (Shi et al. 2018). These methods were used in the *Deepwater Horizon* NRDA studies to determine *Sargassum* occurrence in areas with heavier oiling (Hu et al. 2016). Methods used for monitoring *Sargassum* in the nearshore and shoreline environment can be conducted in tandem with oil monitoring during overflights or shoreline assessment surveys or can be used independent from oiling when appropriate. It may be helpful to develop monitoring protocols during planning exercises if they are not already in place.

Overflight observations are useful in determining the amount of pelagic *Sargassum* present in an area of concern. *Sargassum* observations can be documented at the same time as oil observations. In some cases, it may be difficult to visually distinguish *Sargassum* from emulsified crude oil during overflights due to potential similarities in color and structure/distribution (including determining if *Sargassum* habitat is oiled or not). Close attention should be paid to texture and the presence or absence of sheen, particularly at the margins of the target being observed. Aerial observers must be trained to distinguish *Sargassum* from both oil and other floating material and/or debris (Figure 3-3).

UAS (drones) can be used to map and quantify nearshore and stranded *Sargassum*. UAS allow for relatively inexpensive and quick collection of a large amount of imagery. Methods have been tested to quantify stranded *Sargassum* on beaches based on drone-collected aerial imagery (Weekes et al. 2019), which may be of use to spill responders. These methods could be used and ground-truthed in the initial phases of a spill or *Sargassum* beaching event and repeated as needed throughout the response. Protocols could be developed based on existing documents (see Baldwin et al. 2022 and the 'Uncrewed Aircraft Systems Oil Spill Response Job Aid' [NOAA 2021]).

Figure 3-3. Example overflight photos of unoiled *Sargassum* as false positives for floating emulsified oil. Photo credit: David Wesley/NOAA.

Shoreline Cleanup Assessment Technique (SCAT) survey methods for oil spills (NOAA 2013a) could be readily adapted for *Sargassum* shoreline surveys in the presence or absence of oil, including incorporating *Sargassum* wrack into SCAT surveys and forms, as needed. Additionally, stranded *Sargassum* observations could be made in conjunction with wildlife surveys during spills, as appropriate. Existing *Sargassum* shoreline survey methods could also be adapted for use during oil spills, especially if spills co-occur with substantial *Sargassum* stranding events (see Small et al. 2022).

Considerations for On-water Oil Spill Response

On-water response techniques include mechanical collection methods, *in-situ* burning, and chemical dispersant application. Because oil and *Sargassum* are both aggregated by the same physical forces, in locations where *Sargassum* occurs, especially at certain times of year, it is likely that recoverable oil will contain *Sargassum* patches, especially as time passes following a release. The presence of pelagic *Sargassum* in areas with oiling presents unique challenges for each of these methods. For a thorough description of response techniques, see “Characteristics of Response Strategies: A Guide for Spill Response Planning in Marine Environments” (NOAA 2013b).

Responders deploying offshore countermeasures such as chemical dispersants, mechanical skimming, and *in-situ* burning should consider impacts to *Sargassum* habitat and its associated animals, particularly protected sea turtles. This may include the use of observers and the avoidance or minimization of response actions near concentrations of *Sargassum*. It should be assumed that turtles, other wildlife, and fish are likely to be present in *Sargassum* habitats and at risk unless otherwise demonstrated through properly conducted surveys, i.e., from vessels using personnel qualified to spot small sea turtles. Close coordination with the Wildlife Branch within the Incident Command, and NOAA/NMFS Protected Species specialists is necessary for those overseeing and implementing open water response operations when *Sargassum* is involved, especially in an area that is *Sargassum* Critical Habitat for sea turtles. Essential Fish Habitat and important recreational and commercial fish species are also typically associated with *Sargassum* and coordination with NOAA/NMFS Habitat Conservation specialists is also required.

Guidelines and pre-authorizations for *in-situ* burning and dispersant use have been developed by the regional response teams (RRTs) for regions in which *Sargassum* occurs (Caribbean RRT, RRT-4, and RRT-6). *Sargassum*-related recommendations regarding these methods were compiled from regional contingency plans and appendices for these regions. In addition, the following documents were consulted:

- Biological and Conference Opinion on the Use of Dispersants and *In-Situ* Burning in the United States (U.S.) Region IV (NMFS 2021).
- Biological Assessment for the Preauthorized Use of Dispersant and *In-Situ* Burn Operations in RRT-4 (Boyd et al. 2016).
- Biological Opinion on the Use of Dispersants and *In-Situ* Burning in the United States (U.S.) Caribbean (NMFS 2017).
- Endangered Species Act Biological Assessment and Essential Fish Habitat Evaluation: Use of Oil Spill Dispersants and In-situ Burning as part of Response Actions Considered by the Caribbean Regional Response Team (CRRT Response Technologies Committee 2015).

Chemical Dispersants

Chemical dispersants are most effective on higher concentrations of oil and are likely to be used early on in a spill response. The following recommendations should be followed to minimize dispersant impacts to *Sargassum* and *Sargassum*-associated communities and species:

- *Sargassum* habitat should be assumed to include sea turtles and other wildlife and fish concentrations; therefore, all existing BMPs related to sea turtles or other wildlife and fish occurrences apply to pelagic *Sargassum* concentrations.
- Dispersants should not be applied directly on oiled or unoiled *Sargassum* concentrations, due to the potential to impact *Sargassum* and associated organisms, including sea turtles and fish.

- Trained observers should be used to identify *Sargassum* patches in the area of potential dispersant application, and observations should be reported. Dispersants should not be applied to *Sargassum* to the extent practicable. Sea surface dispersant applications should not be conducted within 1 km (0.5 nautical miles) of *Sargassum* concentrations due to potential for wildlife and fish concentrations to be present, including sea turtles and fish.
- Watch for and report *Sargassum* accumulations while operating vessels or aircraft involved in support of dispersant application during operations.

The use of chemical dispersants under existing guidelines (when not applied directly on or near *Sargassum*) may provide an overall benefit to *Sargassum* and associated communities by reducing the potential for subsequent oil exposure. Potential effects from dispersant application would likely be limited to a few hours post dispersant application due to dilution in the offshore water column. Dispersants applied to the water surface away from *Sargassum* concentrations are unlikely to cause direct adverse effects to *Sargassum* because residual concentrations should be diluted to levels that are not harmful.

In-Situ Burning

In-situ burning is typically used soon after a spill, when oil concentrations on the surface of the water are still high enough and the oil is fresh enough to burn. Operations sometimes involve corralling and concentrating oil in booms prior to ignition. Guidelines for *in-situ* burn operations have been developed for several regions, and situations in which *in-situ* burning is approved are well established (see NOAA 2021 as an example).

The following recommendations should be followed to minimize the impacts of *in-situ* burning on *Sargassum* and *Sargassum*-associated communities:

- Avoid burning unoiled or lightly oiled *Sargassum* to avoid impacts to wildlife and fisheries resources.
- Use observers to identify sensitive wildlife and *Sargassum* prior to burning. If sensitive wildlife is present, take measures to prevent injury to any wildlife and/or *Sargassum*, especially endangered or threatened species, including moving or hazing sensitive wildlife or moving the location of the burn away from *Sargassum*.
- Watch for and report *Sargassum* accumulations while operating vessels or aircraft involved in support of *in-situ* burning during operations.

While policies are in place to minimize the burning of oiled *Sargassum*, *in-situ* burning of oiled *Sargassum* would result in mortality to *Sargassum* and associated species (likely including sea turtles). However, it is likely that animals present in heavily oiled *Sargassum* would suffer severe injury or mortality whether or not burning were applied. In such cases *in-situ* burning may result in an overall reduction of oil impacts to *Sargassum* habitat by removing surface oil faster than it would naturally disperse and degrade, although such decisions should be weighed carefully during a response.

Mechanical Collection

Mechanical oil recovery methods are used more commonly than dispersant application and *in-situ* burning but may also be used in combination with these methods, for example, boom is used to corral oil prior to burning. On-water oil collection methods (i.e., skimming, booming) are likely to recover *Sargassum* in addition to oil where they co-occur. This section addresses impacts to collection gear from *Sargassum* and impacts to *Sargassum* and associated fauna due to mechanical collection operations.

Sargassum Impacts to Mechanical Collection Gear

Sargassum accumulations can cause challenges for on-water mechanical collection operations. *Sargassum* fouls moving parts (e.g., rotating drums, pumps) and filtering and containment equipment (screens, sorbent pads, and boom). These impacts decrease the efficiency of skimming operations and increase the volume of material collected. Additional challenges occur with recovery and disposal. Recovered *Sargassum* has a high water content. Transporting excess water and lightly oiled materials represents a loss of efficiency in oil recovery, so it is best to remove as much water as possible from collected material prior to onshore transportation. During *Deepwater Horizon*, responders attempted to push down or submerge *Sargassum* beneath the water surface to release oil that could then be skimmed; however, these methods still recovered substantial amounts of *Sargassum* (See Chapter 4). In addition to operational challenges, off-gassing of methane and hydrogen sulfide from large amounts of decomposing *Sargassum* can cause safety concerns to workers (see ‘Human Health and Safety Concerns’ below).

In response to the large influxes of *Sargassum* in the Caribbean, new equipment has been developed to collect and divert *Sargassum* prior to stranding on beaches. Examples include *Sargassum* containment boom and collecting vessels/barges. It is possible that some of these advances could be applied to on-water oil spill response methods to improve efficiency in dealing with oiled *Sargassum* during oil spills. These technologies are discussed below (see ‘Response to Mass Stranding Events’).

Recommendations for mitigating impacts of *Sargassum* debris to mechanical collection technology include:

- Utilizing gear modifications normally used to prevent debris from entering skimmers to mitigate interference by moderate amounts of *Sargassum* (though such modifications can present additional wildlife concerns and should be discussed with the natural resource agencies).
- Deploying debris-collecting equipment in advance of or in combination with skimming operations to pick up *Sargassum*.
- Investigating *Sargassum* collection technologies developed in the Caribbean or other locations for potential use during oil spill response.
- Developing technologies that can separate debris (including *Sargassum*) from oil during skimming operations.

Mitigating Impacts to Sargassum and Associated Species

On-water operations will inevitably result in a loss of *Sargassum*, which serves as important habitat for many species. However, the removal of oil from these habitats is likely a net benefit to these species, as it minimizes the potential for continued exposure to oil. Skimming operations typically move at relatively slow speeds (less than 4 knots), so fast-moving animals, such as marine mammals and adult fish and sea turtles, can evade entrainment in skimmers. However, smaller animals, such as juvenile sea turtles, may get collected along with oiled seawater and become injured or killed.

The following recommendations should be followed to minimize the impacts of on-water mechanical recovery on *Sargassum* and *Sargassum*-associated communities:

- When working in and near *Sargassum*, observers should be used to minimize injury and/or mortality to wildlife such as juvenile sea turtles. Sufficient observer coverage should be arranged prior to the commencement of on-water operations.
- Skimmers that use stilling ponds prior to separation of water from oil should be used in areas with *Sargassum* concerns, as they allow for the recovery of entrained animals.
- Avoid and minimize interaction with and collection of unoiled or lightly oiled *Sargassum*.

Considerations for Shoreline Oil Spill Response

Sargassum has the potential to affect shoreline oil spill response in shoreline and nearshore environments. *Sargassum* that has stranded along the shoreline can act as a sorbent, trapping stranded oil. The presence of *Sargassum* wrack on beaches prior to oil stranding can reduce the amount of oil penetration in beach sediments, causing decreased contamination of sediments on oiled beaches relative to those without wrack. However, oiled *Sargassum* can be a source of persistent reoiling and wildlife contamination if not removed. Oiling on the shoreline can also be difficult to detect during shoreline assessment surveys if oil is mixed with *Sargassum* wrack or covered by it, requiring careful examination by SCAT teams and consideration of cleanup tradeoffs (see Chapter 4 for examples).

Methods used to remove shoreline oiling and oiled *Sargassum* wrack can impact ecological communities associated with *Sargassum* wrack via physical disturbance and/or removal of unoiled or lightly oiled *Sargassum* wrack habitat. Removal of *Sargassum* wrack results in a loss of habitat and source of nutrients, leading to decreased invertebrate diversity and lowered organic matter in treated beaches compared to untreated beaches. These effects can exacerbate oil-related impacts to wrack-associated species. Use of mechanical removal methods can cause additional impacts, in particular, vehicle and foot traffic represent a source of disturbance to wrack-associated animals, which can have lethal or sublethal effects. For example, reduced foraging efficiency has been observed for piping plover and other shorebirds in disturbed areas (Bejarano and Michel 2016). Additionally, sediment compaction from shoreline cleanup activities can result in degraded beach habitat for infauna. Beach habitat impacts caused from wrack removal activities (increased traffic, manual or mechanical removal of the wrack itself) can take 2-6 years to recover (Michel et al. 2017).

Tradeoffs between impacts of oil and response methods must be weighed by responders, based on geographic considerations in a particular area. For example, more remote areas with wildlife disturbance concerns associated with beach cleanup might not be treated as aggressively as amenity beaches or areas where oil or oiled *Sargassum* wrack may be directly threatening wildlife. Table 3-3 details considerations for shoreline oil response methods related to *Sargassum* wrack. *Sargassum* accumulations are most likely to occur on exposed beaches, therefore methods discussed in this section are specific to sand beach cleanup. A thorough description of shoreline cleanup methods in all habitats can be found in the NOAA job aid “Characteristic Coastal Habitats: Choosing Spill Response Alternatives” (NOAA 2010).

Table 3-3. *Sargassum* considerations for shoreline and nearshore response methods.

Response method	*Sargassum* considerations
Natural recovery	Natural recovery of spilled oil and oiled *Sargassum* is an option in areas where oiled *Sargassum* is not very abundant, wildlife concerns are minimal, or oil has weathered to the point that it is not transferrable.
Containment methods	Booms and barriers used for nearshore oil containment may not be sufficient for oil containment in the presence of substantial *Sargassum* accumulation, because they do not extend far enough above or below the surface to prevent debris from piling up and sinking the boom, or going over or under the boom, rendering it ineffective. Specialized containment barriers have been developed to prevent *Sargassum* from reaching shorelines and may be used in conjunction with traditional spill response barriers in areas experiencing heavy *Sargassum* accumulations while oil is stranding (see 'Response to Mass Stranding Impacts' below).
Relocation	Wrack relocation prior to oil stranding could be implemented in situations where there is good trajectory information; however, in practice it is unlikely that sufficient trajectory knowledge occurs in time to mobilize resources. Following oil stranding, unoiled or lightly oiled *Sargassum* may need to be relocated to facilitate cleanup operations and minimize the removal of excess wrack and sand, which also conserves wrack resources. Depending on the situation, relocated wrack can be moved aside and then raked back in place after oiled sediment removal, or wrack could be moved higher into the adjacent supratidal (above the high tide line) and either left in place or moved back later to its original tidal elevation. Lightly oiled *Sargassum* has also been raked aside in front of sea turtle nests in some cases to provide a clear and clean path for hatchlings emerging from nests, particularly where emergence dates are closely tracked.
Manual removal (hand tools, assisted by small vehicles in some cases; Figure 3-4, see Chapter 4 for specific examples)	These methods are most effective where there are small amounts of oiled wrack; manual methods have the lowest environmental impact of the relocation/removal methods. Manual methods also remove less clean sand and unoiled wrack than mechanical methods. Manual methods may also be preferred in close proximity to wildlife, such as sea turtle nesting or beach nesting shorebirds and seabirds.
Mechanical removal (heavy equipment; Figure 3-4, see Chapter 4 for specific examples)	Methods can include specialized equipment, such as beach groomers or beach rakes, which are also used to remove wrack and trash from amenity beaches. Beach grooming equipment could be used to cover larger areas with moderate amounts of wrack. However, larger accumulations of oil and/or wrack would require the use of heavy machinery such as excavators. Mechanical methods have a high level of impact on beach communities due to compaction, physical disturbance, and removal of excess clean or lightly oiled material.

Figure 3-4. Examples of sand beach oil spill cleanup methods. (A) Manual oil removal using hand tools such as shovels, rakes, and small screens, which could also be used for oiled wrack. (B) Beach cleaning machine (Cherrington rake), which can be used to remove oil, such as tarballs, as well as oiled wrack. (C) Sifting of sediment piles created by mechanical removal to remove oiled material and separate it from clean or lightly oiled sediments. (D) Excavation of oil mats and debris, which could include buried oiled wrack deposits. Source: Michel et al. (2015).

The following recommendations should be followed to minimize the impacts of shoreline cleanup on *Sargassum* wrack and associated communities:

- Care should be taken to minimize unnecessary removal of *Sargassum* wrack during spill response, due to the importance of wrack for beach geomorphology, ecology, and wildlife (see Chapter 1).
- Avoid and minimize removal of unoiled and lightly oiled wrack. Decisions to remove wrack should be made based on the potential for remobilization of oil and wildlife concerns present in a given location.
- When removing oiled wrack, minimize the amount of clean sand that is removed. Methods which remove the least amount of clean sand along with wrack and oiled sediment are preferred. If mechanical methods collect significant amounts of wrack, clean sand should be sifted from collected material, to the extent possible, and returned to the beach.
- Operations should minimize the footprint of response activities, in order to minimize impacts to beach wrack communities and wildlife from disturbance, compaction, rutting, etc.
- Close coordination with the Wildlife Branch within the Incident Command, and State and USFWS Protected Species specialists is necessary for those overseeing and implementing shoreline operations, in order to mitigate potential for impacts to sensitive species.
- If wrack relocation is necessary on a large scale, relocated wrack should be moved above the high tide line in windrows parallel to shore, avoiding sea turtle nesting areas and beach and dune vegetation.

Human Health and Safety Concerns Regarding *Sargassum* Collection and Disposal

Sargassum accumulations present risks to human health and safety of responders and the general public and should be considered when making decisions regarding *Sargassum* removal. Care should be taken to protect response workers and the general public from these risks. A list of risks and recommendations is found in Table 3-4. Local, State/Territorial, and Federal health and safety agencies should be contacted for further guidance.

Table 3-4. Human health risks to consider during a response involving significant amounts of *Sargassum.*

Human Health Risk	Details	Recommendations
Sediment and groundwater contamination	When large accumulations of *Sargassum* decompose, there can be leaching of heavy metals (e.g., arsenic) into sediments, and potential contamination of groundwater sources.	Test accumulations to quantify heavy metal concentrations prior to disposal (or allowing *Sargassum* to decompose in place). Store and dispose of *Sargassum* accumulations

Human Health Risk	Details	Recommendations
		using methods that will not compromise sediment and water sources.
Hydrogen sulfide and other noxious gas emissions	Accumulations of decaying *Sargassum* may release hydrogen sulfide and ammonia, both of which can irritate the eyes and respiratory system of humans and other animals. Workers handling large amounts of *Sargassum* could be exposed to these gases.	Care should be taken to ensure that exposure remains under recommended limits and work is done in compliance with OSHA regulations for airborne emissions. Air quality monitoring and personal protective equipment (PPE) may be needed.
Allergic reactions	*Sargassum* can contain organisms (primarily hydroids) that sting and cause allergic reactions to some individuals. Stinging jellyfish may also strand and become mixed into *Sargassum* accumulations.	Proper PPE should be used for workers that will encounter large amounts of *Sargassum* to avoid contact hazards.
Bacterial infections	There is potential for *Vibrio* species associated with *Sargassum* to cause illness to exposed workers if open wounds are exposed to the bacteria.	Proper PPE should be used when handling large amounts of *Sargassum,* especially in the water, in order to prevent abrasions during work. Immunocompromised populations should be warned about the potential for infection. Open wounds should be kept out of the water or be covered by a waterproof dressing.

Response to *Sargassum* Mass Stranding or Influx Events

The persistent influxes of *Sargassum* experienced in the Caribbean and other locations in recent years has led to the development of technology specifically designed to address removal and disposal of *Sargassum.* These technologies can have cross-application for oil spill response in which *Sargassum* occurs, especially if oil spills and large influx events were to co-occur. Pertinent methods and equipment are summarized in the following section. *Sargassum* management documents may contain topics of interest to spill planning and response in these areas, including plans and protocols developed by Puerto Rico and the U.S. Virgin Islands (DRNA 2015, Bioimpact 2023) and resources available for the wider Caribbean Region (e.g., Hinds et al. 2016; the Centre for Resource Management and Environmental Studies [CERMES] website, https://www.cavehill.uwi.edu/cermes/projects/sargassum/home.aspx; and the *Sargassum* Information Hub, https://sargassumhub.org/). Additionally, NOAA's Harmful Algal Bloom Event Response program (https://coastalscience.noaa.gov/science-areas/habs/response-and-readiness/) may be able to provide support for planning and response to *Sargassum* influx events.

Barriers/Removal in Nearshore

Sargassum barriers (boom) have been used to prevent or divert *Sargassum* mats from impacting tourist beaches. Barriers designed to contain or divert *Sargassum* are most effective if they reach 30-40 cm above the surface and have skirts extending at least 60 cm below the surface, consisting of 2-5 cm mesh (Chávez et al. 2020). Experience has shown that ideal anchoring systems vary based on the substratum: screw anchors for solid substratum and stingray anchors for sand. Anchor spacing should never exceed 20 m. U-shaped barriers can be used to collect *Sargassum* but must be emptied frequently because algae will begin to decompose and sink within 24-48 hours. V-shaped barriers can be used to divert *Sargassum* to collection boats or platforms. Examples of *Sargassum* boom can be found in Figure 3-5.

Figure 3-5. Examples of *Sargassum* containment boom on land (left) and deployed in the water (right). Source: https://www.desmi.com/products-solutions-library/mesh-boom/.

Bubble curtains create a wall of air bubbles by releasing compressed air from tubing laid on the bottom of a water body (Figure 3-6). Originally designed to block underwater sound, they have a variety of other applications, including exclusion of marine debris and floating seaweed. They can be useful to protect a small area from inundation, such as a marina, canal, or water intake, and can also prevent floating oil from crossing the barrier.

Figure 3-6. Bubble curtains underwater (left) and installed at the mouth of a canal, preventing seaweed from crossing the barrier (right). Source: https://www.diversifiedpondsupplies.com/bubble-tubing/bubble-curtain and https://flkeysaeration.com/wp-content/uploads/2019/01/Marathon-Bubble-Curtain-011319-6.jpg.

Collection Platforms

Water-based *Sargassum* influx collection in nearshore environments is preferred to shoreline collection for many reasons: *Sargassum* is easier to collect from the surface of the water, does not result in shoreline damage, and results in 'fresh' *Sargassum* that may be reused for other purposes. Collection platforms range in size from small autonomous skimmers to larger vessels consisting of a barge pushing a platform (Figure 3-7). Nets and trawls can also be affixed to boats to facilitate *Sargassum* collection (Figure 3-7).

Figure 3-7. Examples of *Sargassum* collection devices. Left: The littoral collection module (LCM), a net system that can be fitted to a small vessel. It is deployed by rotating the net into the water. Source: Gray et al. (2021). Right: An example of a *Sargassum* harvesting system (Sargaboat). *Sargassum* is contained by a high boom that will not get overwhelmed by debris, and then collected using a vessel with a conveyor belt that skims *Sargassum* from the surface of the water and loads it onto a collection barge. Similar designs are based on aquatic weed harvesting vessels modified for use in marine waters. Source: https://theoceancleaner.fr/our-boats/

Sargassum Disposal Methods

Sargassum disposal can occur either in the ocean or landside, and efforts are underway to develop methods to re-use *Sargassum.*

Oceanic Disposal

Oceanic disposal methods consist of releasing the *Sargassum* at the surface in areas where it is not likely to come ashore again or where it will sink. Oceanic disposal has the benefit of not taking up landfill space and keeping nutrients within oceanic ecosystems. Pumping systems have been developed to pump *Sargassum* to the depth at which it becomes negatively buoyant and sinks, typically between 50 and 150 meters deep. Other methods have been tried, such as using conveyors or pulverizing *Sargassum*, but they are not as effective (Gray et al. 2021). Ocean disposal may require special offshore disposal permits from the EPA.

Landside Disposal

Landside options include disposal in a traditional landfill or beneficial use of *Sargassum*. *Sargassum* or oiled *Sargassum* needs to be disposed of at properly lined landfills in order to minimize the potential for contamination of local aquifers from oil and/or heavy metal leachates.

Unoiled *Sargassum* can potentially be converted into products for human use. Due to the recent influx of *Sargassum* in the Caribbean, many efforts are underway to monetize *Sargassum* removed from the environment. In order for *Sargassum* to be used, it is best for ‘fresh’ *Sargassum* to be harvested from nearshore waters, because it has not yet begun to decay and is not mixed with sediments. There are a number of challenges to developing beneficial reuses of *Sargassum*, including the presence of heavy metals in its tissues; variability in chemical content; variable supply; and rapid change in state as it approaches shore and begins to decompose.

Despite these challenges, the use of *Sargassum* and *Sargassum* compounds or extracts (including activated carbon, alginates, cellulose) are being explored for a variety of uses, including: agricultural enhancements; antifouling compounds; bioenergy production; bioplastic manufacturing; bioremediation and purification; clothing; construction materials; paper products; cosmetics; electrochemical production; environmental restoration; food and beverage supplements; lubricants, surfactants and adhesives; and pharmaceutical and biomedical uses. Commercial uses of *Sargassum* have been developed for use in agriculture as fertilizer, mulch, and compost; in footwear as material for shoe soles; in construction to make bricks; in cosmetics; in coastal dune restoration; and for artisanal-scale paper products. Research and commercial development are ongoing for many more potential uses (see Desroches et al. 2020 for a thorough review). Alternative uses for agriculture, livestock feed, and human consumption would need to be carefully evaluated due to concerns such as heavy metal content and salinization of soils.

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Chapter 4. *Sargassum* Case Studies

Case studies provide applied examples of much of what has been presented in prior chapters and an opportunity to consider how prior incidents and responses may inform and contribute to future oil spill planning and response, as well Natural Resource Damage Assessment (NRDA), restoration, disaster preparedness, and coastal resiliency. In this chapter, three case studies are summarized, focusing on different types and scales of incidents: a large crude oil spill of national (and international) significance; a moderate-sized spill of an intermediate fuel oil; and a *Sargassum* influx event (without oil) that affected public water supply and shoreline resources. In addition, the three case histories touch on different geographies within the range of pelagic *Sargassum*–the Gulf of Mexico, South Atlantic, and Caribbean regions.

Deepwater Horizon Oil Spill (DWH), Northern Gulf of Mexico, 2010

***Sargassum* involvement during a Spill of National Significance**

On April 20, 2010, the *Deepwater Horizon* mobile drilling unit exploded and sank in the northern Gulf of Mexico two days later, approximately 64 km offshore of Louisiana, resulting in the largest marine oil spill to date in U.S. waters. The spill released an estimated 3.19 million barrels of oil into the ocean over 87 days, contaminating over 112,000 km^2 of surface waters, 2,100 km of shorelines, and affecting a wide diversity of biotic and abiotic natural resources in the Gulf of Mexico marine ecosystem (DWH NRDA Trustees 2016). The timing of the DWH spill coincided with the natural peak of *Sargassum* occurrence, which is most prevalent in the Gulf of Mexico throughout the spring and summer. *Sargassum* was often observed in convergence zones where oil also aggregated (Figure 4-1). Direct oiling of pelagic *Sargassum* was observed during response and NRDA operations, and chemical analysis indicated that DWH oil was incorporated into *Sargassum* tissues within the footprint of the oil slick. These impacts were detected up to 160 km from the spill source (Stout et al. 2018).

Figure 4-1. Oil and *Sargassum* accumulations in pelagic environments. A convergence line of pelagic *Sargassum* and oil during the *Deepwater Horizon* oil spill (left), and a researcher handling oiled *Sargassum* (right). Sources: Georgia Department of Natural Resources, https://ocean.si.edu/conservation/pollution/oiled-seaweed-after-gulf-oil-spill (left) and Jim Franks, Southern Miss Gulf Coast Research Laboratory, https://www.gulflive.com/mississippi-press-news/2010/05/usm_gulf_coast_research_labora.html (right).

Due to its value as wildlife and fisheries habitat, efforts were made to minimize the removal of clean or lightly oiled *Sargassum* during the response. However, oiled *Sargassum* had the potential to contaminate unoiled locations and expose additional wildlife to DWH oil as it moved around the Gulf, necessitating its removal in some cases. A removal plan was developed specifically to remove oiled *Sargassum* from coastal waters to prevent it from coming ashore and causing wildlife impacts. Methods used involved deployment of boom to corral oiled *Sargassum* mats and excavators and other machinery mounted on barges to collect oiled *Sargassum* from the water's surface. Ultimately, the success and use of targeted oiled *Sargassum* removal operations were limited, occurring for only 3 days off of the coast of Alabama (USCG 2016). All other removal of oiled *Sargassum* occurred along with other oil collection methods.

Offshore response efforts included unprecedented use of chemical dispersants, hundreds of controlled burns, and widespread mechanical collection of oil and oiled debris from the water's surface, including use of various types of oil boom (NMFS 2020). The presence of *Sargassum* in offshore response areas posed challenges for mechanical oil recovery methods (Mark Ploen, QualiTech, pers. comm.). *Sargassum* clumps clogged mechanical equipment such as intakes and screens on oil skimmers, slowing recovery operations as vessels had to stop to clear machinery. The recovery of oiled *Sargassum* necessitated the transport and disposal of more oiled material than anticipated. Additionally, gases emitted from decaying seaweed presented human health and safety concerns, leading to more complex storage requirements for recovered material. An experimental vessel was constructed to separate *Sargassum* from oil prior to mechanical recovery; however, concerns over entrainment of sensitive wildlife due to the design led to it being used for oiled debris in locations without substantial *Sargassum* accumulations. Other ad hoc attempts were made to increase oil collection efficiency among *Sargassum* (e.g., using the weight of skimming equipment to temporarily submerge *Sargassum* beneath the water to release oil to the surface for collection); however, only marginal decreases in *Sargassum* collection or increases in oil collection were realized. Future research and development on efficient methods for oil and oiled *Sargassum* recovery in *Sargassum*-rich regions may be warranted.

Figure 4-2. A sea turtle swimming though oil and *Sargassum* during the DWH oil spill. Source: DWH NRDA Trustees 2016.

Numerous fauna were observed in association with *Sargassum* weed lines during DWH response efforts. Pelagic *Sargassum* is important habitat for post-hatchling and juvenile sea turtles[5] and is designated Essential Fish Habitat for many fisheries species in the Gulf of Mexico. The co-occurrence of *Sargassum* and associated wildlife and fisheries resources in convergence zones along with oil accumulations likely increased the degree of wildlife and fisheries impacts (Figure 4-2). Notably, rescue efforts for sea turtles were focused in convergence areas, which were observed to predominantly contain *Sargassum* mixed with oil (McDonald et al. 2017). During the DWH response, wildlife rescue operations observed 937 juvenile sea turtles in the spill area and captured 573 for more detailed examination and rehabilitation. Of the animals captured, 81% were visibly oiled. The majority of the animals captured were Kemp's ridley sea turtles (51%) but green sea turtles (37%), loggerhead sea turtles (7%) and hawksbill sea turtles (2%) were also captured. In addition to impacts to juvenile sea turtles, concern over the potential for post-hatchling sea turtles to be exposed to oil in pelagic *Sargassum* habitat was one of the reasons for the establishment

[5] At the time of the spill (2010), *Sargassum* was not yet designated as Critical Habitat for loggerhead sea turtles.

of an extensive sea turtle nest translocation program, which moved 274 nests from affected Gulf of Mexico shorelines to an incubation center on the Florida East Coast and released approximately 14,796 hatchlings into the Atlantic Ocean (USFWS 2018). Throughout the response, close coordination with NMFS and USFWS led to the development and implementation of BMPs, monitoring protocols, and observer programs which helped minimize the impact of response actions to wildlife (USCG 2016).

Beached *Sargassum* is a dominant type of wrack on high-energy beaches in the Gulf of Mexico. Shoreline surveys during DWH had to examine *Sargassum* wrack for oil and check under clean wrack to make sure there was no oil beneath it (Figure 4-3). Large accumulations of *Sargassum* interfered with the ability of SCAT teams to detect oil in some cases and slowed shoreline survey and cleanup operations on beaches with large amounts of *Sargassum* wrack. Shoreline cleanup efforts included collection and removal of oiled *Sargassum* wrack from the shoreline, including some subsurface removal. During response efforts, clean wrack was left in place to the degree possible. However, when clean wrack was deposited on top of surface or subsurface oil prior to cleanup, workers moved clean wrack aside prior to oil recovery and replaced it after operations were finished in an area. This process took extra time and effort, and work crews had to be careful to avoid cross-contamination of clean wrack.

Along affected shorelines, oiled *Sargassum* was removed during cleanup operations using both manual and mechanical methods. In shoreline environments impacted by the DWH spill, *Sargassum* and other wrack is an important part of critical habitat for the ESA-listed wintering piping plover and other migratory shorebirds along affected beaches and serves many ecological functions in shoreline environments (see Chapter 1). While the loss of wrack may have affected species that use these habitats, effects of the oil remaining in place would have been more severe and persistent. To avoid impacts to these species during response, shoreline cleanup operations used wildlife observers to prevent impacts to shorebird species and implemented measures to minimize the removal of wrack.

Figure 4-3. Field examples of *Sargassum* occurring on sand beaches during DWH in 2010. Left: An oiled *Sargassum* wrack line, 3,200 m long by 3 m wide with 5% cover of fresh emulsified oil splotches 2-6 cm in diameter and 0.1-1 cm thick throughout the wrack, Elmer's Island, Louisiana. Right: Clean (unoiled) *Sargassum* wrack line on Timbalier Island, Louisiana, with a narrow zone of 1% weathered surface oil residue landward of the clean *Sargassum*. Both locations are designated Critical Habitat for piping plover. Source: NOAA DWH Louisiana SCAT database.

Injury to pelagic *Sargassum* habitat was assessed as part of the DWH NRDA, based on the surface water footprint of DWH heavy (thick) oiling combined with *Sargassum* areal coverage derived from a combination of low-altitude aerial surveys and satellite imagery data (Hu et al. 2016). It was estimated that oil exposure during the *Deepwater Horizon* spill may have caused the direct loss of 479 to 1,749 km^2 or 13-23% of *Sargassum* habitat in the northern Gulf of Mexico (DWH NRDA Trustees 2016; Hu et al. 2016). The total loss of *Sargassum* habitat, including foregone area from lost growth, ranged from 3,048 to 11,141 km^2 (DWH NRDA Trustees 2016). Areas of *Sargassum* that experienced lighter oiling may still have been negatively affected, resulting in sublethal effects and a reduction in habitat function for wildlife and fish. Further research on oil toxicity to *Sargassum*; *Sargassum* behavior under different oiling, oceanographic, and response conditions; and improved methods for *Sargassum* injury assessment may be valuable for future incidents.

DWH NRDA field studies and injury assessments for sea turtles, birds, fish, and invertebrates all documented oiling and response impacts to these resources that occurred in association with *Sargassum* habitats, emphasizing the importance of *Sargassum* (Haney et al. 2014; DWH NRDA Trustees 2016;

McDonald et al. 2017). Field sampling characterizing fish and invertebrate communities associated with *Sargassum* was completed as part of the DWH NRDA (Ruder et al. 2017). Multiple gear types were used to assess different species, life stages, and sizes of fish and invertebrates (e.g., neuston nets, bongo nets, remotely operated vehicle [ROV] video transects). Species documented were similar to those reported in prior *Sargassum* studies including filefishes, triggerfishes, endemic species (*Sargassum* anglerfish, *Sargassum* pipefish), jacks, tunas, mackerels, and dolphinfish, among others. Larval anchovies, clupeids (herring, menhaden, and related species), snappers, and flyingfish were also documented. Decapod crustaceans (shrimp and crabs) were also captured and quantified. Fish and invertebrate impact estimates were based on densities of fish and decapods in *Sargassum* habitats and the area of heavily oiled *Sargassum* directly impacted by the spill. Preliminary findings estimated that oiling impacts to fish associated with *Sargassum* ranged from 341 million to 1.2 billion kg of lost biomass of larval, juvenile, subadult, and adult fish (Ruder et al. 2017). Counts of individuals lost ranged from 1.3 to 5.2 trillion decapods and fish. Five species of adult fish accounted for ~90% of the total biomass lost: amberjack (40%), blue runner (28%), dolphinfish (9%), sea chub (7%), and almaco jack (5%). Dolphinfish accounted for nearly 40% of the juvenile fish biomass lost and tuna species accounted for over 50% of the larval fish biomass lost.[6]

Small juvenile sea turtle injury was closely tied to impacts occurring in oiled *Sargassum* habitats. It was estimated that roughly half of the population of 1- and 2-year-old Kemp's ridley sea turtles were exposed to oil following the *Deepwater Horizon* oil spill, and 10-20% of the population died as a result (DWH NRDA Trustees 2016; McDonald et al. 2017). In total, it was estimated that between 55,000 and 160,000 small juvenile sea turtles were killed as a result of the *Deepwater Horizon* oil spill; many of these turtles would have been using *Sargassum* habitats (DWH NRDA Trustees 2016). Most of this mortality was likely due to oil exposure, although it is possible that some turtles were injured during mechanical skimming and *in-situ* burning of oil in and near *Sargassum* habitats.

Despite the strong association of many species with *Sargassum*, oil spill injury tied to *Sargassum* was not fully addressed for many fauna separately from injury occurring in pelagic environment as a whole during the NRDA (DWH NRDA Trustees 2016). Indirect effects to *Sargassum*-associated species resulting from loss of habitat also likely occurred, due to the loss of habitat functions such as foraging and shelter;

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[6] These estimates were only preliminary and were not included in the injury calculations presented in the PDARP.

however, these impacts were likewise not quantified (NMFS 2020). Additional research quantifying the use and importance of *Sargassum* habitat to various wildlife and fish species may help support future injury assessments for *Sargassum*-associated fauna.

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Fort Lauderdale Mystery Spill, Southeast Florida, August 2000

Oil and *Sargassum* considerations during a moderate-sized spill

On August 8, 2000, a spill of at least ~20,500 gallons of an intermediate fuel oil began washing ashore on Southeast Florida beaches (NOAA 2000, French McCay et al. 2001; NOAA and FDEP 2002). The spill source was never identified but was thought to have been from an unknown commercial vessel traveling north near the western edge of the Gulf Stream which was 8-10 km offshore at the time of the spill. The oil spill affected approximately 32 km of sand beaches from Pompano Beach (Hillsboro Inlet) south to North Miami Beach (Haulover Inlet), centered on the greater Fort Lauderdale area, including John U. Lloyd Beach State Park (now named Dr. Von D. Mizell-Eula Johnson State Park) (NOAA 2000; Figure 4-4). This spill is also referred to as the Golden Beach Mystery Spill, the Southeast Florida Mystery Spill, and the John U. Lloyd Beach Mystery Spill by different sources. *Sargassum* occurs regularly in the Gulf Stream and coastal waters in the area of impact and is often found as wrack on the beach (Figure 4-4). The presence of *Sargassum* led to various response and NRDA concerns and considerations in shoreline, nearshore, and offshore environments during the spill.

Shoreline oiling during the spill included significant amounts of oiled *Sargassum* wrack, tarball strand lines, and intertidal and shallow subtidal (submerged) oil mats and patties in the swash zone and in the trough between the sand beach and the first sand bar (NOAA 2000). Response activities included manual removal of oiled *Sargassum* wrack and tarballs using rakes, shovels, and gloved hands (NOAA 2000; Figure 4-5). Mechanical removal of oiled *Sargassum* wrack was also conducted using mechanical beach rakes typically used for beach grooming. Collected oiled *Sargassum* wrack was mostly disposed of by solid waste incineration. Beach cleanup endpoints during the spill were defined as: 1) no easily observed oil mixed in wrack lines, 2) <5% tarball cover on most beaches (similar to background conditions), and 3) complete oil and oiled wrack removal to the degree possible for high priority nesting beaches. Unoiled wrack was left on the beach.

The spill occurred during sea turtle nesting season, and protecting nests, hatchlings and post-hatchlings from oil and response impacts was a major concern during the spill (NOAA 2000, NOAA and FDEP 2002, Jeansonne et al. 2005). Hatchling and post-hatchling sea turtles can come into contact with oiled *Sargassum* wrack on the beaches as they emerge from nests or encounter oiled floating *Sargassum* once

Figure 4-4. Contemporary photos of Dr. Von D. Mizell-Eula Johnson State Park, formerly John U. Lloyd Beach State Park, which was affected by the Fort Lauderdale Mystery Spill in 2000. Light accumulations of unoiled *Sargassum* wrack (dark color) are visible in both photos. Source: Florida State Parks, https://www.floridastateparks.org/mizell.

they have moved to nearshore waters. At the time of the spill, there were an estimated 530 sea turtle nests on affected beaches, mostly loggerhead sea turtles but also green sea turtles and potentially leatherback sea turtles (NOAA and FDEP 2002, Jeansonne et al. 2005). Hatchlings were emerging from nests each night during the spill, and recent hatchling and post-hatchling sea turtles were expected to be in nearshore and nearby offshore waters in the spill vicinity. To avoid response impacts to sea turtle nests, mechanical raking of oiled *Sargassum* wrack was only used below the high tide line on the active beach face and exclusion areas were established near known sea turtle nests and in important nesting areas such as the John U. Lloyd Beach State Park. Shoreline cleanup work was restricted to daylight hours to protect hatchling turtles and nests. An emphasis was placed on removing as little clean sand as possible during oil and oiled wrack removal, and ruts or depressions on the beach caused by the cleanup were returned to natural grade at the end of each workday to avoid creating barriers or entrapment risks for sea turtle hatchlings. In addition, to minimize the potential impacts of additional oiled *Sargassum* wrack and tarballs that were deposited during the night, sea turtle nest monitors used hand rakes to clear wrack and oil from 3-4 m wide corridors extending from marked sea turtle nests to the waterline, so hatchlings would have a clean path to the sea. In areas with substantial oiling, turtle nests were also caged, and newly emerged hatchlings collected and carried to the water or moved to nearby clean beaches for release, in order to reduce their exposure to oiled *Sargassum* wrack and tarballs (Figure 4-5).

There were also concerns during the response that sea turtles could be exposed to oil accumulated in floating *Sargassum* patches at sea, which are particularly important habitats for recent hatchlings and post-hatchlings (NOAA 2000). NOAA, in coordination with the Florida Fish and Wildlife Conservation Commission, conducted overflights and boat surveys on August 10 to examine floating *Sargassum* for oil presence. By the time of the surveys, all *Sargassum* encountered at sea appeared to be unoiled, so it was concluded that most of the oil and oiled *Sargassum* had moved onshore, so that oiled *Sargassum* was no longer a threat to sea turtles at sea. Observed drift rates of unoiled *Sargassum* during these surveys were used to help inform trajectory models and hindcasts for the spill (French McCay et al. 2001).

Beaches in the spill area are also heavily utilized for recreation, resulting in concerns for human health and safety as well as lost beach use. Due to human health and safety concerns, many of the beaches were closed to swimming for several days (NOAA 2000, NOAA and FDEP 2002). There were documented cases of swimmers, waders, and beach users being oiled, especially on their feet and legs. Beach users were advised not to handle or walk on the *Sargassum* wrack due to the potential for oil contact. Cleaning stations were also established for beach users to remove tar from their feet and legs.

Figure 4-5. Response workers removing oiled *Sargassum* wrack (dark color) from sand beaches during the Fort Lauderdale Mystery Spill in 2000 (left). Marked and caged sea turtle nest and nest monitor at John U. Lloyd Beach State Park during the spill (right). Source: Sun-Sentinel/TCA, from news articles published 9-11 August 2000 (South Florida Sun-Sentinel 2000a, 2000b, 2000c), reproduced with permission.

Submerged oil mats in the nearshore trough between the beach and the first sand bar were also a concern during the spill, both for sea turtles and for recreational beach users (NOAA 2000). Submerged oil surveys and detection were difficult due to visual similarities with large amounts of unoiled decomposing

Sargassum wrack that was also deposited in the nearshore trough, with both oil and wrack appearing as dark linear bands running parallel to shore. Most of these bands were unoiled *Sargassum* wrack. Submerged oil was also found mixed with *Sargassum* and seagrass wrack, as well as buried by a thin veneer of sand, further complicating detection. Because of these factors, overflight and shoreline-based surveys were not effective in determining the presence and distribution of submerged oil mats. Oil presence had to be determined by wading and using shovel probes, snorkeling, and diving. When located, submerged oil was removed by hand by commercial divers. The largest submerged oil accumulation observed by divers was 90-120 m long, 2-3 m wide, and 8-10 cm thick, with 100% oil cover, located within John U. Lloyd State Park. However, complete surveys for submerged oil were not conducted so the full extent of submerged oil mats was not known.

A Natural Resource Damage Assessment (NRDA) was conducted for the spill (French McCay et al. 2001, NOAA and FDEP 2002, Jeansonne et al. 2005, Boltin and Reilly 2005). Direct impacts to floating *Sargassum* habitats and impacts to *Sargassum*-associated fauna were not quantified; however, some of the sea turtle and fish and invertebrate mortality would have occurred in *Sargassum* habitats. NRDA oil trajectory and exposure modeling estimated over 137,000 loggerhead, green, and leatherback sea turtle hatchlings (and post-hatchlings) were exposed to oil at sea, resulting in the death of 7,800 small sea turtles. Many of these turtles would have been in nearshore waters, moving east toward offshore waters and *Sargassum* habitats as the oil moved from the release area toward and onto the beaches (see Chapter 1 for the importance of *Sargassum* habitats to young sea turtles). Sublethal sea turtle impacts were not estimated. In addition to sea turtles, over 250,000 estimated fish and larger motile invertebrates were killed as a result of the spill, equating to 10,930 kg of fish and invertebrate biomass lost due to direct mortality and foregone growth, some of which may also have been associated with *Sargassum* habitats at sea (NOAA and FDEP 2002, Jeansonne et al. 2005, Boltin and Reilly 2005).

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St. Croix *Sargassum* Influx and Water Supply Incident, U.S. Virgin Islands, 2022

***Sargassum* influx leading to infrastructure and ecological concerns (in the absence of oil)**

In mid-July 2022, a large influx of *Sargassum* entered Christiansted Harbor in St. Croix, U.S. Virgin Islands (USVI), impacting the Virgin Islands Water and Power Authority (WAPA) Estate Richmond Plant, a combined seawater desalination and power generation facility. The WAPA plant is the primary potable water source for the island and is supplied by two intakes approximately 70 m from shore in relatively shallow water (FEMA 2022a,b; Figure 4-6 and 4-7). *Sargassum* quickly clogged the two nearshore water intakes and was being drawn into the facility, reducing pumping efficiency and affecting internal plant equipment and operations. The resulting declines in water production quantity and quality represented a critical threat to the island’s population, and could lead to cascading effects on power production, healthcare facilities, and other sectors. Water supply concerns were heightened as the island was experiencing a prolonged extreme drought and the incident occurred during hurricane season, when water storage is necessary to prepare for potential outages. Accumulation and decomposition of *Sargassum* on the shoreline and in adjacent nearshore waters was a further concern due to impacts to coastal water quality; human health and safety (from potential hydrogen sulfide gas); and natural resources, such as sand beaches and nearshore seagrass meadows.

Figure 4-6. Aerial view of the WAPA plant and shoreline including the water intakes and initial booming strategy (yellow line), *Sargassum* on and near the beach (brown and orange colors), and the WAPA pier (left). A wider mass of floating *Sargassum* (orange colors) *observed* during the response, covering the water intakes and nearshore waters ~100 m or more from shore. Photo taken standing near the seaward end of the WAPA pier looking towards the water intakes and shoreline (right). Sources: Civil Air Patrol, FEMA.

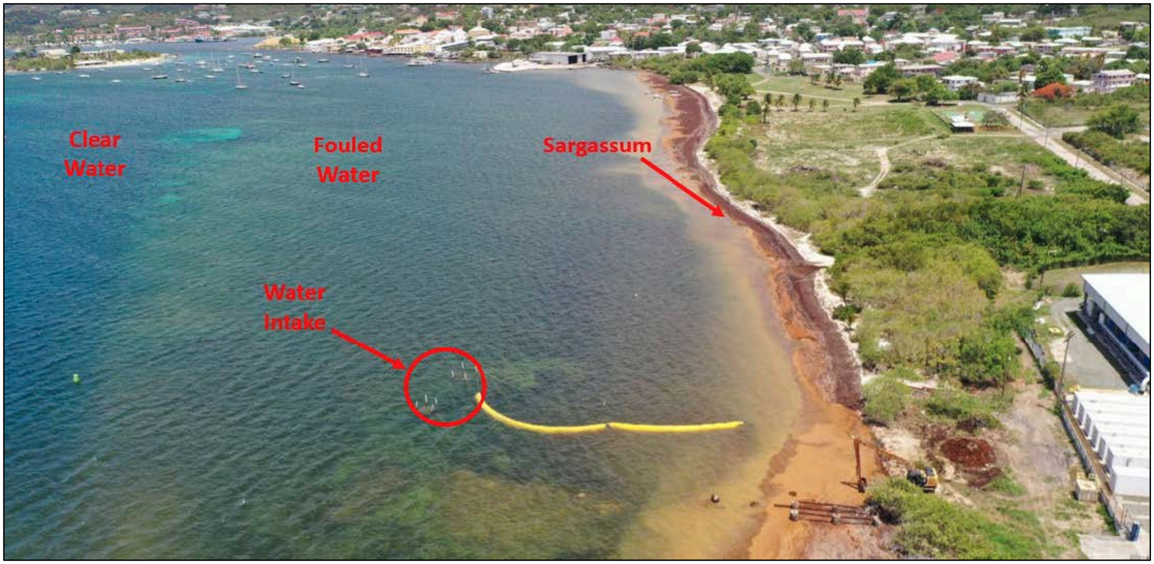

Figure 4-7. The range of *Sargassum* influence in the response area, including *Sargassum* on the beach and in nearshore waters (orange and brown colors) as well as *Sargassum* brown tides (fouled water) extending from the shoreline past the water intakes and further into Christiansted Harbor. The boom (yellow) in this photo is out of place and not functioning properly. A long-reach excavator is removing *Sargassum* from the shoreline and staging it in a pile in the backshore (bottom right). Source: FEMA.

Initial measures were taken to mitigate the situation, including protecting and clearing the water intakes, maximizing filter backwashing, and increasing chlorine injection. However, the amount of *Sargassum* quickly overwhelmed local and territorial resources, causing increased concern over the potential for greater reductions in water supply and plant failure. On 22 July 2022, the USVI Governor declared a State of Emergency due to the *Sargassum* influx and impacts to the water plant (USVI Governor 2022) and shortly thereafter a Federal Emergency Declaration was issued, authorizing the Federal Emergency Management Administration (FEMA) to assist the USVI under the Stafford Act (EM-3581-VI Water Shortage and Health Impact from Unprecedented *Sargassum* Influx; FEMA 2022a). The USVI and FEMA established an emergency response, activating multiple territorial and federal agencies under various emergency support function (ESF) missions. NOAA received an ESF-5 (information and planning) mission assignment and the NOAA Scientific Support Coordinator mobilized to St. Croix on 1 August 2022 for ten days (NOAA 2022). Several NOAA programs contributed to the response, including but not limited to the Office of Response and Restoration (OR&R) Emergency Response Division (ERD) and Disaster Preparedness Program (DPP); the Atlantic Oceanographic and Meteorological Laboratory (AOML); the National Centers for Coastal Ocean Science (NCCOS); and the Caribbean Coastal Ocean Observing System (CARICOOS) part of the NOAA affiliated U.S. Integrated Ocean Observing System (IOOS). Emergency response topics are emphasized in the remainder of this case study, particularly those with cross-cutting interest for oil spill responders.

Monitoring and forecasting *Sargassum* influxes likely to affect the water plant and adjacent shorelines during the response was a major need but proved to be a challenge as no readily available imagery, data, or modeling tools were available at the appropriate scale (FEMA 2022a,b; NOAA 2022). Initially the NOAA AOML *Sargassum* Inundation Risk (SIR) reports (https://cwcgom.aoml.noaa.gov/SIR/) were used, although the temporal and spatial resolution of this tool were not ideal for local response needs. As a result, the protocol developed during the response involved USVI and federal responders reviewing readily available medium scale remote sensing monitoring products to identify large offshore *Sargassum* accumulations that could impact the island, including the University of South Florida (USF) Alternate Floating Algae Index (AFAI) and the NOAA AOML Maximum Chlorophyll Index (MCI), both available at https://cwcgom.aoml.noaa.gov/cgom/OceanViewer/. If large concentrations of *Sargassum* were observed to the east or northeast of St. Croix, regional experts and tools from CARICOOS (https://www.caricoos.org/) were consulted to determine if wind and current conditions were likely to transport *Sargassum* concentrations into the response area. If this were the case, the NOAA SSC facilitated NOAA trajectory support for further assistance with further interpreting existing data on potential incoming threats. Once potential *Sargassum* concentrations were predicted to be within 4-5 km of the shoreline (the limit of resolution for readily available imagery, data, and modeling tools), overflight and vessel observations were used to monitor the situation. The lack of existing local monitoring and forecasting capabilities available during the response highlighted the need to develop these capabilities. Work is underway to develop finer scale *Sargassum* monitoring and forecast modeling capabilities for USVI shorelines in preparation for future influx events (FEMA 2022b; DOI 2022).

Direct response actions consisted of removing *Sargassum* from the water intakes and adjacent shorelines and implementing methods to prevent additional *Sargassum* from reaching the water intakes. Removal of *Sargassum* from the water intakes and the water intake pit was conducted primarily by divers (FEMA 2022a; NOAA 2022). Some removal was also conducted using vacuum equipment. *Sargassum* was removed along 400-600 m of shoreline and immediate nearshore waters from the water plant to the east using a long-reach tracked excavator (Figure 4-7 and 4-8). *Sargassum* was staged temporarily in the backshore and then transferred to haul trucks for disposal. The local landfill was used for *Sargassum* disposal. This was the only feasible alternative, but raised concerns due to limited landfill capacity and environmental considerations such as hydrogen sulfide gas production and leachates such as arsenic and other metals. It is unclear if the landfill disposal area was lined or unlined. Offshore disposal was considered but was deemed not feasible due to lack of equipment and permitting requirements.

Protecting the water intakes from additional *Sargassum* clogging and entrainment over the short term was a response priority. Initially, 90 meters of hard oil spill boom was placed perpendicular to shore, extending to the seaward side of the intakes; however, this boom became overwhelmed with *Sargassum*, which moved it out of place and reduced its efficiency (FEMA 2022a; NOAA 2022; Figure 4-6 to 4-8). As a result, the U.S. Coast Guard developed an improved booming strategy that included 60-m of 91-cm boom in a deflective configuration lying at an approximate 45° angle to the shore running NW to SE, which was offset from and extended past the intakes, with a second protection layer of 30-m boom surrounding the intakes. Oil boom was used because it was readily available; however, it did not extend far enough into the water column to prevent *Sargassum* from passing beneath the barrier. Other actions considered but not implemented due to cost, feasibility, or permitting requirements included: the installation of permanent mooring points or auger anchors to better secure the boom and allow for rapid redeployment; installing an air bubble curtain to protect the intakes; and temporary deployment of mobile high volume pumps in deeper water to serve as alternate water intakes. In the event of plant failure, extensive planning and logistics were conducted regarding alternative drinking water sources and distribution. Long-term solutions under consideration include installing updated or improved screens on the intakes, permanently extending the water intakes and associated piping further offshore and into deeper water, installing permanent bubble curtains, and connecting the plant to other industrial water intakes on the island via pipelines as a backup alternative.

Figure 4-8. Response field operations. Boom maintenance using onshore personnel and small vessels, with *Sargassum* on the shoreline and in nearshore waters (left). Removing *Sargassum* from the shoreline using a long-reach tracked excavator (right). Source: FEMA.

Human health and safety considerations during the response were focused on hydrogen sulfide gas exposure (FEMA 2022a). A safety committee was established to monitor and enforce workforce safety guidelines and personal protective equipment (PPE) requirements. Air quality monitoring was conducted at the water plant, on the shoreline, and in surrounding areas. The exposure limit for response workers was established at 10 ppm of hydrogen sulfide gas, based on U.S. Occupational Health and Safety Administration (OSHA) and U.S. National Institute for Occupational Safety and Health (NIOSH) guidelines. Limited information available on air monitoring data indicated recorded hydrogen sulfide levels of 2.0-4.5 ppm at the water plant, 1.8-4.0 ppm on the shoreline, and 0.4 ppm up to a block away from the shoreline. Levels on the shoreline generally decreased over the course of the response. It is uncertain if PPE for hydrogen sulfide gas was required at any point during the response.

Natural resource concerns that emerged during the response centered on the low-energy sandy beach where *Sargassum* was accumulating (NOAA 2022), which is a potential sea turtle nesting beach.[7] Large *Sargassum* accumulations on nesting beaches can prevent females from nesting, impact existing nests,

[7] This beach has relatively low potential for sea turtle nesting based on frequent USFWS and NOAA surveys conducted during the Hurricane Irma-Maria ESF-10/3 response in 2017-2018; however, nesting was still possible.

and prevent hatchlings from reaching the sea; however, shoreline cleanup to remove *Sargassum* can also impact sea turtle nesting. Prior to the removal of *Sargassum* from the shoreline, an emergency consultation was conducted with the U.S. Fish and Wildlife Service that resulted in the establishment of best management practices (BMPs) to protect nesting sea turtles during shoreline cleanup operations (NOAA 2022). BMPs included conducting daily nest surveys prior to operations; raking *Sargassum* from the substrate rather than digging into the beach; minimizing removal of beach sand; returning the beach surface to natural contours at the end of each work day; protecting shoreline vegetation; conducting operations only during daylight hours; restricting lighting on or near the beach at night; and instructions for what to do and who to contact if turtles, crawls, or nests were encountered. No sea turtles or nests were observed or known to be impacted during shoreline cleanup operations.

Several information needs were identified during the response but were not addressed or implemented. These are discussed below as a reference for future events:

Water quality concerns. A water quality sampling and analysis plan was developed to address water quality concerns resulting from *Sargassum* decomposition on the shoreline and in nearshore waters (FEMA 2022a; NOAA 2022). The plan included the following components: collecting three samples of cloudy water from *Sargassum* decomposition areas and three clear water samples from outside the area of *Sargassum* influence; analyzing each sample for hydrogen sulfide (for water odor and as well as health and ecological considerations), ammonia, biochemical oxygen demand (BOD), total suspended solids (TSS), including microscopic analysis of TSS retained on a 0.45 micron filter; and conducting in-situ measurements for pH, dissolved oxygen, and salinity at the water surface, mid-water, and near the bottom for each sampling location and at varying distances from the water intakes. However, water quality sampling was not implemented during the response.

Decomposition rates of Sargassum. Decomposition rates of *Sargassum* on the shoreline and in the water would have helped inform cleanup priorities, methods, and endpoints, but were not readily available (NOAA 2022). A literature search was conducted on decomposition rates finding limited sources reporting anecdotal estimated rates of 8-16 days for *Sargassum* decomposition on shorelines, although it was thought that rates could vary widely based on conditions such as *Sargassum* amount, thickness, moisture content, temperature, oxygenation, substrate type, position on the shoreline, etc. Little to no information was available for *Sargassum* decomposition in water; therefore, a plan was developed for a litter bag decomposition study near the water intakes, based on standard vegetation litter study methods. The plan involved placing a known mass of *Sargassum* in perforated litter bags in the water column and on the bottom, and periodically weighing and describing remaining *Sargassum* and decomposing material over time. This method could also be applied to better determine *Sargassum* decomposition rates on shorelines. However, the litterbag study was not conducted during the response.

Ecological effects of Sargassum brown tides. Impacts to nearshore seagrasses were raised as a concern early in the response (NOAA 2022, see Chapter 2 for impacts of *Sargassum* brown tides). Seagrasses were not evaluated or monitored as part of the response, as the primary focus was on the water intakes and shoreline. However, response photographs show large amounts of seagrass wrack floating in nearshore waters and deposited on the shoreline in areas impacted by *Sargassum*. Based on NOAA seagrass monitoring for this location conducted during and after the Hurricane Irma-Maria ESF-10/3 response in 2017-2018 and 2020 as well as available aerial photography reviewed from before and after the 2022 *Sargassum* influx, it appears that ~25-75 m of the shoreward edge of continuous seagrasses may have been either lost or diminished (becoming less dense) within the response area (Figure 4-9). Additional investigation would be needed to quantify any seagrass impacts associated with the *Sargassum* influx event, including loss of seagrasses, decreases in seagrass cover, and shifts in community structure. Non-native seagrass, *Halophila stipulacea*, has been documented in the response area and may further colonize impacted areas to the detriment of native seagrasses.

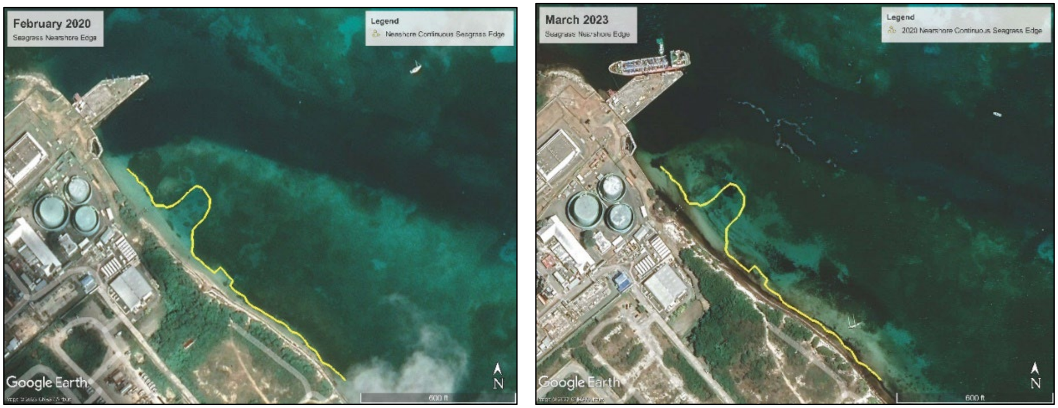

Figure 4-9. The shoreward continuous seagrass edge in 2020 (yellow line) shown for February 2020 (left) as compared to March 2023 (right) in the response area. Darker green shaded areas are continuous dense seagrasses, lighter colored areas in 2023 seaward of the yellow line may represent seagrass impacts. Sources: Google Earth, NOAA.

Case Study References for St. Croix *Sargassum* Influx and Water Supply Incident

DOI. 2022. Interior's Office of Insular Affairs Funds Study of Mitigation Options for *Sargassum* Seaweed Influx in the U.S. Virgin Islands. DOI Press Release, 8/17/2022. https://www.doi.gov/oia/press-releases/.

FEMA. 2022a. Region 2 *Sargassum* Playbook, EM-3581-VI Field-Level, August 2022. FEMA Region 2 Response Division, New York. Note that distribution of this report is limited and may not be publicly available.

FEMA. 2022b. US Virgin Islands *Sargassum* Incident, Region 2 Crisis Action Plan, July 2022. FEMA Region 2 Response Division, New York. Note that distribution of this report is limited and may not be publicly available.

NOAA. 2022. EM-3581-VI Water Distribution and Availability, Christiansted Harbor, St. Croix, USVI. NOAA Response Link (website). Includes multiple postings including NOAA ERD Scientific Support Coordinator reports and related documents. https://responselink.orr.noaa.gov/hotline/10498/. Note that this website is limited to emergency responders with login credentials. Selected materials may be posted in the future on NOAA Incident/Incident Archives News, https://incidentnews.noaa.gov/.

USVI Governor. 2022. Executive Order No. 523-2022, Declaring a State of Emergency in the United States Virgin Islands Due to Unprecedented Influx of *Sargassum* Seaweed Affecting the Territory's Water Supply, 22 July 2022. USVI Office of the Governor, Charlotte Amalie, St. Thomas, VI. https://www.vi.gov/wp-content/uploads/2022/07/EXO-523-2022-State-of-Emergency-Sargassum-2022-07.22.pdf.

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