The potential economic impacts of sargassum inundations in the Caribbean, Part 1: Insights from the literature

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This substantive review is intended to act as a valuable resource for the wider sargassum stakeholder community as well as to inform other aspects of the SargAdapt project including trade-offs in fisheries, tourism and coastal livelihoods of alternative mitigation and management options for sargassum influxes.

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CONTENTS

Executive Summary 1

1 Introduction 3

2 Economic value, economic surplus, and economic impacts 5

2.1 Valuing Ecosystem Services 6

2.2 Economic Impacts and Multiplier Effects 7

2.3 Summary of Economic Value 8

2.4 Economic Value and Natural Hazards 10

2.5 Quantifying market and non-market impacts from harmful events 10

2.6 Complicating factors: Substitution, halo effects and cleanup costs 12

2.7 The importance of baseline measures of economic activity 15

2.8 Estimating changes in economic surplus to market and non-market goods and services from sargassum events 15

3 Effects of Sargassum Events on Ecosystems and Ecosystem Services 17

3.1 Impacts on Coral Reefs 17

3.2 Impacts on Seagrass Meadows 19

3.3 Impacts on Mangroves 20

3.4 Impacts on Beaches 21

3.5 Effects on Ecosystem Services 22

3.6 Summary of Sargassum Impacts on Ecosystems and Ecosystem Services and Select Economic Sectors 24

4 Geographic scope of sargassum influxes in the Caribbean 24

5 The potential scope of economic losses from sargassum: Insights from related literature 27

5.1 Macroalgae inundations and microalgae blooms (HABs) 27

5.2 Economic effects of macroalgae blooms 28

5.2.1 Willingness to pay to prevent and manage macroalgae events 28

5.2.2 Economic impacts from macroalgae on recreation and tourism 30

5.2.3 Impacts on human health from sargassum 30

5.2.4 Costs of beach wrack removal 30

5.3 Economic effects of harmful algae blooms (HABs) 31

5.3.1 Willingness to pay to prevent and manage HABs 31

5.3.2 Economic impacts from HABs on recreation and tourism 32

5.3.3 Economic Impacts on coastal business and property values 32

5.3.4 Economic impacts of HABs on Human Health 33
5.3.5 Summary of insights from the macroalgae and HAB literature 34
6 Coastal and Marine Ecosystem Service Values in the Caribbean 34
6.1 Reviews of the Economic Value of Coastal and Marine Ecosystems in the Caribbean 35
6.2 Regional and National Comprehensive Assessments of Economic Value 35
6.3 Per Hectare Value Estimates 36
6.4 Directed valuation efforts 40
6.4.1 Economic value of beach cleanliness and beach characteristics 40
6.4.2 Economic value of seawater quality 40
6.4.3 Economic value of beach access 42
6.4.4 Economic value of (losses in) coral reef quality 42
6.4.5 Economic value of “blue carbon ecosystems”: mangroves, coastal wetlands, and seagrasses 44
6.5 Gaps in the valuation literature 44
6.6 Common findings and implications for estimating economic losses from sargassum events 46
6.6.1 WTP for improvements in quantity, quality or access will underestimate welfare effects of losses or damages 46
6.6.2 Market prices and quantities will underestimate losses in economic surplus from impacts on recreation and tourism 46
6.6.3 Coastal and marine recreation and shoreline protection service values outweigh other ES values 46
6.6.4 Visual amenities are among the highest valued attributes of beach recreation 46
6.6.5 Understanding site substitution is critical to understand economic losses to recreation and tourism 47
6.6.6 ES values vary widely by location, ecosystem scale, and socioeconomic conditions 47
7 Summary and Next Steps 47
8 References 49

EXECUTIVE SUMMARY

This report provides a comprehensive overview of several branches of literature that provide insight into the potential economic impacts from sargassum events in the Caribbean Region. Recognizing that understanding the scope, magnitude, and distribution of the economic consequences of sargassum events is an important prerequisite for appropriate planning and mitigation efforts, the overarching purpose of this review is to develop a framework and research agenda for market and non-market valuation efforts directed at quantifying economic losses from sargassum.

A review of the theoretical foundations of measuring value suggests that the appropriate measure for the loss of economic value created by sargassum events is lost economic surplus. This review also points to the need for measuring baseline economic activity prior to sargassum events, carefully defining the spatial extent of the market, accounting for resource substitution by producers and consumers and being mindful of halo effects.

The extant literature on the impacts of sargassum events on coastal and marine ecosystems and ecosystem services suggests that sargassum events are likely to have the largest impacts on intertidal zones (beaches and seawater), followed by coral reefs, seagrasses, and mangroves. Impacts on beaches are expected to occur primarily due to biomass effects associated with accumulation of sargassum on shorelines. Adverse impacts on corals are expected to occur primarily due to water quality effects including reductions in light penetration, oxygen availability, and increased temperature, coupled with increased turbidity, eutrophication from nutrient loading and release of toxic ammonia and hydrogen sulphide. Impacts on seagrasses and mangroves are also mostly associated with these "brown tide" effects on water quality, primarily affecting the health and productivity of these ecosystems. For seagrasses the damage occurs largely because of shading and nutrient loading in the water column. For mangroves the damage appears to be from nutrient loading in sediments leading to anoxic conditions. Given these impacts on ecosystems, the effect of sargassum on human wellbeing will vary spatially according to coastline orientation, bathymetry and the proximity of resources and economic activities.

The literature concerning economic effects of macroalgae inundations and HABs suggests that both residents and tourists are willing to pay for programs that reduce the duration and impact of algae events, mostly associated with minimizing visual disamenity associated with biomass on shorelines and reduced coastal water quality. This finding points to a potentially important source of revenue for sargassum management activities. Results from this literature also suggest that algae events will have negative impacts on coastal property values that are more pronounced with the duration of events and may create larger negative impacts on properties located slightly further inland due to the relatively robust nature of beachfront property values. Our review also suggests that impacts on coastal businesses such as restaurants and lodging along affected shorelines are likely to be significant, potentially exceeding the magnitude of impacts from tropical storms. Accurate estimation of lost economic value and activity will require granular data collection from businesses and recreational sites before, during and after sargassum events, a careful delineation of the geographical scope of impacts, and measurement of consumer and tourist substitution effects.

Our review of the research on the economic value of coastal and marine ecosystems in the Caribbean suggests that the value of coastal and marine recreation and tourism tends to outweigh other ecosystem

values, with possible exceptions of the shoreline protection service afforded by reefs and the carbon sequestration service provided by seagrasses and mangroves. Not surprisingly, ecosystem service values are found to vary widely by location, ecosystem scale and socioeconomic conditions, suggesting that caution is in order when attempting to transfer value estimates across locations. Estimates of economic losses due to sargassum events derived from the benefits transfer approach are likely to be insufficient for sargassum management on the national scale.

Numerous studies in the literature find that willingness to pay for fee-based recreation in coastal and marine areas often exceeds actual (market) prices paid, which suggests that market prices and quantities will underestimate economic losses from sargassum impacts on recreation. Our findings also suggest that estimates of the value of improvements in resource quantity tend to be significantly lower than estimates of the value of equivalent losses. Using welfare estimates derived in the context of environmental improvements is therefore likely to underestimate economic losses from sargassum. We also highlight notable gaps in the literature regarding the value of ecosystem services that may be impacted by sargassum, including numerous provisioning, regulating, and supporting services provided by reefs, mangroves and seagrasses, and non-use values for all coastal and marine ecosystems.

Collectively, this review suggests a great deal of information regarding the potential economic consequences of sargassum influxes is at hand, but important gaps remain. Policy recommendations regarding appropriate spending for sargassum mitigation and management will be improved with targeted data collection and directed valuation efforts designed to accurately measure economic losses.

1 INTRODUCTION

Sargassum seaweed (comprising the two holopelagic species *Sargassum natans* and *S. fluitans*) first arrived on Caribbean and West African shorelines in unprecedented quantities in 2011 (Franks et al., 2012; 2016; Smetacek and Zingone, 2013). It continues to cause disruption to various sectors of national economies (particularly tourism and fisheries) and extensive impacts on ecological and human health (Resiere et al. 2018; Chávez et al., 2020; UNEP-CEP 2021). While the exact causes of these recent events are still being debated (e.g., Brooks et al., 2018; Putman et al., 2018; Oviatt et al., 2019; Johns et al., 2020; Lapointe et al., 2021), there is general agreement that this phenomenon is the result of a combination of biophysical and climatic factors of anthropogenic origin which encouraged an extraordinary proliferation of the seaweed in a new source region across the Equatorial Atlantic (UNEP-CEP 2021). This seasonally variable blooming of sargassum, coined by Wang et al. (2019) as the 'Great Atlantic Sargassum Belt' is now considered part of a 'new normal' to which the region must learn to adapt (UNEP-CEP 2021). Adaptation requires learning from new knowledge and understanding of the issue, and although vast progress has been made through significant scientific research efforts over the last decade, there are still many gaps. Among these gaps is a comprehensive understanding of the potential impacts of sargassum inundation of coastal ecosystems, including impacts on their myriad valuable ecosystem services, and the economic implications of this for the Caribbean.

To mitigate adverse effects on environmental quality and human wellbeing from sargassum inundations, appropriate responses must be designed, developed, and implemented. An understanding of the potential scope, nature and magnitude of economic costs that results from these events is an essential prerequisite to directing the appropriate resources toward prevention or mitigation of future losses (Hoagland and Scatasta, 2006). That is, to determine whether the costs of various management approaches to sargassum management are worth incurring, we must compare those costs to the benefits derived from management and mitigation measures (Risén et al., 2017). These benefits are primarily associated with avoiding the losses in economic value that are created by sargassum events.

Despite the widespread impacts and obvious economic damage to the region, funding for sargassum management remains elusive for most countries in the Caribbean (Oxenford et al., 2021). In addition to its relatively new impact on the region, part of the reason for shortcomings related to sargassum management and financing is the relative dearth of information regarding the economic consequences of sargassum events (JICA-CRFM, 2019). To fill this gap, market and non-market economic valuation methods can be used to assess economic losses from sargassum to fisheries, recreation and tourism and other ecosystem services. Understanding the magnitude, scope and distribution of economic losses induced by sargassum will allow policy makers to proactively weigh the costs and benefits of alternative management actions, direct scarce budgetary resources to their most impactful outcomes and thereby enhance the efficiency of efforts to mitigate impacts on livelihoods (Larkin and Adams, 2007). Value estimates can also be used to identify appropriate and efficient financing mechanisms and can enhance community engagement by illustrating the impact of sargassum on economic opportunities and human wellbeing in terms that are easily understood.

The purpose of this two-part report is to provide a comprehensive overview of the potential scope and magnitude of economic impacts from sargassum events in the Caribbean Region and to provide a framework for valuation efforts directed at quantifying economic losses. Part 1 provides a review of

several branches of literature that are pertinent to understanding economic impacts from sargassum in the Caribbean, including the theoretical foundations of measuring value from neoclassical and ecological economics, research into the impacts of sargassum events on key Caribbean coastal ecosystems (coral reefs, mangroves, seagrass meadows and beaches) and associated ecosystem services, estimates of economic losses from similar natural hazard events, such as other beach-cast seaweeds and harmful algal blooms (HABs), and empirical estimates of the economic value of coastal and marine ecosystem goods and services in the Caribbean region. We attempt to draw insights from this literature on the potential economic implications for sargassum inundations in Caribbean coastal environments. In Part 2, we use scenario analysis and results from the literature to illustrate the potential scope and magnitude of economic impacts from sargassum events at select sites in the Caribbean (Barbados, Dominica, Grenada, St. Lucia and St. Vincent and the Grenadines) and provide recommendations for data collection efforts and directed valuation research aimed at improving the accuracy of value loss estimates. Figure 1 illustrates our general approach.

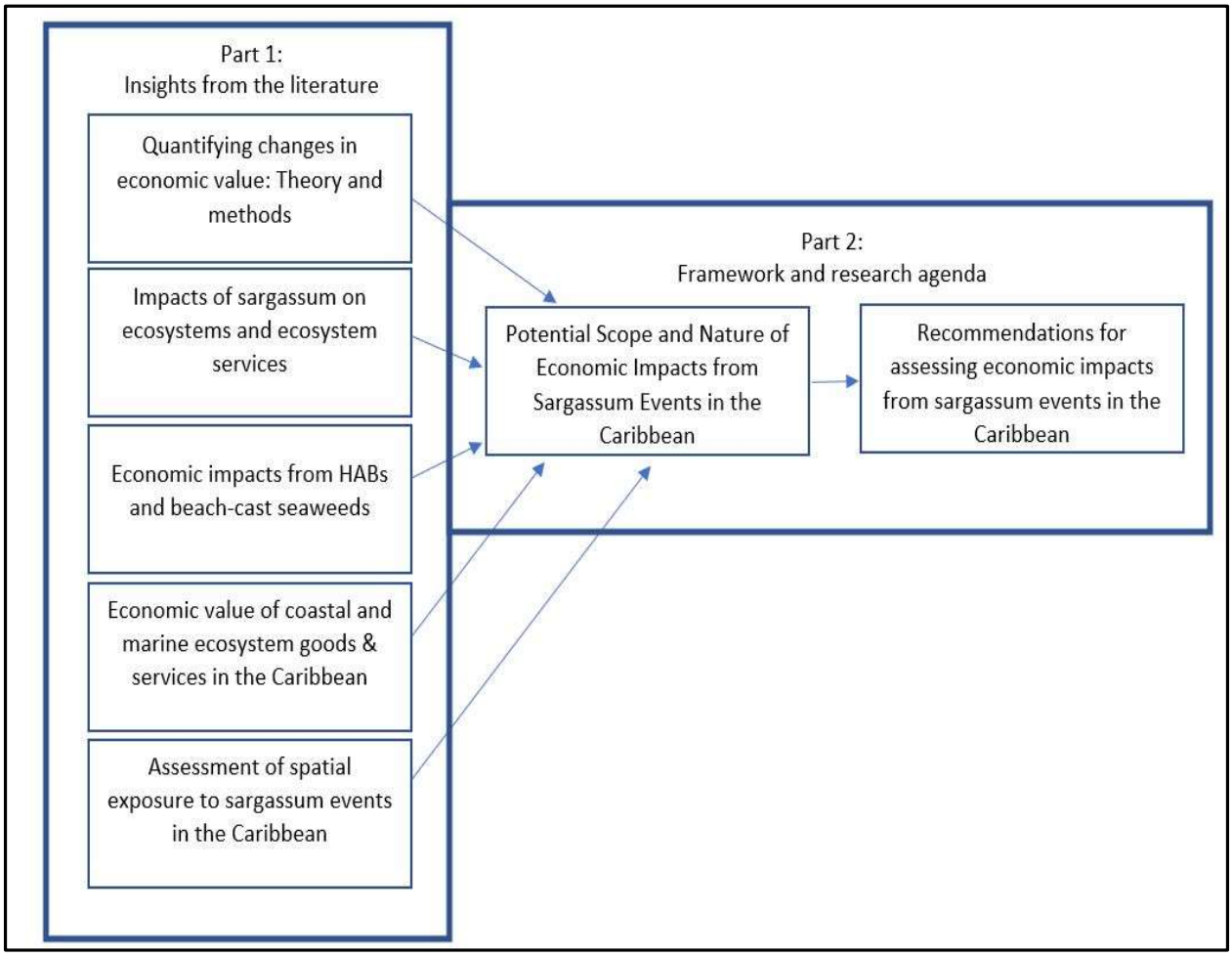

Figure 1: Framework for understanding the economic impacts of sargassum events in the Caribbean

The remainder of the paper is organized as follows. In section 2, we review the fundamentals of economic value and economic surplus and provide a general framework for understanding economic losses associated with harmful events, including several complicating factors and cautions. Section 3 provides a review of the extant literature on the impacts of sargassum events on coastal and marine ecosystems and ecosystem services. Section 4 presents an overview of the limited valuation research associated with the economic impact of sargassum events and the considerably broader body of literature related to the economic impacts from other beach-cast seaweeds and harmful algae blooms (HABs). Section 5 provides a review of research pertaining to economic values of coastal and marine resources in the Caribbean, noting important gaps in the literature. This is followed by a brief review of the spatial exposure to sargassum influxes based on historical data from Barbados, Dominica, Grenada, St. Lucia and St. Vincent and the Grenadine in section 6. We conclude the report in section 7 and provide an overview of Part 2.

2 ECONOMIC VALUE, ECONOMIC SURPLUS, AND ECONOMIC IMPACTS

The economic definition of "value" is what a good, service or state of the world is worth to people. This definition of value is best understood using the concepts of economic surplus (net gains), willingness to pay (WTP) and willingness to accept (WTA). Value or worth created by a good or service is synonymous with the net gains that are created by a good or service that would not be realized if that good or service were not available. In the case of goods and services that are traded in markets, these net gains mostly accrue to producers (sellers) and consumers (buyers) and are termed producer surplus (PS) and consumer surplus (CS). Producer surplus is the difference between the lowest amount that the seller would be willing to accept (WTA) to give up the good or service and the market price (P) that they receive when a transaction takes place. For example, if a fisher is willing to accept $4.00 per kg of fish to cover his time and other costs of harvest but receives a price of $7.00 per kg when the fish is sold, then he receives $3.00 per kg in economic (producer) surplus. Similarly, consumer surplus is the difference between the maximum amount that the buyer would be willing to pay (WTP) and the market price (P) that they pay. For example, if a fish consumer is willing to pay $9.00 per kg of fish (because this what the fish is worth in terms of enjoyment from consumption) but pays only $7.00 per kg, then the consumer receives $2.00 per kg in economic (consumer) surplus.

In the absence of "external" costs or benefits that accrue to a third party,[1] total value (total net gains) is the sum of consumer surplus (CS) and producer surplus (PS), shown in Figure 2. These values represent net gains to the respective market participants that would not be realized in the absence of market transactions. Total costs of production are found as the area underneath the marginal cost (supply) curve, and gross revenues are the product of market price and quantity sold (PS + cost of production).

[1] "Negative externalities" are costs or damages that are created by the production or consumption of a good or service that are incurred by someone other than the buyer or seller. Common examples include pollution from production or consumption imposing costs in the form of adverse impacts on human or environmental health. In addition to the consumer and producer surplus that accrue to the buyer and seller of the pollution-causing good, other members of society are made worse off due to the adverse effects of pollution. Examples of "positive externalities" include benefits that are realized by other members of society when individuals choose to acquire education or healthcare. In addition to the consumer surplus that accrues to the student/patient/buyer and producer surplus that is realized by the school/doctor/seller, other members of society can be made better off from the economic gains created as the educated/healthy individual is a more productive member of society.

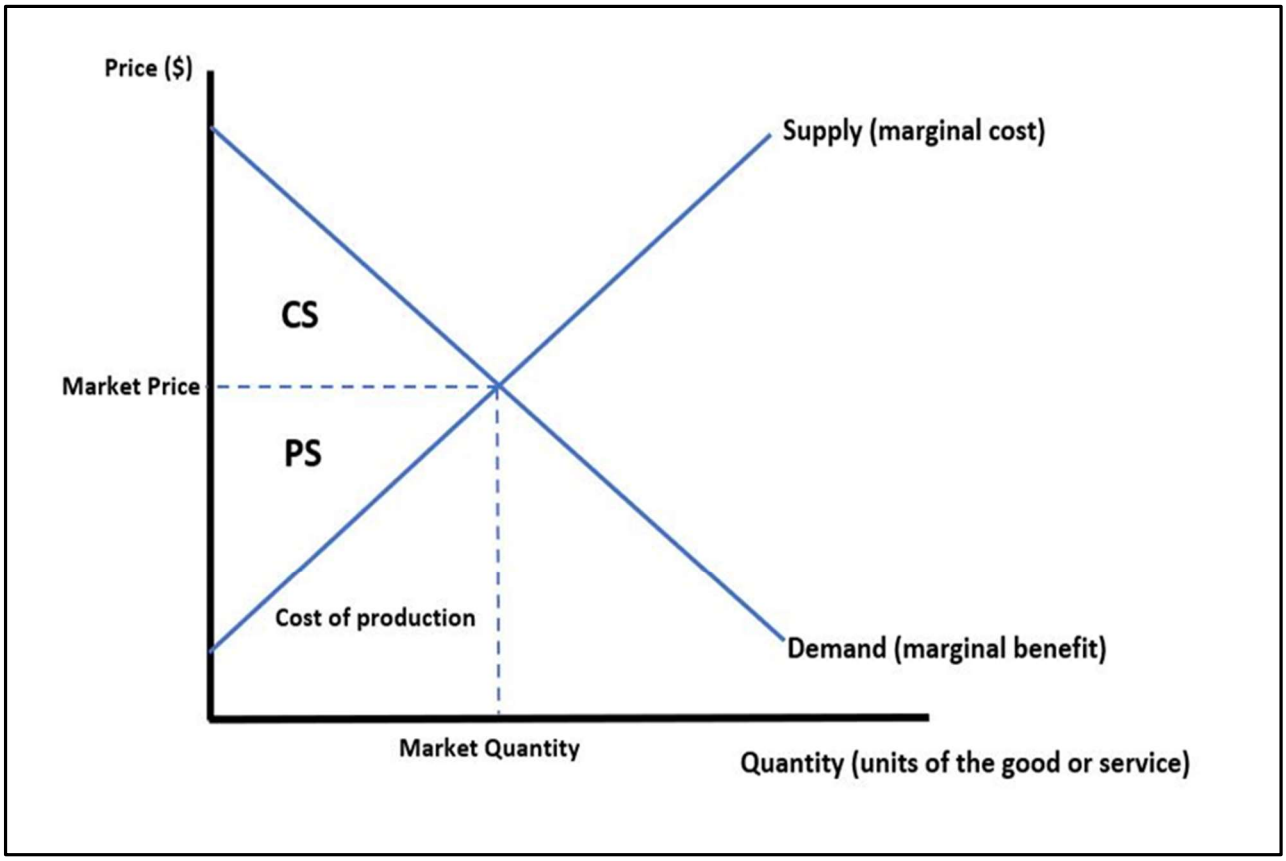

Figure 2. Economic surplus is the sum of net gains to buyers (CS – consumer surplus) and net gains to sellers (PS – producer surplus)

Transactions between consumers (buyers; demanders) and producers (sellers; suppliers) create economic surplus for both parties, equivalent to the sum of CS and PS. Returning to the fish sales example above, the total value (economic surplus) created by the sale of one kg of fish would be $5, the sum of producer surplus ($3.00) and consumer surplus ($2.00). This seemingly abstract concept is critical for understanding the value of economic losses from harmful events such as sargassum inundations because value (net gains) is unlikely to be equivalent to the gross value of the associated market transactions (price multiplied by quantity). That is, neither costs nor revenues alone are an accurate measure of economic value. In the fish example, the gross value from the sale of one kg of fish is $7.00 (one unit multiplied by market price).

2.1 Valuing Ecosystem Services

It is important to recognize that economic value created by the natural environment does not necessarily involve market transactions. For example, recreational experiences at open-access natural areas and many of the protective and regulating services provided by ecosystems provide significant contributions to human wellbeing. Because these goods and services are not directly sold to people, but rather are provided "free" by natural systems, estimating the economic value these "non-market" goods and services is not straightforward.

Despite the lack of market sellers, buyers and formal transactions, changes in human welfare associated with changes to ecosystem goods and services should be included in measures of economic value, and estimating such values still rests on the concept of economic surplus. That is, to understand and measure value of ecosystem goods and services, we must identify and quantify net gains that are created by their existence.

For example, suppose that to enjoy a recreation experience on a coral reef, an individual incurs $50.00 in direct and indirect costs associated with travel to the site and foregone earnings. If this trip creates $150.00 in benefits (enjoyment) to the individual, its value (economic surplus) would be $100.00 (benefits – costs). Note that in this example, measuring economic value requires estimating the direct and indirect costs associated with participating in recreation as well as the benefits (willingness to pay) that accrue the recreationist. Alternatively, consider the economic value of a coral barrier reef that provides benefits to people by attenuating wave energy and protecting coastal assets from damage during storm events. Assuming that no costs are incurred to maintain the reef in its current state, measuring the value of the reef's coastal protection service would require estimating the amount that coastal property owners would be willing to pay to maintain the level of protection afforded by the reef.

It is important to note that economic value can include economic surplus derived in the absence of any direct use or interaction with species or natural systems. These "non-use values" include benefits that accrue to people from the knowledge that species or ecosystems exist, are available for future generations or for potential future use.[2] Measuring "non-use" economic values involves estimating the amount that people are willing to pay (in money, time, or other resources) to maintain the species or ecosystem in its present state or the amount that people are willing to accept to forgo the associated benefits. Importantly, a large body of literature suggests that non-use values comprise significant portions of the total economic value of many ecosystem goods and services, a subject we return to later in this report.

2.2 Economic Impacts and Multiplier Effects

When defining and measuring the economic value of the goods and services provided by the natural environment, in addition to measures of economic surplus, the value of economic activity created in substitute, complementary and proximate markets should also be measured. For example, when considering the economic value of recreation services afforded by healthy coastal and marine ecosystems, in addition to the net gains experienced by beach recreationists, economic surplus may materialize through visitor spending at nearby restaurants, lodging and retail establishments as well as through sales of fuel, equipment, food and other goods and services needed for a day of recreation. This spending creates both consumer and producer surplus associated with the transactions and may lead to improved employment opportunities and incomes throughout the economy (Holmes et al., 2015).

Importantly, because a portion of each dollar spent by consumers represents earnings by someone else in the economy and some of that generated income is spent on other goods and services, each new dollar spent and earned ripples through other businesses and households creating "economic multiplier effects". These impacts are commonly partitioned into direct effects, indirect effects, and induced effects, and can be calculated at different spatial scales (e.g., local, regional, national). Direct effects are market

[2] Evidence that these existence values, bequest values and option values are real is easily found by observing the sacrifices that people make in terms of expenditure of time and/or money to support the protection of species and ecosystems that they never actively interact with.

contributions to the national economy and are typically approximated using measures of gross total revenues, total employment, or gross incomes. Indirect effects are impacts on the incomes and wages of the suppliers of inputs used in the industry in question when those earnings are subsequently spent on other goods and services. Finally, induced effects are the economic impacts of spending of generated income by households who are either directly or indirectly employed in the industry. Indirect and induced effects taken together are often referred to as value added effects (Fedler, 2010).

If linkages between economic sectors are known or estimable, the total economic impact of earnings or spending in a particular market can be approximated. Such estimation is typically facilitated by input-output models, which empirically delineate forward and backward linkages between a change to one economic sector and the rest of the economy. These linkages form the basis for multipliers which measure the extent to which a given economic activity (direct effect) propagates other economic activity (indirect and induced effects). Value-added effects can therefore be represented with a numeric multiplier that converts direct expenditures to total economic impact (Fedler, 2010). For example, if the estimated value-added multiplier for tourism is 1.5, then each $1.00 of direct spending by tourists results in an additional $1.50 of indirect and induced effects, for a total of $2.50 in economic impact. Economic impact analysis and the use of input-output models should not be considered a substitute for the calculation of total economic value or economic surplus, because net gains to market participants are not estimated, and non-market values are excluded (Hoagland, et al, 2005). For more details on input-output analysis see Miller and Blair (1985).

2.3 Summary of Economic Value

To summarize, economic value is a multifaced concept, comprising market values and non-market values, with the latter including use and non-use values. We summarize these ideas for coastal and marine ecosystem goods and services in Table 1. It should be recognized that the total economic value of a particular ecosystem service may be different from the arithmetic sum of the values shown in Table 1. Indeed, to the extent that values between or within ecosystems are complementary, the true economic value of a healthy and functioning ecosystem may be more than the sum of the individual components of value (Turner et al., 2003). Such complementarities may exist through ecological facilitation whereby one species or ecosystem generates or enhances conditions in a way that makes the environment more suitable for other organisms or ecosystems (Bertness and Callaway, 1994; Stachowicz, 2001). For example, the value of nearshore reefs may be enhanced by the quality of coastal mangroves. Conversely, if value categories are mutually exclusive, the total value of an ecosystem may be less than the sum of individual values. For example, values from non-extractive uses such as snorkeling or diving may be diminished by extractive uses such as fishing and oil extraction. Going forward, we should recognize that estimating the total economic value of a good or service, or the total economic loss from damage to an ecosystem, involves identifying and measuring multiple categories of economic surplus.

Table 1: Components of Economic Value for Coastal Ecosystem Goods and Services

Value	Category	Primary Value (use and non-use)	Ancillary Economic Impacts
"On-site" Use Values	**Extractive direct use value**	Value (economic surplus) of fish, sand and other products extracted from the ecosystem	Jobs and incomes created by spending associated with extractive uses
	Non-extractive direct use value	Economic value (economic surplus) to users created when the ecosystem is *used without extraction*, most commonly for recreational, aesthetics or research purposes	Jobs and incomes created by spending associated with recreation and tourism; amenity value of proximity to the ecosystem capitalized into nearby property values
	Indirect use value	Economic value associated with services provided by the ecosystem and its species such as habitat provision, water cycle services, carbon sequestration and coastal protection	Benefits from lower spending or avoiding costs to human health and wellbeing as associated with the provision of these ecosystem services
"Off-site" Non-use Values	**Existence value**	Value to people derived from simply knowing that the ecosystem and its species exist and are protected	Jobs and incomes created by spending associated with tourists drawn to "green" destinations
	Option value	Value to people derived from preserving the option for possible use of the ecosystem and its species in the *future*	Jobs and incomes created by spending associated with tourists drawn to "green" destinations
	Quasi-option value	Value to people derived from preserving the option for possible exploration of potential uses of the ecosystem and its species in the *future*	Jobs and incomes created by spending associated with tourists drawn to "green" destinations
	Bequest value	Value to people derived from preserving the ecosystem and its species for future generations	Jobs and incomes created by spending associated with tourists drawn to "green" destinations
Total economic value = Use values + non-use values + ancillary economic impacts			

2.4 Economic Value and Natural Hazards

Recognizing that quantifying economic value requires measuring net gains or economic surplus, understanding the change in economic value associated with events that harm or degrade ecosystem services requires estimating the loss in economic surplus and economic impacts that result from those events (Hoagland and Scatasta, 2006). For example, an influx of sargassum seaweed in a coastal area may decrease total economic surplus by diminishing the quantity or quality of market-based activities such as commercial fishing, fee-based recreation, and tourism. Loss of economic value may also be associated with non-market effects that transpire through lost economic surplus to people who use or value coastal and marine ecosystems that are affected by the event. This might include lost economic value from not being able to participate in extractive and non-extractive uses of affected coastal and marine resources (e.g., the welfare loss from not being able to surf, sunbathe or swim in the sea), as well as lost economic value associated with "non-use" sources of wellbeing (e.g., lost existence, option or bequest associated with the knowledge that coastal and marine ecosystems and species are damaged). Adverse ancillary market impacts would also be realized in associated and proximate commercial markets such as lodging, gear and equipment sales and the sale of food and beverage (Hoagland and Scatasta, 2006). Further, to the extent that the natural hazard creates adverse effects on human mortality and morbidity, economic effects might also be apparent through higher costs in the health care system.

2.5 Quantifying Market and Non-Market Impacts from Harmful Events

Market impacts from natural hazard events such as harmful algal blooms or sargassum inundations can be approximated by multiplying estimates of "lost" market transactions (goods or services that would have been produced and sold were it not for the harmful event) by expected or historical market prices associated with those transactions. For example, if a sargassum event results in fishers not being able to bring product to market for a period, we could estimate the "lost" quantity of catch (Q) for each species *i* and multiply those quantities by expected market price (P) for each species[3]:

(1) Lost gross market value of foregone commercial fish harvest = $\sum_{i=1}^{N}(Q_i * P_i)$

Note that similar calculations could be constructed for the reduced or "lost" quantity (Q) of hotel rooms or apartments, restaurant meals or retail sales. Such estimates of market impacts are relatively easy to calculate and interpret (Hoagland and Scatasta, 2006). Yet, this gross value is unlikely to be an accurate estimate of the lost economic value associated with foregone commercial activity, as the value shown in (1) is not a measure of lost economic surplus. That is, the measure in (1) is not coincident with foregone net gains.

Figure 3 below illustrates this idea using the supply and demand model of a market for commercial fish or any other market activity such as lodging, restaurants or retail sales. Harmful events such as sargassum inundations may affect suppliers' ability to deliver a product to market (e.g., fishers cannot access fishing

[3] Historical data can be used to estimate "lost" harvest, by comparing landings during environmental events to a baseline level of harvest. Because harvests may exhibit considerable variation over time due to numerous factors including changes in fishing effort, seasonal stock abundance or other natural and anthropogenic causes, establishing a baseline level of harvest and estimating the deviation from that baseline may require more rigorous analytical techniques such as regression-based event studies (Jin et al., 2008).

grounds) and/or demanders' willingness or ability to purchase the product (e.g., patrons are not attracted to coastal businesses). The former case is shown in panel A) as a decrease (leftward shift) in market supply,

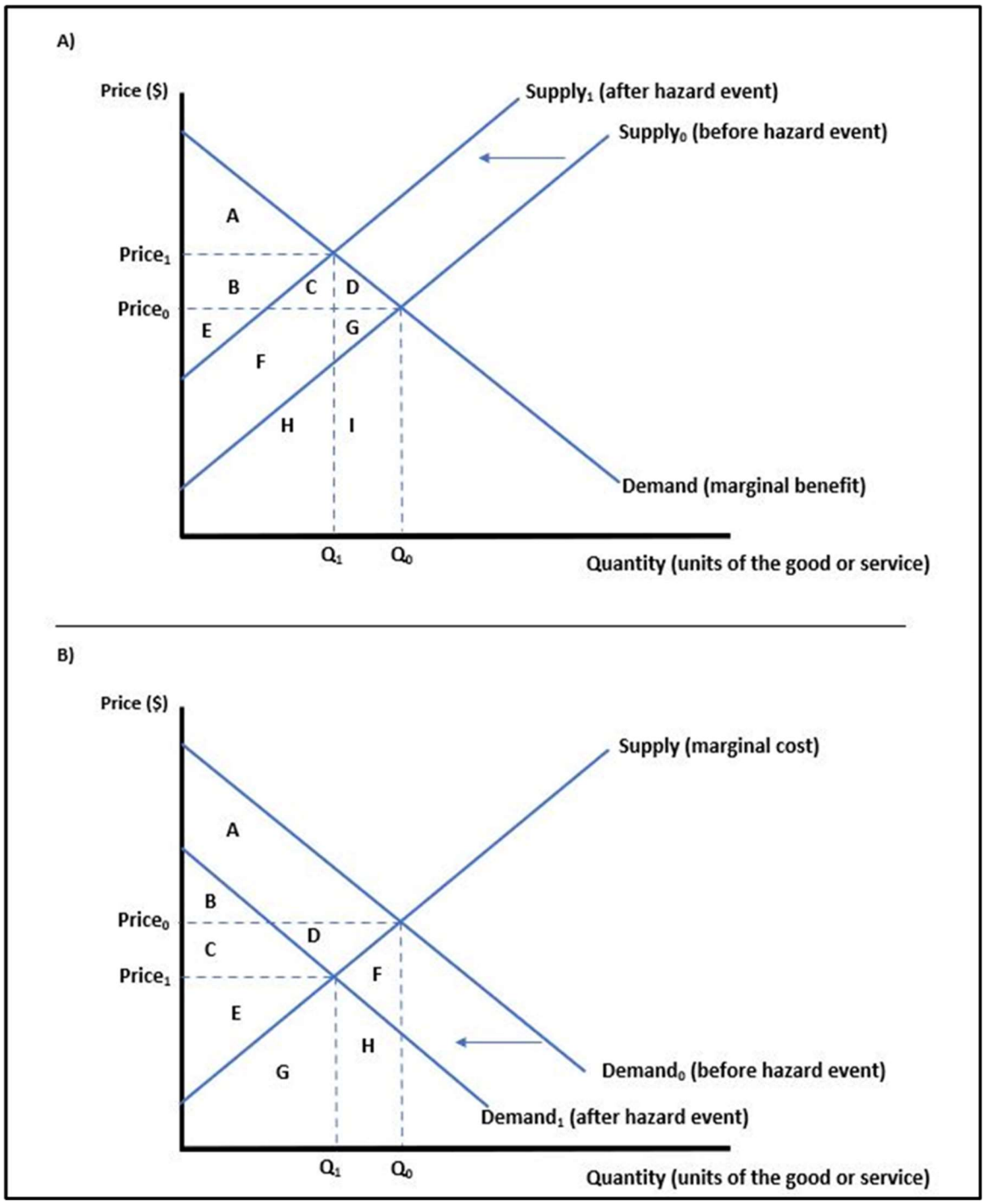

Figure 3: The impact of harmful events on net gains from market activities (adapted from Anderson et al., 2000)

and the latter case is shown in panel B) as a decrease in market demand. The supply shift (panel A) reduces total net gains to (A + B + E) with lost economic surplus equivalent to area (C + D + F + G). Note that lost gross revenues are equivalent to area [(B+C) - (G+I)], which may or may not be a reasonable approximation to lost surplus (A + B + E). In the case of a decrease in demand (panel B), total net gains are reduced to area (B + C + E), with lost economic surplus equal to area (A + D). Gross revenues are reduced by area (C + D + H). Again, note that lost economic surplus and lost gross revenues are similar, but not necessarily equivalent.

When harmful events impact demand for goods and services that are not traded in markets such as coastal recreation activities, producer welfare is not a concern and lost economic value is measured by the decrease in consumer net gains (consumer surplus). Panel A) in Figure 4 below shows consumer surplus (CS) and total spending associated with recreation, measured as the difference between average costs (e.g., travel costs and expenses incurred to visit the site, opportunity costs of time) and trip demand (marginal benefits). Panel B) depicts a decrease in demand that would be expected if recreation quality diminishes due to a harmful event such as a sargassum influx. Lost net gains to recreationists are shown as the decrease in consumer surplus (Area A). In cases where a harmful event causes a particular recreation site or activity to be inaccessible, the demand curve would shift all the way to the left, resulting in a complete loss of consumer surplus. In addition to consumer surplus losses associated with lower quality or less frequent use, ancillary impacts on suppliers of market-based inputs (e.g., beach chairs, jet ski rides) will occur due to decreased demand as in Figure 3, panel B).

2.6 Complicating factors: Substitution, halo effects and cleanup costs

Noting that lost economic value and lost gross market value are not necessarily equivalent, using market values to estimate economic losses from sargassum events requires caution and the consideration of several factors that may result in the gross market value estimate in (1) being an overestimate or underestimate of lost economic surplus. First, in the case of an impact on supply, it may be the case that when unable to harvest marine species due to the harmful event, some fishers pursue other employment opportunities that generate economic surplus. Because this resource substitution is expected to generate economic value that would not be realized if the fisher were actively fishing, excluding labor substitution by displaced fishers results in gross market value overestimating the true economic impact on fishers (Anderson et al., 2000). As such, information on suppliers' ability to substitute to other forms of employment and income is an essential component of understanding changes in economic value.

Further, when the quantity of fish available for sale in markets is reduced and prices rise, it is likely that consumers will increase their demand for other sources of protein, perhaps including imported seafood. This shift in consumer demand will at least partially fill voids in the supply chain, offsetting losses to the directly affected sectors and creating positive economic effects for sellers of substitutes for seafood (Hoagland and Scatasta, 2006; Jin et al., 2008). This same logic applies to adverse impacts on demand for goods and services areas affected by sargassum – demand will shift to unaffected or less affected substitute goods and areas. For example, consumers who would otherwise purchase goods and services from businesses near the coast may shift to commercial establishments located inland when sargassum is present. In the case of non-market goods and services such as coastal recreation that are interrupted or affected by sargassum events, it is logical to assume that some recreationists will engage in other activities that generate welfare gains, at least partially offsetting the economic losses from reduced coastal quality or access. Indeed, Casas-Beltrán (2020) finds evidence of this type of substitution by

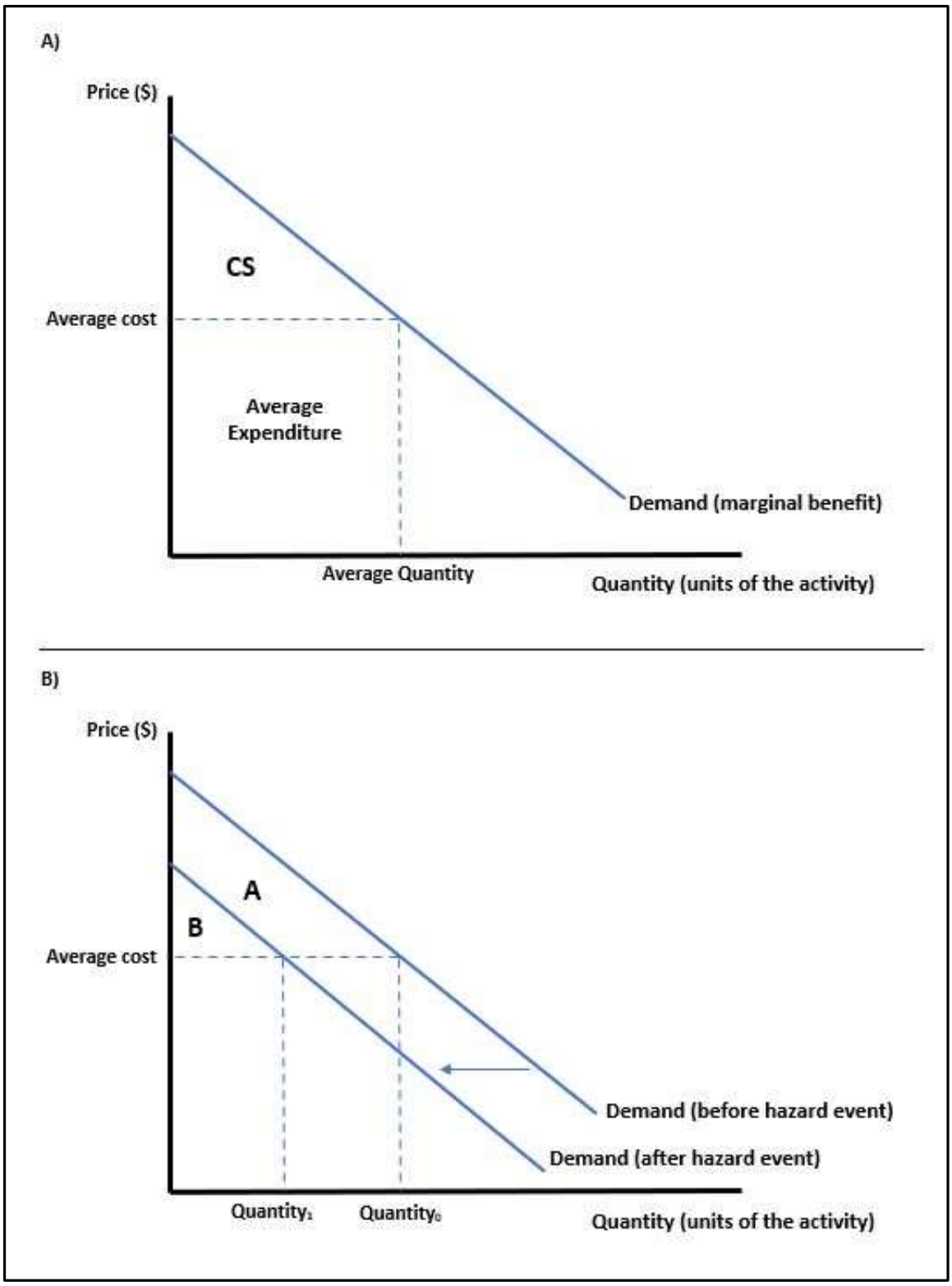

Figure 4: The impact of harmful events on net gains from non-market activities (adapted from Anderson et al., 2000)

tourists in Mexico - when beach conditions degrade due to the presence of sargassum, tourists substitute toward inland recreation at cenotes, creating positive economic impacts and negative environmental effects associated with increased pollution. Hence, when attempting to measure the economic impacts of sargassum events, it is important to establish geographical and market boundaries for the assessment of economic losses and to recognize that losses in one area or market may be offset by gains in another (Ding et al., 2011).

In addition to these complications that may cause foregone gross revenues to overestimate economic losses, it should also be recognized that gross revenues may underestimate losses by excluding indirect impacts on associated markets. For example, if access to fish harvest is restricted, adverse economic impacts will occur in the supply chain due to forward and backward linkages with other markets. Suppliers of inputs (e.g., gas, bait, labor) and suppliers of goods and services that rely on output that is not produced (e.g., restaurant meals) will also be affected. These suppliers will also earn and spend less income. Together, these upstream and downstream impacts and income-related effects comprise "indirect effects" and "induced effects" which should be accounted for to produce an accurate estimation of economic losses (Ding et al., 2011).

It is important to note that consumers may incorrectly associate acute impacts from harmful events in a broader context, indirectly creating adverse economic effects in similar or related markets (Hoagland and Scatasta, 2006). These "halo effects" are the result of environmental cues that may bias decision-making and can span a broad scope of markets. For example, publicized news of or experience with a harmful event such as a sargassum inundation in one location (e.g., region of a country or countries within a region) may cause tourists to cancel trips to other nearby or similar locations that are unaffected. Such impacts have been noted for sargassum events in Mexico (Casas-Beltrán, 2020), impacts of harmful algal blooms (HABs) on seafood demand (Wessels et al., 1995; Bechard, 2020b) whereby demand for uncontaminated seafood is affected by news of cyanobacterial contamination in other areas or species, and in the context of destination image and consumer purchases (Lee and Lockshin, 2011). Estimating the scope of halo effects, while complicated, is an important consideration when attempting to quantify the loss in economic value associated with sargassum events and in designing policy to mitigate losses.

Finally, it is important to note that harmful events may induce individual or collective management actions to mitigate losses that affect the economic value of the event. In the context of sargassum events, these might include efforts to physically remove seaweed biomass from coastal areas or the construction of physical barriers to prevent sargassum from reaching coastlines. For proper accounting of lost value, the event should be defined in terms of net impacts (i.e., net of sargassum removed or mitigated) and the market value of the associated expenditures (e.g., costs of labor, materials, and equipment) should be included in the total cost of the event. Losses in value associated with damaged or foregone ecosystem services induced by the management action should also be calculated and added to the total costs of the event. For example, physical removal of sargassum from beaches may involve the use of heavy equipment that compromises the physical integrity of coastlines leading to heightened erosion and/or adverse impacts on coastal species. The tradeoff between the costs of sargassum management measures and the overall costs of sargassum events is obviously a primary focus of this research and is explored in more detail in part 2 of this report.

2.7 THE IMPORTANCE OF BASELINE MEASURES OF ECONOMIC ACTIVITY

This review of economic value highlights the importance of establishing baseline levels of market and non-market economic activity against which to measure losses. For example, measuring economic impacts on market activities requires an understanding of prices and the quantity of output that would prevail in the absence of the harmful environmental event. Measuring impacts on non-market activities such as coastal recreation requires measures of demand (use) that would prevail under normal conditions. The most straightforward approach to establishing these baselines would be to use historical averages (e.g., historical harvest and prices in affected fisheries). However, such measures are likely to mask seasonal or annual variation and may result in biased estimates of impacts (Jin et al., 2008). For example, observed losses in revenue due to harmful environmental events may actually be caused by temporal variation in supply. It is therefore critical to account for seasonal and annual variations in harvest when establishing baseline harvest levels (Jin et al., 2008). Without a stable baseline against which to measure losses, creating accurate estimates of impacts is tenuous (Larkin and Adams, 2007).

2.8 ESTIMATING CHANGES IN ECONOMIC SURPLUS TO MARKET AND NON-MARKET GOODS AND SERVICES FROM SARGASSUM EVENTS

When market goods are affected by sargassum events (e.g., harvest and sale in commercial fisheries, bookings at coastal lodging establishments, fee-based coastal recreation, retail sales), the loss in economic surplus to producers and consumers plus ancillary economic impacts should be estimated. Ideally, this estimation will involve calculation of lost consumer and producer surplus plus indirect and induced economic impacts, which requires estimation of supply and demand functions and calculation of lost surplus as outlined in Figure 3. These functions can be estimated by applying regression analysis to cost, price and quantity data collected from market participants including marginal production costs and quantity supplied by sellers and prices and quantity demanded by buyers. Importantly, these functions should be estimated under normal (baseline, pre-event) conditions and again when the market is impacted by sargassum.

When such calculations cannot be undertaken due to budget or time constraints, market losses to sellers can be approximated by calculating the loss in gross revenues relative to pre-event (baseline) induced by the sargassum event (1), netting out production costs and adjusting lost revenues for any remedial/new income realized through input substitution by producers. As noted above, this will require information on baseline market prices, quantity of sales, costs of production and suppliers' willingness and ability to substitute other forms of employment and income.[4] Recognizing that the amount spent on a good or service can be considered a lower bound on its value to consumers (i.e., the good is worth at least what a buyer pays for it), market losses to buyers can be approximated by adjusting gross revenues (spending by consumers) for spending on substitute goods and services. Again, this requires a careful delineation of the geographic and temporal scope of "the market" for which we wish to estimate impacts and a careful measure of the scope and magnitude of "the event".

[4] The ability of sellers to substitute toward other forms of employment and income will likely vary across and within markets and may vary over time. Estimating the scope and magnitude of resource substitution will therefore require that information be collected directly from sellers. We provide details on how such information could be collected later in Part 2 of this report.

The estimation of losses in economic surplus created by impacts on non-market goods and services such as open-access recreation in coastal areas would ideally be calculated by estimating the demand function shown in Figure 4, calculating the shift in demand induced by the sargassum event, and calculating the loss in consumer surplus. In the absence of detailed information on recreation demand, losses in consumer surplus to consumers/recreationists can be calculated using estimates of WTP derived from non-market valuation techniques.[5] Given that many non-market goods and services involve costs to consumers (e.g., coastal recreation opportunities that require spending on travel and/or gear), lost economic surplus can be approximated by subtracting unit consumption costs from estimates of WTP, multiplying by estimates of use/demand, and netting out welfare gains from the consumption of substitute goods or services. For example, suppose a sargassum event results in a decrease in demand for beach recreation. Lost economic surplus can be estimated by subtracting average travel/trip costs from estimates of WTP per beach visit and multiplying by the number of beach trips that are foregone due to the sargassum event.

Recognizing that some recreationists will substitute toward other activities when beach visits are less attractive, net gains to consumers from substitute activities should be subtracted from this estimate. Again, we note the importance of defining the geographic and temporal scope of the affected market. If sargassum events cause beach recreationists to substitute toward goods and services that are located inland (e.g., recreation at terrestrial parks), losses in consumer surplus will be mitigated by welfare gains from this other form of recreation. However, if the scope of the affected market is defined to include only recreation activities on the impacted coastline, these gains would not be subtracted, and economic losses will appear larger. The same logic applies to the economic impacts on tourism. When sargassum is present, some tourists are likely to substitute to other destinations altogether. At the regional scale, adverse economic impacts from sargassum in one destination may be partially mitigated by economic gains in other, substitute destinations. Measuring economic impacts on the regional scale should therefore account for inter-destination substitution, while measuring impacts on the national scale should account for intra-destination substitution. All else equal, economic impacts will be inversely associated with the availability of substitute sites and destinations, and sites with limited alternatives to coastal recreation are likely to suffer greater economic losses.

For ecosystem goods and services that are typically consumed at no cost (e.g., the change in shoreline protection service afforded by reefs, the change in aesthetic value of coastlines, impacts on coastal real estate, lost non-use values from damage to species and ecosystems), lost economic surplus can be approximated by multiplying estimates of willingness to pay (WTP) for those goods and services derived from non-market valuation procedures by the extent of estimated losses. For example, if a sargassum event results in the degradation of mangrove or coral reef ecosystems, lost economic surplus can be approximated by multiplying estimates of WTP for related ecosystem services by the extent of the loss.

[5] In the context of recreation, these techniques include the travel cost method, the contingent valuation method, choice experiments and the benefits transfer method. We provide specific recommendations for applications of these methods in Part 2 of this report.

3 EFFECTS OF SARGASSUM EVENTS ON ECOSYSTEMS AND ECOSYSTEM SERVICES

Sargassum inundations refer to large-scale accumulation and subsequent decomposition of sargassum in coastal environments. Such events, involving 100s to 1000s of tons of wet sargassum have recurred repeatedly along Caribbean coastlines since the first sargassum influxes to this region in 2011 (Chávez et al., 2020; Desrochers et al., 2020; Marx et al., 2021; Salter et al., 2021). Despite this, only a relatively limited number of studies to date have examined the impacts of these inundations on coastal ecosystems and their services in any detail, although many authors refer to anecdotal reports of ecosystem damage, and numerous images on social media, and articles in the popular press clearly illustrate many of the impacts (McLawrence et al. 2017; Louime et al. 2017). Figure 5 shows images of sargassum inundations in Barbados and Antigua. The remainder of this section provides a summary of findings of targeted scientific studies by coastal ecosystem. Table 2 provides a summary of impacts on ecosystems and ecosystem services, also delineated by coastal ecosystem.

3.1 IMPACTS ON CORAL REEFS

The reported impacts on coral reefs have largely been from the leachates and particulate organic matter that are formed as the trapped accumulations of sargassum begin to decompose within 24 hours of arrival. This results in the development of a 'brown tide' (a plume of discolored and poor quality water) which can spread considerable distances away from the accumulations of sargassum, travelling along the shoreline as well as several hundred meters offshore where it may encounter coral reefs and associated ecosystems (Figure 5; van Tussenbroek et al., 2017; León-Pérez et al., 2021; Hendy et al., 2021). This brown tide reduces light penetration to benthic communities, oxygen availability and pH, and increases turbidity, water temperature, nutrient loading (high levels of nitrates and phosphates), bacterial loading, and presence of toxins (e.g., high ammonium and hydrogen sulphide concentrations, and heavy metals such as arsenic, cadmium, chromium etc.) (e.g., van Tussenbroek et al., 2017; Rodríguez-Martínez et al., 2019; Hendy et al., 2021; Rodriguez-Munoz et al., 2021).

The most widely reported impacts of this brown tide on coral reefs and their associated faunal communities result from eutrophication (high nutrient loads), low levels of oxygen (i.e., hypoxic or even anoxic conditions), and presence of toxic ammonia and hydrogen sulphide. For example, van Tussenbroek et al. (2017) describe partial or total mortality of six reef-building coral species in a Mexican lagoon system as a result of sargassum brown tides between 2013 and 2016. Likewise, Silva et al. (2016) reported similar coral mortality on artificial structures in a Mexican reef lagoon. The combined effects of high ammonium and hydrogen sulphide concentrations, together with low oxygen conditions as a result of sargassum brown tides, is also responsible for multiple mass mortality events with 78 reef-associated faunal species, including fishes, crustaceans, echinoderms, molluscs and polychaetes being recorded among the dead (Rodríguez-Martínez et al., 2019). Other authors report similar mass mortality events, as well as describing more frequent but smaller mortality events (Cruz-Rivera et al. 2015; Engel 2019; Chavez et al., 2020; López-Contreras et al. 2021), and there are widespread reports of such events in the popular press. Other, sub-lethal impacts of sargassum brown tides have also been reported. For example, the larval dispersal capacity of broadcasting corals can be reduced or even stopped by the presence of sargassum leachates in seawater (Antonio-Martínez et al., 2020). These authors used controlled experiments to show that

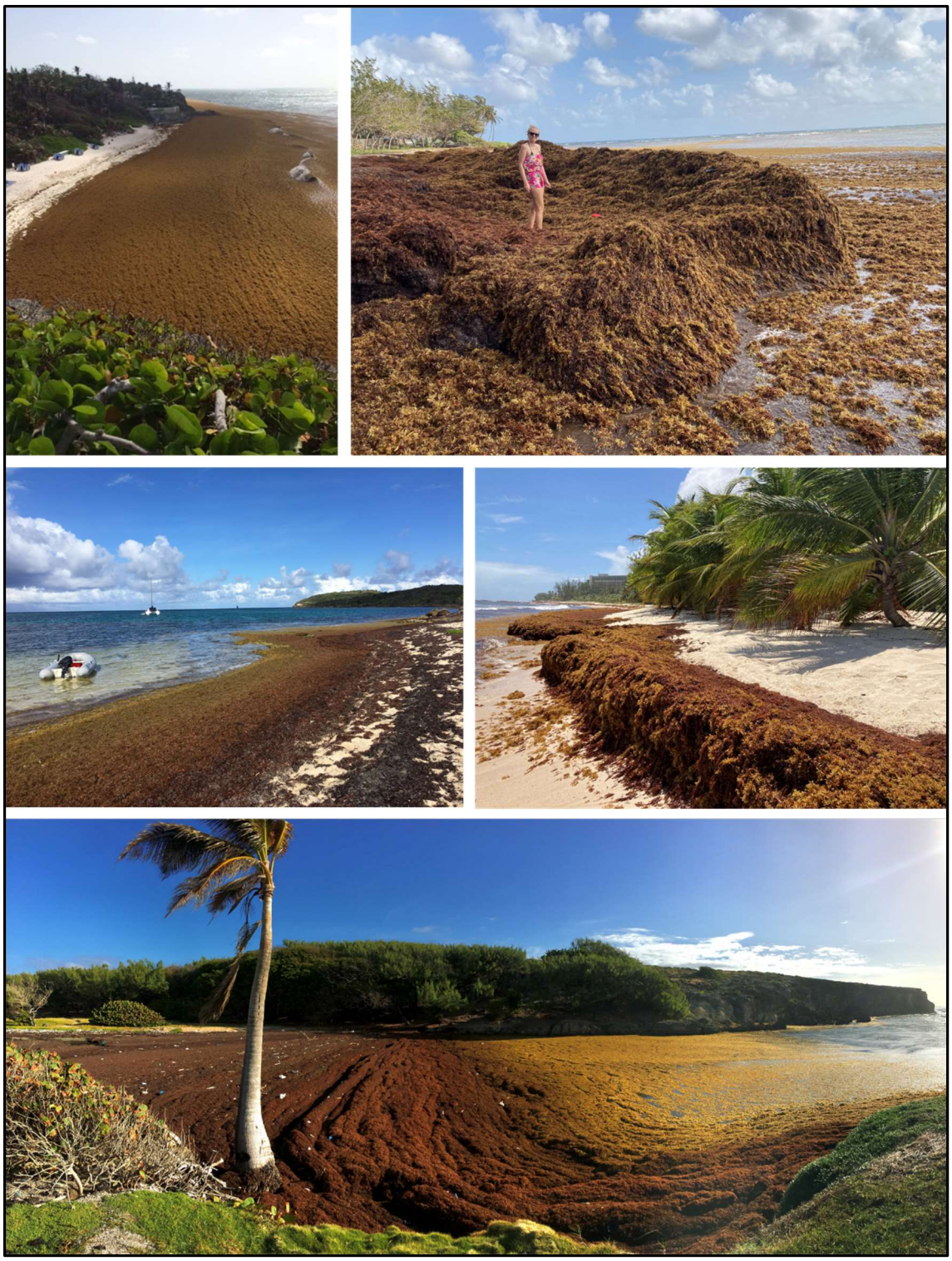

Photo credits: Top L – J. Horrocks, Middle L – A. Cox, all others – H. Oxenford

Figure 5: Examples of sargassum accumulations on the coasts of Barbados and Antigua (middle left image)

swimming behavior of elkhorn coral (*Acropora palmata*) larvae are adversely affected by sargassum leachates. They concluded that continued presence of sargassum in coastal waters may compromise coral resistance by inhibiting larval dispersion and reducing genetic diversity. Further, Cabanillas-Terán et al (2019) report a change in the trophic dynamics of the long spined sea urchin (*Diadema antillarum*), a keystone herbivore in many Caribbean coral reefs, in response to sargassum brown tide events. The urchins appear to switch to a macroalgae diet that is much less diverse, and which, as the authors point out, has implications for carbon and nitrogen assimilation in reef systems.

Although the sargassum 'holobiont' community is described by Lopez et al. (2020), the potential impacts of sargassum-associated bacteria and other attached microorganisms (epibionts) remain unstudied. However, the rapid spread of the new Stony Coral Tissue Loss Disease (SCTLD) along the Caribbean coast of Mexico, compared with its slower spread in Florida is possibly related to the higher bacterial loads in brown tides, or as Chavez et al. (2020) point out, it could be a consequence of the poor water quality associated with brown tides adding to synergistic stresses on corals in shallow coastal habitats.

Other impacts on coral reefs and their associated species occur directly as a result of shading, physical smothering and entrapment by the sargassum mats themselves, rather than from the brown tides. The thick dense sargassum mats that build up when the seaweed becomes trapped along the shoreline that may also extend several hundred meters offshore, have had lethal consequences for air breathing species foraging nearshore, including turtles and marine mammals that were unable to surface for air (Engel, 2019). Dozens of green turtles and several dolphins have died in these circumstances on the southeast coast of Barbados (Julia Horrocks, Barbados Sea Turtle Project, pers. comm.). These large thick sargassum mats are also very effective at blocking light and thus shading benthic communities. In the case of reef building corals which rely heavily on autotrophic feeding (use of sunlight) by the millions of zooxanthellae they typically host in their tissues, shading will likely result in corals suffering periods of significant stress from under-nourishment. Furthermore, when this sargassum begins to decompose and sink on mass, it smothers benthic communities including reefs. This can be exacerbated when barriers placed in lagoons to intercept the sargassum before it reaches the shore, result in the accumulated sargassum sinking directly onto reef habitat offshore (Rodríguez-Martínez et al., 2019). Smothering will further interfere with alternative heterotrophic feeding by corals.

There have also been suggestions that pelagic sargassum could potentially bring rafter and associated species that maybe exotic to different ecosystems, compromising their equilibrium (McLawrence et al, 2017; Monroy-Velázquez et al., 2019).

3.2 Impacts on Seagrass Meadows

The reported impacts on seagrass meadows and their associated communities, like corals, fishes and invertebrates have again largely been caused by exposure to the poor water quality of sargassum brown tides, as described in the previous section. For example, van Tussenbroek *et al*. (2017) found that during brown tide events, light illumination over seagrass beds decreased significantly, whilst temperatures increased by more than 1 ^{o}C. These changes alone resulted in oxygen concentrations in the water column remaining at typical night-time levels (5 mg/L) instead of rising to 9 mg/L as expected during daylight hours. Furthermore, acute nutrient loading increased nitrate and phosphate levels in the water column and resulted in 15 to 35-fold more organic matter accumulating in the sediment. They reported losses of between 61 and 99.5 percent of seagrass below-ground biomass at four locations in the Mexican Caribbean: Mirador Nizuc, Puerto Morelos, Xahuayxol and Xcalak, mainly affecting the shallower areas and those closer to the coast. They noted that these losses were quite substantial, with a documented

loss of 5,700 m^2 of seagrasses at Mirador Nizuc alone. In addition to a general reduction in seagrass biomass affecting all three common species of seagrass (*Thalassia testudinum, Halodule wrightii* and *Syringodium filiforme*), van Tussenbroek *et al*. (2017) also reported significant shifts in species composition of seagrass meadows, with replacement of seagrass species by calcareous algal species such *Halimeda* spp., and epiphytic and drift algae. Similarly in Mexico, Hendy et al. (2021) reported even worse conditions with near anoxic water (0.5 mg/L for oxygen), up to a 5 ^{o}C increase in temperature and a 73% decrease in light over seagrass meadows during sargassum inundations compared with areas not exposed to the seaweed. This resulted in a 7-fold decrease in productivity of seagrasses and a decrease in taxonomic diversity of the meadows (including loss of fish and corals) and altered species distributions, with algae becoming the dominant species in seagrass meadows impacted by sargassum. Likewise in Bonaire, after the sargassum inundations of 2018, 29 ha (11%) of shallow *Thalassia testudinum* seagrass beds near the mangroves were severely impacted and at least 4 ha died (leaving only remnants of shoots without viable rhizome systems). These 'dead' areas were replaced by drift algal masses after a few months and subsequently encroached by the invasive seagrass, *Halophila stipulacea*. Likewise, Bartlett and Elmer (2021) report significant loss of *T. testudinum* during sargassum events in the Turks and Caicos Islands and observed that these former seagrass meadows have been reduced to sandy plains more than 100 metres from shore.

Similar to the impacts on coral reefs, Engel (2019) reported mortalities of conch, turtles, crabs, lobster, worms, and many infaunal creatures in the seagrass meadows of Lac Bay, Bonaire as a consequence of sargassum inundations, mostly related to hypoxic conditions in the brown tides, but also from entrapment in the case of green turtles.

Apart from damage caused by brown tides, several authors also reported direct damage from shading and smothering, and from clean-up activities. For example, Engel (2019) noted that considerable damage to seagrass beds occurred from the use of mechanical equipment and human trampling during sargassum removal efforts in Bonaire.

3.3 Impacts on Mangroves

Very few studies have reported direct impacts of sargassum on mangroves, but a review of the related literature suggests that there is a general decline in the health of mangrove trees associated with sargassum events. In Bonaire, Engel (2019) reported that large tracts of mangrove forest (70 ha representing 30% of the forest) at Lac were affected by sargassum inundation of the bay. She noted that the leaves of the mangrove trees turned yellow shortly after sargassum arrived and began to rot. Although the regular coloration returned after 2 - 3 months, a comparison of mangrove growth rates between two areas indicated slower growth in the area that experienced sargassum compared with the area that had no sargassum. DCNA (2019) noted that anoxic conditions created by brown tides results in the build-up of anoxic sediments which threaten survival of trees, and the function and structure of mangrove forests in the Dutch Caribbean islands. Hernandez et al. (2020) show a decrease in the standing mangrove and canopy cover extent in coastal areas of southwest Puerto Rico as a direct result of sargassum inundations and used the plant health (NDVI) index derived from remotely sensed images to show a decrease in standing healthy vegetation (mangroves) or even a transition to barren or open areas. They note that sargassum can penetrate deep inside the fringing mangrove forest during high tides where it becomes trapped and decomposes, which can lead to anoxic conditions with potential changes to the biochemistry and hydrodynamics of the mangrove root system. This is supported by preliminary results of trials using

100% sargassum as a substrate for mangrove seedlings that show yellowing or death of the seedlings (Pers. comm., Mona Webber, Director, Centre for Marine Sciences, University of the West Indies).

3.4 Impacts on Beaches

Beach erosion and shoreline retreat have been reported for the Mexican Caribbean, where a comparison of the shoreline profile at Puerto Morelos, Mexico June 2008 to June 2019, indicated a 54% decrease in beach volume (from 28 to 13 m^3 sand per m of shoreline) and a 52% loss in beach width (from 31 to 15 m) that could be directly attributed to sargassum inundations (Chavez et al 2020).

On the other hand, on some beaches along the Mexican coastline, sargassum has been found to enhance dune formation, likely through input of nutrients, organic matter, phytohormones and alginates that promote the growth of sand-holding plants (Chavez et al., 2020). These authors report that both native and exotic plants have naturally colonized accumulations of sargassum on the back beach. Other studies have shown the benefit of beached sargassum for nourishing dune plant growth (Williams and Feagen 2010) and reducing beach erosion (Innocenti et al., 2018). Another study suggests that sargassum inundations represent a new and potentially highly significant source of carbonate sediment to the region from the calcareous epiphytes that sargassum hosts (Salter et al., 2020). They calculated that carbonate import to Mexican Caribbean lagoon systems for the year 2018 (the most severe to date with regard to sargassum inundations) averaged 179 kg $CaCO_3$/m of shoreline, and thus could potentially buffer declines in sediment supply resulting from coastal habitat degradation (e.g., nearshore reefs and seagrass meadows) caused by the massive sargassum inundations.

Sargassum inundations on sandy beaches have been reported to impact endangered sea turtle nesting success (Azanza-Ricardo and Perez-Martin, 2016), even reducing stretches of suitable nesting beach by 25% in some cases (Maurer et al., 2015). These latter authors also noted that this can result in a concentration of nesting on the unaffected beaches which increases the chances of females digging up previously laid nests. Azanza-Ricardo and Perez-Martin (2016) noted that impacts on nesting loggerhead turtles were greater than green turtles due to the smaller size of the adults and thus greater probability of becoming stuck. Other authors, however, report that adult turtles are generally still able to navigate the piles of sargassum to lay eggs on the upper part of the beach (Chavez et al., 2020; Rodríguez-Martínez et al., 2021). However, the incubation conditions can be significantly altered by buried or surface sargassum (Maurer et al., 2019; 2021). Decomposing sargassum has been reported to induce lethal temperatures for turtle embryos in Puerto Morelos National Park (Chavez et al., 2020), and it is also well known that even small changes in temperature (which can occur when the dark-colored dried sargassum is lying on the sand surface) can alter the sex ratio of developing hatchlings and thus potentially impact the demography of future turtle populations (Maurer et al., 2015; Chavez et al., 2020). Several authors further report that accumulations of sargassum on the beach impede newly hatched sea turtles from safely reaching the sea (Maurer et al. 2015, Gavio and Santos-Martinez 2018). Although studies are lacking, it has also been suggested that other beach fauna such as the commercially important land crabs and other species that require access to coastal habitats for spawning, will be negatively affected by sargassum inundations that could reduce reproductive success, increase energy expenditures, and necessitate changes in space use (Maurer et al., 2021).

Furthermore, many authors have reported direct damage to sandy beaches resulting from unintended removal of sand (resulting in substantial beach erosion) during clean-up activities (e.g., Rodriguez-

Martínez et al., 2016; Webber and Aiken, 2018; JICA-CRFM 2019). Severe negative impacts on sea turtles and their habitats are caused by attempts to clear sargassum from beaches, especially when heavy machinery is used which may directly destroy nests or cause beach compaction which deters nesting activity and interferes with the emergence of hatchlings (Chavez et al., 2020). These authors also report that offshore barriers used to keep sargassum from the shoreline can trap hatchlings, especially those with fine mesh underwater skirts.

3.5 Effects on Ecosystem Services

Most authors imply or directly mention loss of ecosystem services that would result, or have already, resulted from observed sargassum-related damage to the ecosystems, although none specifically quantify the service losses.

Among the myriad services that authors mention as damaged or compromised by sargassum inundations are: loss of abundance and biodiversity of benthic organisms; loss of valuable nursery habitat with implications for fishery production; reduced coastal protection and greater vulnerability to the impacts of extreme weather; reduced maintenance of nearshore water clarity, and beach width with significant impacts on tourism through loss of aesthetic beauty and recreational opportunity (e.g., van Tussenbroek et al., 2017; DCNA, 2019; Engel, 2019; Chavez et al., 2020; McConney and Oxenford, 2020; Hendy et al., 2021). Many of these authors and others also link the ecosystem service losses caused by sargassum inundations to negative impacts on coastal livelihoods and national economies (e.g., Webber and Aiken, 2018; JICA-CRFM 2019; UNEP-CEP 2021). In many cases where losses are not directly observed or reported, authors have drawn on the large body of literature that speaks to loss of ecosystem services of these coastal ecosystems when damage occurs from the many other stressors that have been studied in more detail than sargassum influxes. Examples of direct observations and/or inferred losses to ecosystem services directly resulting from sargassum inundations are detailed here.

Hendy et al. (2021) summarized the damage to ecosystem services of seagrass meadows along the Mexican Caribbean coastline, stating that sargassum has caused a trophic collapse of the flora and fauna, and a concomitant change from a highly complex habitat to one of reduced complexity and evenness. They noted that the loss of corals and seagrasses, known as 'ecosystem engineers' that provide habitat and structure for many organisms, including juveniles and vulnerable species, has reduced the trophic complexity of food webs altering the flow of energy and creating changes throughout the entire ecosystem and associated ecosystems. They go on to point out that loss of climax seagrass communities and coral will lead to greater impacts from storm events (i.e., reduced coastal protection services), and loss of seagrass habitats will also reduce carbon sequestration. They conclude by recognizing that loss of these ecosystem services will lead to economic losses in the state of Quintana Roo from declines in tourism that have already been seen.

DCNA (2019) noted that if sargassum inundations become a recurrent occurrence in the Dutch Caribbean, near-shore ecosystems will be put under much stress with detrimental consequences for coastal stability and other ecosystem services. They listed loss of filtering capacity, shoreline protection, nursery function and carbon sequestration among the ecosystem services impacts that would occur with damage to mangroves from sargassum inundations. Likewise, they listed loss of sand stabilization, filtering capacity (i.e., clear water, pathogens), and carbon sequestration among the ecosystem services that would occur with sargassum damage to seagrass meadows. They also highlighted loss of biodiversity among the

seagrass and mangrove communities and thus loss of resilience to future environmental changes, and potential impacts to fishery production.

Engel (2019) noted that areas of *Thalassia testudinum* seagrass meadows that were killed by the sargassum inundations in Bonaire and subsequently invaded by the non-native seagrass species would offer fewer ecosystem services such as carbon sequestration and sediment stabilization, since its biomass is generally lower and its rhizome system less robust than the climax native species. The canopy height of the invasive species is also lower and will provide less shelter for juvenile fish, resulting in reduced fish biodiversity. She also pointed out that the nutritional value of the invasive species is lower and would therefore likely impact the green turtle population foraging in the bay.

Likewise, van Tussenbroek et al. (2017) noted that the significant damage to seagrass meadows in the Mexican Caribbean may take years or even decades to recover, and if sargassum inundations continue they will likely never recover. Bartlett and Elmer (2021) suggest that recovery of seagrass beds in the Turks and Caicos Islands, some located more than 100 meters off the coast, is expected to take decades, portending significant socioeconomic impacts associated with the conch and lobster fisheries that they support. Thus, it is expected that coastlines that are exposed to sargassum inundations and have lost seagrass meadows will continue to experience turbid waters with less stable shorelines and will be more vulnerable to impacts of storms and hurricanes. Profound changes to species community composition of these coastal ecosystems are also expected to cause adverse impacts on carbon sequestration, food webs and other ecological functions.

There is no doubt in the scientific and popular literature that sargassum inundations have a huge negative impact on the ecosystem services provided by sandy beaches and coastal waters with regard to their aesthetic appeal, recreational opportunities (including beach use, nearshore bathing and watersports), shoreline protection and support for coastal businesses (beach vending, fish markets, restaurants, boat haul-outs etc.) (Rodriguez-Martínez et al., 2016; Collado-Vides et al., 2019; JICA-CRFM, 2019; UNEP-CEP 2021; León-Pérez et al., 2021, Bartlett and Elmer, 2021).

Accumulation of seaweed on shorelines also inhibits access to nearshore waters for swimming and other forms of recreation. Tourists have been reported to avoid affected resorts (Milledge and Harvey, 2016) with coastal tourism experiencing extensive booking cancellations (JICA-CRFM, 2019). Furthermore, the ammonia and hydrogen sulphide gases that are produced by anaerobic decomposition of wet sargassum along shorelines not only emit a vile odor, but exposure to high concentrations of these gases has human health implications (Resiere et al. 2018; UNEP-CEP, 2021) and negatively impacts coastal businesses (JICA-CRFM 2019). Clean and wide white sand beaches are the showpiece of the Caribbean tourism product, hence reductions in beach access and quality from sargassum inundations has had notable socio-economic impacts, which together with the unanticipated costs of clean-up have had negative impacts on national economies (JICA-CRFM, 2019; UNEP_CEP, 2021).

Adverse impacts on coastal marine ecosystems are also known to affect the productivity of nearshore fisheries (classified under provisioning ecosystem services). Impacts commonly reported by fishers include obstructed access to landing sites, increased time spent at sea to maneuver around seaweed mats, clogged fishing gear (traps and nets) as well as damage to fishing equipment and vessels due to entanglement and corrosion from hydrogen sulphide (JICA-CRFM, 2019; Ackah-Baidoo 2013; Solarin et al., 2014). Catches have also changed in size (reductions and fluctuations) and composition across the Caribbean possibly due to the influxes (JICA-CRFM 2019).

3.6 Summary of Sargassum Impacts on Ecosystems and Ecosystem Services and Select Economic Sectors

Our review of the literature regarding impacts of sargassum on coastal and marine ecosystems and their ecosystem services suggest widespread impacts on beaches, seawater, coral reefs, seagrasses, and mangroves. The relative magnitude of impacts on ecosystem services appears to follow this general order. That is, beaches and seawater are expected to suffer the greatest impacts, followed by reefs, seagrasses, and mangroves. Impacts on beaches are expected to occur primarily due to biomass effects associated with accumulation of sargassum on shorelines. Adverse impacts on corals are expected to occur primarily due to water quality effects including reductions in light penetration, oxygen availability and increased temperature, coupled with increased turbidity, eutrophication from nutrient loading and toxic ammonia and hydrogen sulphide. Impacts on seagrasses and mangroves are also mostly associated with these "brown tide" effects on water quality, primarily affecting the health and productivity of these ecosystems through shading, nutrient loading and low oxygen in sediments. The associated impacts on ecosystem services are highly dependent on local context and generally are positively correlated with the extent of declines in ecosystem health. In contrast, adverse impacts on beaches tend to be associated with the amount of accumulated sargassum, including efforts to remove it with heavy machinery and other physical means. Some ecosystem services from beaches (e.g., recreation and tourism) are therefore impacted by the presence of sargassum, while others (e.g., coastal protection) are impacted by the removal of sargassum. Table 2 summarizes ecosystem services and stakeholders that are expected to be impacted by sargassum events, as well as appropriate measures of economic value.

4 Geographic scope of sargassum influxes in the Caribbean

In addition to understanding the nature of impacts on coastal and marine ecosystem goods and services and applying appropriate measures of economic value to those impacts, estimating economic impacts from sargassum events in the Caribbean requires an understanding of how these events are distributed across the region. As noted in UNEP (2021), the nature and magnitude of impacts from sargassum are expected to vary spatially according to several factors, including the physical features and position of affected coastlines, coastal dynamics, and the proximity of vulnerable ecosystems, resources, and economic activities. For example, nonlinear coastlines and complex submarine topography can cause stranding of sargassum mats, which eventually decompose, deteriorating water quality in the area. Sargassum events occur primarily on Atlantic-facing (windward; east and south) coasts of islands, leaving leeward (west) coasts largely unaffected.

To provide insight into the spatial distribution of exposure to sargassum and potential impacts in the Lesser Antilles region, Degia et al. (2022) map historical sargassum influxes in Barbados, Dominica, Grenada, St. Lucia, and St. Vincent and the Grenadines using available data and aerial imagery from Google Earth. Qualitative exposure ratings (high, medium, low) are developed for "coastal zone sub-areas" with similar characteristics for each island,[6] and combined with spatial maps of asset categories and economic sectors including tourism, fisheries, coastal communities, and coastal ecosystems. Exposure by ecosystem

[6] The coastlines of Barbados, Dominica, Grenada, and St. Lucia are partitioned into 8, 6, 4 and 4 subareas respectively. Due to its multi-island composition and complex coastlines, St. Vincent and the Grenadines is also partitioned into 3 island groups.

Table 2: Ecosystem services affected by sargassum, stakeholders and measures of economic value.

Ecosystem	Affected Ecosystem Services	Affected Stakeholders	Sargassum Impacts	Measures of Economic Value ($)
Beaches and nearshore seawater	Recreation Storm protection Cultural activities and identity Biodiversity Visual amenity	Tourists Coastal communities Watersport operators Hoteliers Coastal property owners	Reduced access Reduced quantity and quality of recreational experiences Decreased spending by tourists and recreationists Reduction in property value Heighted risk of loss from storm damage Reduced non-use value from losses to species	Willingness to pay Revenue & profit from commercial operations Market value of coastal property
Coral Reefs	Recreation Storm Protection Seafood Cultural activities and identity Biodiversity	Fishers Coastal communities Tourists Divers/ snorkelers Watersport operators Hoteliers Coastal property owners	Reduced harvest Reduced quantity and quality of recreational experiences Decreased spending by tourists and recreationists Reduction in property value Heighted risk of property loss Reduced non-use value from losses to species	Revenue & profit from harvest Willingness to pay Revenue & profit from commercial operations Market value of coastal property
Seagrasses	Storm Protection Seafood Water clarity Biodiversity Carbon Sequestration	Coastal Property Owners Fishers Tourists Coastal communities General public	Reduced fishery productivity Reduction in property value Heighted risk of property loss Reduction in carbon sequestration	Revenue & profit from harvest Market value of coastal property Willingness to pay Social cost of carbon
Mangroves	Storm Protection Materials Food Water clarity Recreation Biodiversity Carbon Sequestration	Fishers Coastal communities Tourists Coastal property owners General public	Reduced fishery productivity Reduction in property value Heighted risk of property loss Reduction in carbon sequestration	Revenue & profit from harvest Market value of coastal property Willingness to pay Social cost of carbon

type and economic sector are summarized in Table 3.

The exposure mapping is island-wide but low resolution / level of detail and is based on observations of sargassum in aerial photographs on beaches or the very nearshore. However, the mapping does not show the spatial extent of sargassum influxes and associated brown tides in detail, especially not onshore-offshore extents. When combined with asset mapping, it indicates where sargassum influxes have been occurring in proximity to assets within the same coastal zone sub-area. This provides enough information to suggest areas or assets that should be prioritized for further study, but not enough to conclude, for example, that because a given sub-area is highly exposed to sargassum that every asset in the sub-area is exposed to the same level or at all. Such questions can be partially answered by closer inspection of the space and dynamics involved. For example, the southeast coast of Barbados is highly exposed to sargassum, but the coral reefs in this area are likely not near enough to shore to be impacted directly by the sargassum itself, which tends to accumulate on the beach. Further study would be required to assess whether plumes of water polluted by sargassum decay (brown tides) would typically travel offshore to reach the reefs in this area. Similarly, most coastal wetlands in Barbados are not permanently or even frequently connected to the sea, because a lack of permanent surface water flow allows a beach berm to build-up between the watershed outlet and the sea. The exposure of the coastal wetland to impacts of sargassum influxes depends on coastal hydrodynamics and morphology which determine whether sargassum can be transported into the wetland.

Results of the exposure mapping suggest high sargassum exposure on the south coasts of Barbados, St. Lucia and St. Vincent and the Grenadines. Beaches in all areas are among the most impacted ecosystems. In Barbados, coral reefs are also affected, while mangroves and seagrasses are also affected in St. Lucia. Across all highly impacted locations, economic activity related to tourism and fisheries is vulnerable to loss. A medium level of exposure is reported for coastlines in Dominica and Grenada, primarily affecting coral reefs and mangroves in Dominica and mangroves and seagrasses in Grenada. Economic activity related to fisheries and coastal communities is most vulnerable to loss.

Table 3: Coastlines, ecosystems and economic sectors affected by historic sargassum events and sargassum exposure rating (adapted from Degia et al. (2022)

Country	Coastlines affected	Primary ecosystem types	Primary economic sectors	Sargassum exposure rating
Barbados	South	Beaches, coral reefs	Tourism and fisheries	High
	East	Beaches, wetlands	Fisheries	High
	Northeast	Pocket beaches	Recreation	Medium
Dominica	South	Coral reefs, mangroves	Fisheries, coastal communities	Medium
	East	Beaches	Fisheries, coastal communities	Medium
	Northeast	Beaches, coral reefs, seagrasses	Fisheries, tourism	Low
Grenada (mainland)	Southeast	Mangroves, seagrasses, beaches	Fisheries, tourism, coastal communities	Medium
	East	Mangroves, seagrasses, beaches	Fisheries, coastal communities	Medium
	North	Beaches	Tourism, coastal communities	Medium

St. Lucia	South	Wetlands, mangroves, seagrasses, beaches	Fisheries, tourism, coastal communities	High
	East	Wetlands, mangroves, seagrasses, beaches	Fisheries, coastal communities	High
	North	Wetlands, mangroves, seagrasses, beaches	Coastal communities	Medium
St. Vincent & the Grenadines (mainland)	South	Beaches	Tourism, coastal communities	High
	East	Beaches	Tourism, fisheries, coastal communities	High
	Northeast		Fisheries, coastal communities	High

5 THE POTENTIAL SCOPE OF ECONOMIC LOSSES FROM SARGASSUM: INSIGHTS FROM RELATED LITERATURE

Due to its relatively recent appearance in the Region and limited geographic and temporal scope, there are few, if any, empirical examinations of the economic losses associated with sargassum events in the Caribbean. Directed market and non-market valuation research addressing impacts on recreation and tourism, fisheries, coastal business, and ecosystem services such as shoreline protection and habitat provision are clearly warranted to fill this gap. Estimates of the economic costs associated with sargassum events will allow policy makers to understand the potential scope and distribution of economic impacts so that appropriate measures can be taken to mitigate losses.

In advance of such research efforts, insights into the potential economic impacts of sargassum in the region can be derived by combining information on the economic value of coastal and marine ecosystem goods and services in the region and estimates of economic losses from similar natural hazard events, with information regarding the potential timing, duration, and magnitude of sargassum events in the region. Below we summarize these two strands of literature. In this section we focus on the economic impacts from macroalgal and microalgal blooms. In section 6 we review the literature on coastal and marine ecosystem service values in the Caribbean.

5.1 MACROALGAE INUNDATIONS AND MICROALGAE BLOOMS (HABS)

An extensive body of literature examines the economic impacts of damaging environmental events, including storms (e.g., Bakkensen et al., 2018; Collalti and Strobl, 2021; Robinson and Bangwayo-Skeete, 2016), drought (Ding et al., 2011), floods (Haddad and Teixeira 2015), wildfires (Diaz 2012), oil spills (Negro et al. 2019; Ribeiro et al. 2021) and algae blooms. The latter category includes proliferations of macroalgae including sargassum and blooms of microalgae. Blooms of microalgae are often termed "harmful algae blooms" (HABs), but different uses of this term appear in the literature. It is therefore important at the onset of a review of impacts caused by algae to clarify terminology. Some authors (e.g., Gallardo-

Rodríguez et al., 2014) define HABs as referring exclusively to blooms of toxin-producing microorganisms including microalgae and cyanobacteria, commonly termed "red tides" based on the algae species and color of the affected water (Charlier et al., 2006). Noting that blooms of macroalgae are indeed harmful in other ways, other researchers (e.g., Wells et al., 2015), include species of floating macroalgae (including sargassum) under the "HAB" umbrella. Because there are important differences in impacts from micro- and macro-algae, especially as related to human and environmental health effects, we use the former definition here, categorizing HABs as blooms of toxic microalgae and discuss impacts from macroalgae events separately.

5.2 ECONOMIC EFFECTS OF MACROALGAE BLOOMS

Non-toxic macroalgal species such as sargassum cause the most harm through biomass effects. As detailed above, these effects include shading of submerged corals and vegetation, oxygen depletion, habitat loss from hypoxia/anoxia, disruption of food web dynamics and structure, displacement of indigenous species and disruption to biogeochemical cycles (Anderson et al., 2000; van Tussenbroek et al., 2017; Rodríguez-Martínez et al., 2019; Hendy et al., 2021; Rodriguez-Munoz et al., 2021). Large accumulations of macroalgae biomass also create physical impediments and visual disamenities to shorelines and nearshore areas.

While there have been no directed valuation studies to estimate the economic losses associated with sargassum events in the Caribbean region, several recent studies estimate the potential economic impact of seaweed in other coastal areas of the world. Green tides associated with the proliferation of floating macroalgae in the family *Ulvaceae* (green macroalgae) in marine systems are similar in many ways to sargassum influxes.[7] These 'green tides' have been increasing in frequency over the last two decades, commonly occur in coastal areas of Europe and Asia (Smetacek and Zingone, 2013; Yang et al., 2018), are seasonal in nature, non-toxic, and often characterized by the accumulation of large amounts of biomass on beaches and in coastal waters. China's Yellow Sea and the North Atlantic coast of France are two areas greatly impacted by such green tides in recent years.

5.2.1 Willingness to pay to prevent and manage macroalgae events

Numerous studies use non-market valuation methods to estimate willingness to pay (WTP) to avoid or mitigate damages from macroalgae events. When aggregated to the relevant population, these WTP measures are considered estimates of the economic costs of those events. That is, if someone is willing to pay $X to avoid a harmful event, it can be assumed that the event resulted in $X in damage.

Taylor and Longo (2009) estimate residents' preferences and WTP for programs to control algal blooms in Varna Bay, Bulgaria, a port city and tourist destination on the coast of the Black Sea. Importantly, the algal blooms in this location are frequent but non-toxic, creating impacts that are largely associated with visual amenity and recreation, characteristics similar to sargassum inundations in coastal areas where the primary economic activities are associated with recreation and tourism. Results suggest that respondents are willing to pay more for programs that reduce the duration and visual impact of bloom events, and that respondents with higher income and education, that enjoy swimming more and live closer to the sea are

[7] It is important to note that some research on the effects of "green tides" include blue-green microalgae (now reclassified as cyanobacteria) that produce a deadly toxin called microcysti.

willing to pay more. Willingness to pay for high levels of water visibility is also found to increase with the duration of the bloom event, suggesting that lengthier disruptions to coastal conditions induce higher willingness to pay for marginal improvements. Per-person WTP to reduce the duration of bloom events from 6 weeks to 1 week if high visibility is maintained is found to be €17.00 (approximately US$25.00 in 2009). Aggregated across the population of Varna (roughly 357,000 people) Taylor and Longo (2009) suggest that residents would be willing to pay approximately € 2.2 million (US $ 3.0 million) for this high level of control.

Shan et al. (2019) estimate willingness to pay (WTP) for the ecological restoration of shorelines, coastal water quality, marine creatures and marine biodiversity affected by green tides in Jiaozhou Bay, on the western coast of the Yellow Sea in China, an area that has been affected by lengthy inundations of green macroalgae (family *Ulvaceae*) since 2007. Respondents are found to be more concerned about the natural appearance of the landscape and coastal water quality relative to marine creatures and biodiversity. Annual WTP for ecological restoration is estimated to be 214.56 CNY per person (approximately US$ 31.00 using exchange rates in 2018), or approximately 2.02 billion CNY (US$ 0.30 billion) when applied to the population of Jiaozhou Bay. Willingness to pay for mitigating the impacts of green tides was higher for female respondents, younger respondents, and those with higher incomes.

Risén et al. (2017) estimate WTP by residents of a Baltic Sea resort for a program to regularly remove and utilize beach-cast macroalgae (specifically, red macroalgae *Polysiphonia fucoides* and *Ceramium tenuicorneto*) to produce bioenergy and biofertilizer through anaerobic digestion. Mean WTP for cleanup of macroalgae on sandy beaches is found to be largely homogenous across respondents and is positively associated with the size of the cleanup program as well as respondent income and education. The authors suggest that aggregate benefits from the program could total a range between € 1.0 million and 1.6 million.

Yang et al. (2018) quantify the social cost of green tides in the Yellow Sea, China, including management costs, which encompass prevention and mitigation costs, and "residual costs", which include market costs for aquaculture and tourism, as well as non-market recreational activities.[8] Yang et al. (2018) also estimate willingness to pay for two programs that would remove green algae, one at sea and one onshore. Respondents included residents and tourists who had prior knowledge of green tides. Average WTP for the program that would harvest green macroalgae at sea was 62 CNY per year (approximately US $10.06 in 2014) for Qingdao residents, and 82 CNY (US $13.31) for tourists. WTP for the program that would harvest macroalgae on shore was surprisingly similar, at 62 CNY and 77 CNY for residents and tourists respectively.

More recently, Ofori and Rouleau (2020) estimate the public's willingness to pay (WTP) to support seaweed cleanup in Elmina, Ghana, a location where employment and incomes are highly dependent on commercial fishing and tourism and where, like the Caribbean, pelagic sargassum inundations have

[8] Regarding management costs, the application in Yang et al. (2018) is different from other examinations of costs of HABs in that the drivers of green tide events are hypothesized to stem from local coastal and marine activities such as marine-based nori farmers unintentionally supporting the propagation and dissemination of ulva on the rafts and nets used to grow nori, and the growth of crab farming in the region contributing to eutrophication. Because the causes of green tides are deemed within management control, prevention is feasible, though costly.

occurred since 2011. WTP for seaweed cleanup is found to be positively associated with household income (with the notable exception of high-income households) and education and inversely associated with years of residence, distance to the beach and having positive or indifferent attitudes about invasive seaweeds. Mean household WTP per month to support seaweed cleanup is estimated to be roughly US $7.00, which is approximately 3.3 percent of average monthly household income.

Xu et al. (2021) assess resident and tourists' willingness to pay higher taxes for the management of the green macroalgae (*Ulva Prolifera*) blooms in Qingdao, China. Approximately 90 percent of respondents were willing to pay some amount for management of *U. prolifera*. Mean WTP values ranged from roughly 59 CNY to 69 CNY (approximately US $9.23 to US $ 10.80), with higher WTP values associated with the broader scopes of removal. Respondents who indicated a higher degree of belief in the program, those with stronger concern for the environmental impacts of algae blooms and those who perceived marine quality to be poor were willing to pay more for the control of algal blooms.

5.2.2 Economic impacts from macroalgae on recreation and tourism

Yang et al. (2018) estimate the economic impacts to tourism from green tides in the Yellow Sea, China finding that green tide events induced a loss of tourism revenue in Qingdao between 22 and 25 percent. Highlighting the importance of spatial scope, the authors note that this loss should be interpreted as a "local impact", as the transfer of tourist spending to other locations was not accounted for in the calculation. In their comprehensive study of the economic impacts of green tide events in the Yellow Sea, China, Yang et al. (2018) find that more than 90 percent of impacts were attributable to losses in (local) tourism revenue.

5.2.3 Impacts on human health from sargassum

Though non-toxic, sargassum inundations are associated with harmful impacts on human health, particularly respiratory issues caused by hydrogen sulphide and ammonia gasses that are produced when sargassum decays anaerobically (i.e., when left in a wet environment), and skin rashes following physical contact with sargassum (CRFM 2019). As noted in Resiere et al. (2018), doctors in Guadeloupe and Martinique reported more than 3,300 and 8,000 cases respectively in the first eight months of 2018 alone. While very few of these cases resulted in patients being treated in intensive care, the magnitude of afflictions suggests an important health concern for the region for which additional research is warranted.

5.2.4 Costs of beach wrack removal

Sargassum events often lead to public and private management actions such as the physical removal of sargassum from beaches and attempts to block sargassum from reaching shorelines. As noted in section 2.6 above, the associated costs for labor, materials, and equipment as well as the costs of damaged or foregone ecosystem services induced by the management action should be included in the total cost of the sargassum event. The existing literature on the physical and environmental costs of cleanup is relatively sparse but suggests that the physical costs of cleanup can be quite significant. For example, Webster and Linton (2013) report that the cost of raking and removal of sargassum from Texas Gulf Coast exceeded US $2.91 million per year. Lapointe et al. (2021) report that the 2018 Caribbean-wide clean-up of sargassum cost US $120 million.

Chavez et al. (2020) provide details on the costs of sargassum cleanup in Mexico, noting that the Mexican government spent approximately US $ 17 million to remove over 500,000 tons of seaweed from coastal areas in 2018, and an additional US $ 2.6 million to remove 85,000 tons in 2019. Chavez et al. (2020) also

report costs associated with sargassum cleanup by private entities, including wages, machinery to remove sargassum from beaches, boats to assist with collection, disposal costs including transport, and barriers to prevent sargassum from reaching beaches. As example of these expenses, Chavez et al. (2020) note that hotels between Cancun and Puerto Morelos spent between US $128,000 and 284,000 on wages and transport of the sargassum to disposal sites alone, equipment purchased by hotels is reported to cost approximately US $ 82,000.

Wang et al. (2009) estimate the total economic cost associated with a rapid large-scale effort to remove floating green macroalgae (*Ulva prolifer*a) off the coast of Qingdao, China in advance of the 2008 Olympic sailing competition. Between June 28 and July 14 of that year, more than 750,000 tons of floating green algae were removed from nearshore waters and coastlines, and approximately 25 km of booms and 37 km of nets were deployed to contain the algae. The effort involved thousands of workers, more than 1,000 boats and over 200 trucks that were used to transport the algae inland for disposal. A lower bound on the total costs of cleanup were estimated to be approximately US $83.7 million, which was paid by local, provincial, and national governments. This value amounts to roughly US $116.00 per ton of seaweed removed, an estimate that is on par with similar results from the literature. It is important to note that these values do not include economic impacts to tourism or ecosystem services.

5.3 Economic effects of harmful algae blooms (HABs)

Like sargassum inundations and other macroalgae events, HABs are associated with nutrient pollution and warmer water temperatures and have detrimental impacts on human health, ecosystem function, the visual and olfactory appeal of coastal areas and waterbodies for commerce and recreation (Alvarez et al., 2019). Both HABs and sargassum inundations are expected to have the most pronounced market-based economic effects on human activities near waterbodies, including fisheries, recreation and tourism, and associated commercial ventures such as lodging, food and beverage (Hoagland and Scatasta, 2006).

Despite these similarities, important differences between these two types of harmful algae-related events should be recognized, including different impacts on human and environmental health and different pathways by which human wellbeing is affected by blooms.

Further, most HABs do not physically prevent water access, but rather make access risky and/or less appealing. It therefore seems likely that while the categories of economic costs from HABs and sargassum events will be similar, the relative magnitudes of cost categories will be different. Against this backdrop of similarities and differences between sargassum and HABs, we turn to the literature addressing the economic effects of HABs for additional insights into understanding and measuring the economic impacts of sargassum.

5.3.1 Willingness to pay to prevent and manage HABs

As is the case with macroalgae, researchers examining the impacts of HABs have employed non-market valuation methods to estimate willingness to pay (WTP) to avoid or mitigate damages from HABs. For example, Nunes and van den Bergh (2004) estimate willingness to pay for the prevention of harmful algae blooms (HABs) along the coastline of the Netherlands. Willingness to pay is found to be positively associated with frequency and duration of beach visitation and proximity of residence to the beach. The authors suggest that aggregate welfare losses from failing to prevent pollution events related to HABs would be between €225 and €326 million (roughly 0.08 percent of Dutch GDP in the year 2000).

Kosenius (2004) estimates tourists' willingness to pay for a 25 percent reduction in the harmful algal blooms and a 50 percent reduction in the risk of toxic effects from eating mussels in the small tourist-dependent coastal town of Hanko, Finland. Results from this study suggest that mean willingness to pay for HAB reductions was 24.90 Euro per person per year (roughly US $31.00 in 2004). Respondents who considered HABs to be a problem and those that spent more on their vacation were more willing to pay for HAB reduction.

5.3.2 Economic impacts from HABs on recreation and tourism

Alvarez et al. (2019) estimate the change in consumer surplus to boaters in southwest Florida resulting from site closures due to HABs. Results suggest average per trip losses from site closures of US $17.26, with total losses in Lee County from site closures due to cyanobacterial HABs in 2018 summing to roughly US $3.5 million.

5.3.3 Economic Impacts on coastal business and property values

Market and non-market valuation techniques have been applied to estimate the economic impact of HABs on coastal business activity and real estate values. For example, Oh and Ditton (2005) find that a microalgae bloom in 2001 created a total economic loss of 5 percent of total output in the three surrounding counties and a 57 percent decrease in visitation to the affected area. Oh and Ditton (2005) highlight the importance of granular data collection from businesses (e.g., customer counts, sales revenue) and recreational sites (site visits, measures of site quality) before, during and after harmful environmental events for accurate estimation of economic activity that would have transpired were it not for the event.

Larkin and Adams (2007) estimate the economic impacts of red tide events and tropical storms on coastal restaurant and lodging businesses in Ft. Walton Beach and Destin Florida from 1995 to 1999. Red tide events were found to reduce restaurant and lodging revenues by 29.3 and 34.6 percent respectively, with a total loss of 32.3 percent to these two tourism-dependent sectors during each month of a HAB event. It is important to note that these estimates pertain to impacts on businesses located on the affected shorelines, and that the effects of consumer substitution to alternatives further inland were not measured.

Bechard (2020b) examine the impact of HABs on the fishery and seafood sector of Pinellas County in southwest Florida from January 2002 to December 2018, finding a reduction of 14.8 percent in monthly taxable sales revenue during months with persistent blooms of red tide. Pointing to the importance of halo effects, the authors suggest that losses to the fishery and seafood sector are in part due to reductions in consumer demand for species that were not affected by contamination.

Bechard (2020a) examine1.3 million transactions involving sales of coastal residential properties in Southwest Florida between 2002 and 2018 to estimate the impact of harmful "red tide" algal blooms (*Karenia brevis)* on the value of coastal real estate. Results suggest that property prices within one mile of the ocean decline approximately 5 percent during persistent blooms, and that properties slightly further inland, up to 5 miles from the coast, decline by approximately 10 percent during bloom events. This suggest that prices of properties closest to the coast may be more robust to impacts from temporary environmental events (e.g., visual amenity, access). Bechard (2020) also finds that negative impacts on coastal property values increase with the duration of bloom events, and that impacts on condominiums are more significant (roughly 2 to 3 percent higher) than impacts on other coastal properties.

5.3.4 Economic impacts of HABs on Human Health

Comparing impacts from microalgae HABs and macroalgae events, effects on human health are the least similar. Unlike macroalgae, some microalgal species produce toxins which can contaminate air, water and accumulate in fish, causing poisoning syndromes when inhaled or ingested through drinking affected water or consuming fish or shellfish. These afflictions include paralytic, diarrhetic, amnesic, and neurotoxic shellfish poisoning (Anderson et al., 2000), skin irritation, gastrointestinal illness, respiratory problems, seizures, liver and kidney damage, paralysis and potentially death (Kouakou and Poder, 2019). While sargassum is not inherently toxic, its anaerobic decomposition on shorelines and nearshore areas produces ammonia and hydrogen sulphide gases which can be toxic to marine organisms and have health impacts on humans at high concentrations.

The associated human health effects of HABs are therefore much broader and decidedly more serious than those associated with exposure to decaying sargassum and other macroalgae. Indeed, in their comprehensive estimate of the economic impacts of HABs in the United States over the six-year period 1987 to 1992, Anderson et al. (2000) find that public health costs comprise 45 percent of the direct and indirect costs associated with HABs, noting that these costs are largely due to toxic fish and shellfish poisoning resulting in illness and death. Impacts to commercial fisheries and recreation are found to comprise 37 and 13 percent of the total costs of HABs, respectively, with monitoring and management costs making up 4 percent. We review impacts of HABs on human health recognizing that a comparison with impacts from sargassum may be less relevant than impacts on recreation, tourism, and coastal commerce.

Focusing on digestive and respiratory illnesses, Kouakou and Poder (2019) review 16 studies that examine the economic costs of HABs on human health, including expenses associated with healthcare and medication, lost income due to illness, costs of pain and suffering, costs of death and impacts on health-related quality of life. In addition to providing a range of estimates of health costs associated with HABs, this review provides important insights regarding data and assumptions required for such analysis. For example, estimating the economic costs of healthcare and medication associated with environmental events requires the identification of symptoms or adverse health effects, the incidence of those afflictions in the affected population, the treatments required to provide care or relief, the duration of treatment and the associated per-person or per-visit market cost. Variation in reporting of symptoms, the severity of symptoms across a population and the costs of care across providers necessitates the use of simplifying assumptions such as using average or median values to calculate aggregate costs. Estimates of the costs of lost quality of life from HABs are calculated using estimates of the quality-adjusted life years (QALYs) lost due to illness associated with exposure to the HAB and assigning a value to those QALYs.

Kouakou and Poder (2019) find that mild, moderate, and severe cases of respiratory illness due to contamination by HAB cost roughly US $86.00, $1,235.00 and $14,600.00 per-person respectively (2016 dollars), while mild, moderate and severe cases of digestive illness cost roughly US $86.00, $1,015.00 and $12,600.00 respectively. Importantly, they find that the costs of death comprise an overwhelming majority of the total healthcare costs associated with HABs. The authors also suggest that unreported illnesses are the most significant source of bias in cost estimates, noting that up to 90 percent of afflictions go unreported, perhaps due to a preponderance of mild cases coupled with local knowledge and familiarity with care. It is therefore suggested that the estimates of healthcare costs from known cases are multiplied by 10 to create an estimate for a given population. Other limitations noted by Kouakou and

Poder (2019) include establishing direct causal links between symptoms and exposure to HABs and a dearth of information regarding chronic, long term health effects from exposure.

5.3.5 Summary of insights from the macroalgae and HAB literature

Our review of the literature concerning economic effects of macroalgae inundations and HABs suggests several important considerations for the examination of impacts from sargassum events in the Caribbean. First, pointing to a potential source of revenue for management and mitigation, numerous studies find that both residents and tourists are WTP for programs that reduce the duration and visual impact of algae events. WTP is consistently found to be positively associated with income and education, respondent proximity to the coast, frequency of participation in coastal recreation and duration of algae events. Importantly for marketing efforts, WTP for algae management is mostly related to impacts on visual amenity and coastal water quality, rather than on less visible ecosystem services such as biodiversity. Understanding resident and tourist WTP for sargassum clean-up and mitigation programs in the Caribbean is clearly an important area for future research.

Results from this literature also suggest that algae events that affect coastal access and visual amenity will have negative impacts on coastal property values. These impacts are expected to be positively correlated with the duration of events, may affect condominiums more than houses and may create larger impacts on properties located slightly inland due to the robust nature of beachfront property values. The impact of visual and olfactory impacts on property values in the Caribbean appears to be another important area for research.

Our review also suggests that impacts on coastal businesses such as restaurants and lodging along affected shorelines are likely to be significant, potentially exceeding the magnitude of impacts from tropical storms. An important takeaway for accurate estimation of the economic activity that would have transpired were it not for the event is the need for granular data collection from businesses and recreational sites before, during and after sargassum events. This literature also highlights the importance of defining the geographical scope of business impacts and measuring consumer substitution effects.

Regarding healthcare costs, research in the context of HABs suggests that a large majority of illnesses will go unreported. Hence, examinations of the health impacts of sargassum events should recognize that relying only on reported cases of harm may significantly underestimate true health impacts.

6 COASTAL AND MARINE ECOSYSTEM SERVICE VALUES IN THE CARIBBEAN

A broad body of literature employs market and non-market valuation methods to estimate the economic value of coastal and marine goods and services in the Caribbean. This literature – spanning more than 100 articles and technical reports – includes comprehensive assessments of ecosystem service values for individual countries and the region, numerous directed valuation studies that attempt to monetize the value of specific ecosystems or ecosystem services and a few reviews of the literature. Coupled with the above information on measuring economic value and economic impacts from harmful events such as HABs, this literature can provide important insights into potential scope and magnitude of economic impacts from future sargassum events in the region.

6.1 Reviews of the Economic Value of Coastal and Marine Ecosystems in the Caribbean

Several comprehensive literature reviews of economic valuation efforts for ecosystem goods and services in the Caribbean are available. These include Schuhmann and Mahon (2014), Heck et al. (2019) and IDB (2021). These reviews note several common findings and point to critical gaps in the valuation literature. For example, coastal and marine resource valuation studies in the Caribbean tend to focus on more obvious and measurable benefits, such as those associated with recreation and tourism, coastal protection, and fisheries. Perhaps not surprisingly, these categories of ecosystem services are also found to generate the most economic value. Tourism values are commonly found to far exceed other ecosystem service values. A notable and recently discovered exception here is the value of carbon sequestration services provided by mangrove ecosystems. These values appear to be similar to recreation values in some locations, according to Heck et al. (2019), one of the only studies to attempt valuation of this ecosystem service. Another related common finding is that, apart from coastal protection values, regulating and supportive ecosystem services are infrequently the subject of valuation efforts. Provisioning services related to benefits from genetic/pharmaceutical applications contained in coastal and marine ecosystems are also very limited. To the extent that these ecosystem services are affected by sargassum events, these appear to be important avenues for future research.

6.2 Regional and National Comprehensive Assessments of Economic Value

Comprehensive assessments of economic values provided by coastal and marine ecosystems in specific countries in the region include the *Coastal Capital* series produced by the World Resources Institute for the Dominican Republic, Belize, Jamaica, St. Lucia and Trinidad & Tobago (Wielgus et al., 2010, Cooper, et al., 2009, Kushner et al., 2011 and Waite et al., 2011; Burke et al., 2008a and Burke et al., 2008b, respectively), and Heck et al. (2019) who use results from the literature to estimate the ecosystem service values provided by coral reefs and mangroves in Jamaica, Grenada and the Dominican Republic. These studies illustrate that coastal and marine ecosystems in these nations provide significant economic value.

For example, visitor spending on accommodation, reef recreation, and miscellaneous expenditures in Tobago and St. Lucia in 2006 was found to create US$ 43.5 million in economic impacts (direct effects) for Tobago and US$ 91.6 million for St. Lucia, roughly 15% and 11% of GDP in the two countries, respectively (Burke et al., 2008a). This spending creates an additional US$ 58–86 million and US$ 68–102 million in indirect economic impacts. The authors also find that shoreline protection services provided by coral reefs in 2007 (avoided damage to coastal infrastructure) is estimated to be between US$ 18 and 33 million per year for Tobago and US$ 28 to 50 million for St. Lucia (Burke et al., 2008a). By contrast, coral reef associated fisheries create total (direct and indirect) economic impacts of US$ 0.8 – 1.1 million per year in Tobago and US$ 0.5 – 0.8 million per year in St. Lucia. The authors note that these fisheries also provide other important contributions to economic value, including employment, cultural values, and a social safety net.

Kushner et al. (2011) estimate the economic value of Jamaica's coral reefs in terms of their contribution to wave attenuation and beach erosion. The authors find that at current rates of beach erosion, annual losses in economic value will total US$19 million over 10 years at the three major beach destinations in the country (Negril, Montego Bay, and Ocho Rios), and that if beaches erode faster due to coral reef degradation, total economic losses will total US$ 32.7 million per year. Waite et al. (2011) find that gross

revenues from reef-related fisheries averaged less than 0.3 percent of Jamaica's GDP, mostly attributable to domestic sales rather than exports.

Heck et al. (2019) review ecosystem service valuation studies pertaining to coral reefs and mangroves across the Caribbean, and find that ecosystems in the Caribbean create an estimated annual economic value of approximately US$ 15 billion, with tourism and recreation and carbon sequestration providing the vast majority of values.[9] Heck et al. (2019) find that coral reefs provide approximately $6.2 billion in ecosystem services, mostly from tourism and recreation, while mangroves provide approximately $6.7 billion in benefits, mostly from carbon sequestration. The Heck et al. (2019) study shows that ecosystem service values are location specific. For example, recreational fisheries values are found to provide vastly more economic value than commercial fishery values in the Dominican Republic (approximately $81.4 million and $0.75 million respectively) whereas the opposite is true in Grenada, where commercial and recreational fisheries produce $22.7 million and $15.7 million in economic value respectively.

A recent study by the Inter-American Development Bank (IDB, 2021) provides a comprehensive summary of market-based (use) values associated with the Mesoamerican reef system and provides further evidence that ecosystem service values vary widely across locations. The total use value of the reef-related tourist sectors in Belize, Honduras, Guatemala, and Mexico are found to be US$ 546.8 million, 182.6 million, 6.3 million, and 15,440.4 million respectively, while the total use value of the reef-related fishing sector in these four countries is estimated to be US$ 19.6 million, 99.5 million, 42.2 million, and 21.9 million, including indirect impacts. The benefits transfer method was used to estimate the total use value of shoreline protection services which are found to range from US$ 9.0 to 12.25 million in Belize, from 7.90 to 10.76 million in Honduras, from 1.94 to 3.99 million in Guatemala and from 301 to 411 million in Quintana Roo, Mexico.

6.3 Per Hectare Value Estimates

Costanza *et al.* (2014) use the benefits transfer method applied to local case studies from around the world (from the Ecosystem Service Valuation Database)[10] to estimate the value of 17 ecosystem services for 16 biomes and an aggregate global value in 2007 'International dollars' per hectare per year.[11] These values represent "updated" estimates from earlier work by Costanza *et al.* (1997). This report suggests average unit values for coral reef, for mangrove and seagrass ecosystem services of 2007Int.$ 352,249, $ 193,843 and $ 28,916/ha/year. It is important to note a high degree of variation in values per hectare for coral reefs is reported in Costanza *et al.* (2014), which range from a low of value of approximately Int.$ 37,000/ha/yr to over $2 million /ha/yr.

Spalding et al. (2018) couple analysis of more than 80,000 social media images and texts with national visitation data to create spatial maps of tourist activities around reefs and estimate the economic value

[9] The authors note that many ecosystem service values for these ecosystems have not been measured. It seems likely that this dearth of value estimates contributes to the lower estimated values derived from other ecosystem services such as most supportive and regulating ecosystem services.

[10] The Ecosystem Services Valuation Database (ESVD) is a free online repository of valuation studies, whose focus is "to gather information on economic welfare values related to ecosystem services measured in monetary units".

[11] International dollars are theoretical units of currency standardized to have the same purchasing power as a US dollar using purchasing power parity exchange rates. International Dollars can be considered equivalent to US dollars in terms of exchange value.

of “reef-adjacent” tourism in the insular Caribbean. Results of this study suggest that reef-adjacent expenditures sum to approximately US$5.7 billion annually, with total expenditure related to all reef-associated tourism (on-reef and reef-adjacent) over US$7.9 billion. Over 11 million visitors are found to be attracted to the region for reef-associated tourism. Average annual values associated with 660 visitors per square kilometer of reef are estimated to be US$ 473,000. Three nations with especially high valued reefs are Barbados, Puerto Rico and the US Virgin Islands where average expenditures sum to over US$ 3 million per square kilometer of reef per year.

A review by Brander et al. (2006) shows that the world average value of coral reef recreation is US $ 184.00 per visit, with considerable variation across location, method and goods and services. Coral reef recreation in the Caribbean has the highest mean value of all areas analyzed, roughly US$400.00 per visit. Of all recreational activities analyzed, diving and snorkeling produce the highest values, typically over US$ 200 per visit depending on location.

To provide additional insight into the potential economic losses from damage to coastal and marine ecosystems from sargassum events, we extract data from the Ecosystem Services Valuation Database (ESVD) for coral reefs, mangroves, seagrasses and beaches for countries in the Wider Caribbean Region.[12] Table 4 below presents the mean, standard deviation, median, minimum, and maximum value per hectare per year for coral reefs, mangroves and seagrasses respectively, as well as the number of valuation studies found within the ESVD for each ecosystem service, per ecosystem type. Missing values indicate that no studies or corresponding values were found for that ecosystem service.

The number of studies reported in the ESVD confirm findings from Schuhmann and Mahon (2014), Heck et al. (2019) and IDB (2021) that provisioning services (principally food production from fisheries) and cultural services (principally opportunities for recreation and tourism) are the most widely studied ecosystem services, along with regulating services associated with moderation of extreme events. Values from the ESVD also suggest that these services tend to provide the highest values per hectare, with reefs in the Caribbean providing an average value of US$2,400.00 per hectare for recreation and US$1,900.00 for moderation of extreme events and roughly US$740.00 for food production, values that are slightly lower than those derived by Spalding et al. (2018). Mangroves in the region provide average values of approximately $34,000.00 per hectare for recreation, $128,000.00 for food production and $3,600.00 for moderation of extreme events. This latter value is clearly a gross underestimate, as mangroves are known to provide valuable buffers against damage from storms (Hochard et al., 2021; Granek and Ruttenberg, 2007). Barbier (2016) provides a review of the nascent valuation literature regarding the storm protection service of mangroves and finds significantly larger values than those reported in Table 4.

[12] For our purposes, the Wider Caribbean Region is defined according to the United Nations Environmental Programme (UNEP) as “the 28 UN Member States that border the Gulf of Mexico, the Straits of Florida and the Caribbean Sea out to a distance of 200 nautical miles from shore” (UNEP 2021).

Table 4: Descriptive Statistics for Ecosystem Service Values for Coral Reefs, Mangroves, Seagrasses and Beaches for Countries in the Wider Caribbean Region. Values are expressed in International Dollars per hectare per year.

Ecosystem	Ecosystem Service	Number of valuations	Mean	Standard Deviation	Min	Max
Coral Reefs	Aesthetics					
	Climate regulation					
	Erosion prevention	2	$1908.00	$522.00	$1538.00	$2277.00
	Existence values	4	$167.00	$335.00	$0.04	$669.00
	Food	12	$738.00	$968.00	$8.07	$3212.00
	Information for cognitive development	1	$134.00	$0.00	$134.00	$134.00
	Maintenance of genetic diversity					
	Maintenance of life cycles					
	Moderation of extreme events	4	$1930.00	$1320.00	$883.00	$3747.00
	Opportunities for recreation and tourism	38	$2430.00	$4680.00	$0.01	$20377.00
	Raw materials					
	Waste treatment					
Mangroves	Aesthetics	5	$162.72	$165.43	$0.08	$333.94
	Climate regulation	13	$1226.17	$3789.05	$2.45	$13246.00
	Erosion prevention	3	$832308.56	$1437849.41	$5.18	$2492592.17
	Existence values	7	$167220.06	$341417.65	$2007.39	$938813.79
	Food	80	$128420.54	$731902.91	$-1.97	$4642836.59
	Information for cognitive development	5	$66.70	$93.99	$0.03	$199.18

	Maintenance of genetic diversity	1	$40937.54	$0.00	$40937.54	$40937.54
	Maintenance of life cycles	5	$6481.36	$4518.84	$0.14	$10802.22
	Moderation of extreme events	8	$3591.05	$3992.46	$0.39	$9253.06
	Opportunities for recreation and tourism	36	$33948.54	$122059.93	$0.40	$690830.57
	Raw materials	12	$49521.43	$116597.64	$0.60	$389621.56
	Waste treatment	11	$1678.81	$1960.80	$5.92	$5108.03
Seagrasses	Aesthetics					
	Climate regulation	4	$35.48	$65.57	$2.45	$133.83
	Erosion prevention					
	Existence values	1	$802.95	$0.00	$802.95	$802.95
	Food	4	$131.68	$182.14	$13.13	$401.48
	Information for cognitive development					
	Maintenance of genetic diversity					
	Maintenance of life cycles	4	$8101.67	$3118.33	$5401.11	$10802.22
	Moderation of extreme events	5	$8791.18	$4739.97	$4628.43	$16192.91
	Opportunities for recreation and tourism	25	$1408.00	$2010.56	$0.96	$6691.29
	Raw materials					
	Waste treatment	5	$3104.21	$1892.68	$1278.91	$5108.03
Beaches	Aesthetics	3	$2.43	$1.08	$1.23	$3.33
	Opportunities for recreation and tourism	11	$28.84	$9.48	$18.40	$37.01

6.4 DIRECTED VALUATION EFFORTS

In addition to information contained in comprehensive assessments of the economic value derived from coastal and marine ecosystems in the region, important insights can also be gained by examining valuation case studies that address changes pertinent to sargassum events, including the value of beach access, beach cleanliness, seawater quality, and changes in the quality of coral reefs, mangroves, and seagrasses. As noted in Vegh et al. (2018), directed valuation studies that focus on incremental changes to ecosystems in smaller geographic areas produce more credible value estimates than global or regional valuation estimates. It is also important to note that many of the directed valuation efforts related to coastal and marine quality estimate WTP for quality improvements. Sargassum is expected to decrease the quantity and quality of coastal and marine resources, and as such value estimates for improvements may not be directly applicable. As demonstrated by Schuhmann et al. (2019), WTP estimates for quality improvements are often lower than WTP to avoid similar losses. Hence, estimates of WTP for gains in coastal and marine quality are likely to underestimate welfare losses from resource degradation.

6.4.1 Economic value of beach cleanliness and beach characteristics

One of the most obvious consequences of sargassum events in the Caribbean is the effect on the visual appeal of the region's beaches. A wide variety of valuation studies have examined the impact of visual disamenities on visitors' willingness to pay for coastal recreation and tourism. For example, Loomis and Santiago (2013) applied estimate beach users' WTP to pay for improvements in water clarity and beach cleanliness in northeast Puerto Rico. The absence of trash was among the most important attributes to beachgoers. The authors estimated that respondents were willing to pay an average of US$54 and US$51 for improvements to water clarity and approximately US$100 for beach cleanliness.

Beharry-Borg and Scarpa (2010) estimate tourists' and locals' willingness to pay beach entry fees for a range of attributes related to coastal and marine quality, including the number of pieces of plastic litter encountered per 30 meters of beach length. Results suggest that willingness to pay to reduce beach litter ranged from $2.32 to $7.72. Schuhmann et al. (2015) examine tourists' willingness to pay lodging prices for a range of coastal attributes including litter on the beach, beach width, and proximity to the beach. Results suggest that beach cleanliness and proximity were the most important attributes examined, with respondents willing to pay up to US$ 300.00 per night for lodging near beaches that are free of litter. Importantly, the amount that visitors would have to be compensated to accept a high level of the litter disamenity exceeds the typical price paid for lodging, meaning that when a high amount of litter is present on beaches many visitors will choose alternative destinations.

While the results of WTP studies related to avoiding litter on beaches are not directly applicable to WTP to avoid sargassum on beaches, results of these studies present a clear and relevant conclusion: tourists and locals have strong preferences for clean beaches and are willing to pay to avoid beaches that are relatively free of visual disamenity.

6.4.2 Economic value of seawater quality

In addition to affecting the cleanliness of beaches, sargassum is expected to affect the cleanliness and visibility of nearshore water, another attribute that is known to attract visitors to Caribbean coastlines. Sargassum inundation events often result in a 'brown tide' or extensive plume of discolored seawater, both due to the floating yellow-brown biomass on the water surface and from leachates and particulate organic matter as the seaweed begins to decay. This results in significantly reduced water clarity and loss of the iconic turquoise color. Results from studies estimating willingness to pay for clear/clean seawater

(or WTP to avoid unclear/unclean water) can therefore provide insight into the potential economic value of sargassum influxes.

Several studies have illustrated the economic importance of seawater quality in terms of economic returns to coastal recreation and tourism. Importantly, numerous studies that examine multiple coastal and marine attributes including seawater quality find that seawater quality is the most important attribute examined. For example, in Peng ang Oleson (2017) estimate willingness to pay by beach users in Hawaii for improvements to seawater quality, and other environmental attributes in the coastal zone. Average WTP for reduced days of bacterial exceedance was estimated at $11.43 per beach day, and a further $30.72 to ensure no instances of bacterial exceedance. For underwater visibility to improve from 15 feet to 30 feet, the WTP was estimated to be $35.71 per day, with respondents willing to pay an additional $14.80 to improve visibility from 30 feet to 60 feet. Similarly, average WTP for improvements in coral reef cover from 10% to 25% was $15.33 per day, with an additional $4.89 to improve reef cover to 45%.

In a similar study in Hawaii, Penn et al. (2016) find that water quality is the most important beach attribute among residents and tourists. Tourists were willing to pay more to avoid instances of poor water quality than residents (US$78 and US$26 per day respectively). Importantly, WTP to avoid poor beach conditions was greater than that to pay for beach quality improvements. Pakalniete et al. (2017) estimate Latvian citizens' WTP for improving seawater quality for recreation, avoiding reductions in marine biodiversity and limiting new occurrences of invasive alien species in coastal and marine waters of the Baltic Sea. Of these attributes, they find that WTP is highest for better seawater quality.

Kosenius (2010) estimates the public's WTP higher taxes for nutrient-reduction scenarios that would improve the water quality in the Gulf of Finland, in the Baltic Sea. Water quality is described in terms of water clarity (visibility), abundance of non-attractive fish, status of bladder wrack (brown macroalgae), and the duration of cyanobacteria blooms. Results suggest that respondents considered clear water to be the most important attribute followed by scarce occurrences of blue–green algae blooms, results that are clearly relevant for understanding the impacts of sargassum on seawater quality.

In terms of economic impacts of seawater quality in the Caribbean, Schuhmann et al. (2017) estimate visitor preferences and willingness to pay higher trip costs for changes in four coastal and marine attributes in Barbados: beach width, water quality, diving/snorkeling quality and storm risk, where water quality was defined in terms of the probability of getting a stomach infection from bathing or swimming in seawater. Results suggest that water quality was the most important attribute examined, with visitors willing to pay more than US$2,000 more per trip for the cleanest level of seawater quality and requiring more than US$3,000 in compensation to accept the lowest level of seawater quality on their trip.

Using the same data as Schuhmann (2017), Schuhmann et al. (2019) estimate the potential impact of changes in beach width, coral reef health, the quality of marine life and seawater quality on visitors' willingness to return to Barbados. Of the attributes examined, sea-water quality was found to have the highest impact on return visitation. The smallest change in seawater quality (increasing the probability of an infection by 5 percent) is found to produce a larger impact on the stated probability of return visitation than the highest levels of losses in beach width, coral health, and marine life (50 percent losses).

Again, while these results provide important insights into how sargassum-related changes to seawater quality might affect economic returns from recreation and tourism, an important caveat is in order. Much of the research examining the economic importance of seawater quality defines quality in terms of risk to

human health due to marine pollution (e.g., stomach or skin infections), impacts that may not be directly applicable to changes in seawater quality associated with sargassum. We note that studies that examine seawater quality in terms of visibility/clarity show similar results but are less common in the literature.

6.4.3 Economic value of beach access

Sargassum events are also expected to affect access to coastal areas, hence valuation studies that examine WTP for beach access (or WTA compensation for reduced access) can be useful for understanding the potential impacts of sargassum. Dixon et al. (2012) estimate coastal residents' and tourists' willingness to pay parking fees for improved access to public beaches in South Carolina, finding that both groups are willing to pay for improved public beach access. Tourists are willing to pay more than coastal residents to secure this amenity (US$6.33 vs. US$2.46 per day respectively).

Bin et al. (2005) estimate the economic value of beach recreation in at seven beaches in North Carolina. Value estimates range from $11.00 to $80.00 per beach day for day trips and between $11.00 and $41.00 for overnight trips. The authors find significant variation in value estimates across sites, noting that unique site characteristics and the perception of exclusivity may influence the recreational value of beaches.

The literature regarding the economic value of beach access highlights the importance of site substitution – an issue that is highly relevant for analysis of impacts of sargassum influxes and the Caribbean beach tourism product. For example, Han et al. (2015) find that if a destination or recreational site is unfavorable based on tourist motivations, some tourists will substitute for another comparable site. Variables such as beach cleanliness, level of attachment to the destination, and availability of nearby substitute sites are found to influence tourists' site choices. Applications pertaining to site substitution and sargassum in the region include Casas-Beltrán et al. (2020), who found that 59% of residents and 47% of tourists in Riviera Playa in Mexico reported spending less time at the beach because of sargassum influxes, and depending on the duration of their stay, were likely to engage in alternative tourist activities most notably swimming in open cenotes (or sinkholes).

6.4.4 Economic value of (losses in) coral reef quality

Losses in coral reef quality due to sargassum events are expected to create adverse economic impacts related to lost recreation opportunities, biodiversity, habitat, fisheries production, and shoreline protection services. Numerous valuation studies have attempted to monetize these values in the Caribbean region by estimating WTP for the associated goods and services. As noted in Schuhmann and Mahon (2015) most of these studies focus on effects that are relatively easy to observe and measure, such as those related to reef-based recreation, especially recreation in marine protected areas, shoreline protection services and fisheries.

Scuba divers' willingness to pay for coral quality improvements in Barbados estimated by Schuhmann et al. (2013) range from approximately US$53 to US$122 per two-tank dive, depending on the baseline level of quality. Results from Schuhmann et al. (2013) also suggest that divers' willingness to pay to avoid losses in coral cover depends on the nature of those losses. For example, divers' willingness to pay to avoid losses in coral cover from 35 percent coral cover to 25 percent is approximately US $27 per dive, willingness to pay to avoid losses from 25 percent coral cover to 15 percent is approximately US $42 per dive and willingness to pay to avoid to losses from 15 percent coral cover to 5 percent is approximately US $53 per dive. These results suggest that the value losses from declines in reef quality will depend not only on the magnitude of loss, but also the pre-impact baseline level of quality. The values presented in

Schuhmann et al. (2013) are notably similar to those found by Parsons and Thur (2008) who valued changes in coral cover in Bonaire National Marine Park.

As an example of potential economic losses from sargassum to scuba diving, assuming that roughly 50,000 tourists visit Barbados per month, that three percent of stay-over tourists engage in Scuba diving (Schuhmann et al., 2017) and each diver participates in one two-tank dive per trip, losses to tourist divers from coral reef degradation could range from approximately US $40,000 to US $80,000 per month, assuming no other changes to the quality of dives (e.g., encounters with marine species, visibility).[13]

Beharry-Borg and Scarpa (2010) estimate WTP for coastal and marine attributes by snorkelers and non-snorkelers in Tobago, finding that snorkelers are willing to pay up to $50.00 for high coral cover (45 percent). A high degree of heterogeneity in preferences and WTP is discovered across and between groups.

Recreational and cultural values to Bermudian households associated with reefs are also estimated by van Beukering et al. (2009). Households are found to have an average WTP of US$42 per month for minimizing marine pollution (the ability to swim anytime and anywhere) and US$32 per month per household for maintaining coral reef quality (i.e., coral and fish diversity). Average WTP for water clarity (maintained by a healthy coral reef system) was US$27 per month.

van Beukering et al. (2009) also estimate the value of reef-associated tourism in Bermuda. The authors report that 68 percent of all tourists are willing to pay additional funds to support activities that preserve Bermuda's coral reefs. The average cruise ship tourist is willing to pay US$28 per visit to Bermuda and the average airplane tourist is willing to pay US$19. This study highlights the idea that economic losses from coral reef degradation are likely to extend beyond tourism and beyond direct users of reefs. The economic value of coral reefs associated with reduced shoreline protection services are estimated in numerous directed valuation studies, including research efforts in the Caribbean. For example, van Zanten et al. (2014) estimate the relative wave energy dissipation for four types of coral reef in the US Virgin Islands. Coupled with flood risk maps and estimates of land values, the authors infer the coastal protection value of coral reefs from a 100-year probability event as the avoided losses in land values. Results suggest that the annual short-term coastal protection value of coral reefs in the US Virgin Islands is US $1.23 million, with combined short-term and long-term effects valued at US$ 8.87 million per year. An important takeaway from this study and others (e.g., Pascal et al., 2016; Rao et al., 2015) is the recognition that the coastal protection value of coral reefs is spatially dependent, varying according to reef size and type and the degree of coastal development in the area.

WRI's Coastal Capital series (Burke, et al., 2008a, Burke, et al., 2008b, Cooper, et al., 2008, Wielgus et al., 2010, Waite, et al., 2011, Kushner, et al., 2011) includes values of coral reefs associated with shoreline protection in St. Lucia, Trinidad and Tobago, Jamaica and Belize and the Dominican Republic, estimated by calculating the value of coastal real estate that is both vulnerable to damage and protected by reefs,

[13] These are conservative estimates of potential losses in consumer surplus to divers from reef degradation for several reasons. First, it is likely that many divers engage in more than one two-tank dive per visit to Barbados. Further, these values represent losses from changes in coral cover only, and do not include ancillary losses to reef fish diversity, water quality and visibility or encounters with marine species, most of which are expected to be impacted by sargassum influxes. We also exclude dives by locals.

multiplied by the probability of a 25-year storm event. Coral reefs in Belize provide an estimated US$120–$180 million in avoided damages per year.

The approach by Kushner et al. (2011) to estimate the value of changes in beach width in Jamaica is to first model the contribution of reef degradation to wave height via the loss of rugosity-induced friction, and subsequently predict the change in beach erosion that would result. Average per visitor loss in consumer welfare due to beach erosion attributable to coral degradation is estimated to be US$26.10 per vacation. The total loss of consumer surplus from current rates of reef degradation is estimated to be more than US$19 million over 10 years, and up to US$33 million if erosion rates increase due to further reef degradation.

6.4.5 Economic value of "blue carbon ecosystems": mangroves, coastal wetlands, and seagrasses

Relative to research on the economic value of coral reefs, there are far fewer directed valuation studies that estimate the economic value of ecosystem services from mangroves, seagrasses, and coastal wetlands in the region. In a review and meta-analysis of ecosystem service values provided by mangroves, Brander et al. (2012) report eight studies from the Caribbean, six of which focus only on the value of provisioning services (fish and/or wood production values), while two provide estimates of regulating services (coastal protection values in Belize are estimated by Cooper, et al., 2009 and in El Salvador by Milon and Scrogin, 2006) and only one (Milon and Scrogin, 2006) provides estimates of water quality benefits. Brander et al. (2012) note that so few studies have attempted to estimate the carbon sequestration benefits of mangroves that they could not be included in their analysis.

Despite the relative lack of direct value estimates for mangrove ecosystem goods and services in the Caribbean, several important insights emerge from valuation studies conducted in other areas. For example, Brander et al. (2012) find the value of mangroves per hectare is lower in larger mangroves than in smaller mangroves (i.e., relative scarcity is positively associated with value), but that the abundance of other mangroves in the vicinity contributes to productivity and has a positive effect on wetland value. As is the case with other ecosystem values, mangrove ecosystem service values are positively associated with population size and GDP per capita.

Vegh et al. (2018) provide a review of ecosystem services and associated value estimates for mangroves, seagrasses and coastal marshes. They report that regulating services provided by mangroves and marshes such as coastal protection and erosion mitigation provide significantly higher economic value (up to US$ 10,800 and US$ 3,700 per hectare per year respectively) compared to other ecosystem services such as fisheries production and provision of raw materials (roughly US$ 1,000 and US$ 600 per hectare per year).

6.5 GAPS IN THE VALUATION LITERATURE

Despite the depth and breadth of the valuation literature for tropical coastal and marine ecosystem services, several notable gaps emerge. For example, value estimates for several ecosystem services (including many that may be impacted by sargassum) have not been thoroughly explored or are entirely absent from the literature, including provisioning services such as medicinal or bioprospecting values associated with coral reefs, many regulating and supporting services provided by reefs and mangroves, such as contributions to climate regulation and fisheries production, and non-use values for all coastal and marine ecosystems. Dewsbury et al. (2016) note the general dearth of value estimates for seagrass ecosystems, likely attributable to limited public awareness of the ecosystem service benefits that these

ecosystems provide. Dewsbury et al. (2016) suggest that carbon sequestration values and the value of seagrass contributions to the health of nearby coral reefs are especially lacking.

While the coastal and marine valuation literature generally suggests that many of these values are considerably lower than those associated with recreation and tourism and coastal protection, more recent research from terrestrial applications suggests that further investigation is warranted. For example, Heck et al. (2019) find carbon sequestration values of mangroves in the Caribbean are significantly larger than the value of other ecosystem services.

Regarding non-use values, our review of the ESV database confirms that estimates of existence, option and bequest values for coastal and marine ecosystems are scarce in the Caribbean. A notable exception is Hargreaves-Allen (2009) who estimates the economic value of Gladden Spit and Silk Cayes Marine Reserve in Belize, finding that the net present value of the Reserve over the next 25 years ranges from US$ 41 to 93 million, of which roughly 68 percent is attributable to non-use values. Research in Pacific locations (e.g., Robinson et al., 2022; Marre et al., 2015; Subade and Francisco, 2014) also suggests that non-use values for coral reefs are significant. Robinson et al. (2022) find that residents of Hawaii and mainland U.S. experience large welfare losses from reductions in coral cover and fish numbers caused by climate change, while Marre et al. (2015) find that non-use values comprise between 25 and 40 percent of mean willingness to pay for reef conservation in New Caledonia. Subade and Francisco (2014) find that the main motives for WTP for coral reef conservation by non-coastal residents in the Philippines were non-use values.

Results from the terrestrial recreation valuation literature suggest that non-use values are at least as large as and often larger than use values. For example, Walsh et al. (1984) find that non-use preservation values (existence, option and bequest) are roughly equivalent to recreational use values for the (1980) status quo levels of wilderness protection in Colorado, and that non-use values exceed use values for all levels of increased wilderness protection.[14] Walsh et al. (1990) estimated the economic value of protecting forest quality at 11 National Forests in Colorado, finding that option, existence and bequest values accounted for 72.6% of the total economic value of these forests. Kramer et al. (2003) estimate the economic value of protecting the high-elevation spruce-fir forest ecosystem in the southern Appalachian Mountains and find that existence and bequest values comprised up to 57 and 30 percent of total value respectively. Haefele et al. (2016) provide a conservative value estimate of $62 billion for U.S. National Parks and suggest that up to $33.5 billion (54 percent) is associated with purely passive or non-use values.

These findings, which are consistent over four decades, suggest that welfare losses from damage to coastal and marine ecosystems induced by sargassum events may be much larger than (perhaps more than double) the economic losses associated with diminished use values. Because non-use values tend to be higher for those who have direct experience with the ecosystem in question, it seems logical that the extent of non-use value losses from sargassum events may extend to a significant portion of tourists who have visited affected Caribbean locations in the past. Failure to include non-use value losses in estimates of the economic damage to coastal and marine ecosystems is therefore likely to produce significant underestimates of the true economic implications sargassum events.

[14] An additional notable result of this study is that non-use values increased with recreational use. That is, familiarity and experience with a resource is associated with higher non-use values. The more people experience nature, the more they are willing to pay to preserve it, even if their own future use is in question.

6.6 COMMON FINDINGS AND IMPLICATIONS FOR ESTIMATING ECONOMIC LOSSES FROM SARGASSUM EVENTS

Across this wide and diverse body of literature, several commonalities emerge that point to important considerations for understanding and estimating the scope of economic losses from sargassum inundations in the Caribbean. These include the importance of targeting valuation studies toward understanding the loss in economic surplus from reduced quality or access, insights into the relative magnitudes of different ecosystem service values, and factors that are expected to create geographic variability in value estimates.

6.6.1 WTP for improvements in quantity, quality or access will underestimate welfare effects of losses or damages

First, willingness to pay for losses in the quantity or quality of coastal and marine ecosystem services are commonly found to exceed WTP for similar gains. According to Schuhmann et al. (2019) this may be due to an endowment effect (people tend to place higher value on things that they own or possess) or the related concept of loss aversion (the pain or discomfort from losing something exceeds the pleasure or comfort from an equivalent gain). Regardless of the reason, this finding suggests that using estimates of WTP for ecosystem quality improvements (which are more common in the valuation literature) will likely underestimate the value of similar losses. Caution should therefore be exercised when designing new valuation studies to estimate the economic losses associated with sargassum or if the benefits transfer method is used in combination with estimates of economic surplus or WTP derived in the context of quality improvements. Valuation studies directed at estimating the economic consequences of sargassum events in particular locations should focus on estimating WTP to avoid losses in quantity, quality and/or access to coastal and marine resources or willingness to accept (WTA) to be compensated for such losses.

6.6.2 Market prices and quantities will underestimate losses in economic surplus from impacts on recreation and tourism

Numerous studies in the peer-reviewed literature find that WTP for fee-based recreation in coastal and marine areas (e.g., scuba diving, snorkeling) is far higher than actual (market) prices paid. As economic value is best measured in terms of economic surplus, this finding suggests that using market prices and quantities will underestimate the economic losses from reduced availability or quality of recreational experiences.

6.6.3 Coastal and marine recreation and shoreline protection service values outweigh other ES values

Across numerous studies, the value of coastal and marine recreation and tourism is found to outweigh other ecosystem service values, with possible exceptions of the shoreline protection service afforded by reefs and the carbon sequestration service provided by mangroves. This finding suggests that priority research areas for understanding the potential economic costs of coral reef degradation are recreation and tourism and shoreline protection, and carbon sequestration and shoreline protection for mangroves.

6.6.4 Visual amenities are among the highest valued attributes of beach recreation

Across numerous studies estimating the economic value of beach recreation access and quality, visual amenities such as beach cleanliness and water clarity are consistently found to be the most valuable attribute. Coupled with numerous studies indicating significant value associated with seawater quality, suggests sargassum events that result in biomass on beaches and in coastal waters will have significant impacts on the economic surplus derived from coastal and marine recreation.

6.6.5 Understanding site substitution is critical to understand economic losses to recreation and tourism

Across numerous studies of beach recreation, the availability of proximate sites of similar quality is found to be inversely associated with losses in economic surplus due to diminished quality or access. At the local scale, this suggests that economic losses from sargassum events will be higher in areas where recreationists cannot easily substitute toward unaffected coastal areas or inland recreation. Likewise, impacts are expected to be higher for destinations where sargassum impacts are more widespread and for those that have relatively few opportunities for recreation outside of the coastal zone.

6.6.6 ES values vary widely by location, ecosystem scale, and socioeconomic conditions

Ecosystem services value estimates differ widely across locations, with variation attributable to ecosystem size and quality, the presence of adjacent ecosystems, the degree of coastal development, dependence on tourism, the availability of substitute sites or ecosystems and socioeconomic factors such as per capita GDP. Coastal protection service values from coral reefs and mangroves are commonly found to be positively associated with the level of shoreline development, population density, per capita GDP, and tourism activity (factors that are obviously correlated). Generally, the implication of this finding is another caution against using the benefits transfer valuation method - applying value estimates from a "study site" to another site is unlikely to produce reliable and policy-relevant value estimates. Deriving estimates of the impacts of sargassum on economic surplus that are accurate enough to inform policy will require directed valuation studies. An exception may be the value of (WTP for) coral reef quality to scuba divers, which appears quite similar across several studies in the region.

7 SUMMARY AND NEXT STEPS

This report has presented a comprehensive overview of several branches of literature related to measuring the scope and magnitude of economic losses from sargassum events in the Caribbean. Our goal is to assemble insights from this review to formulate a framework and research agenda designed to measure sargassum-induced economic losses. Understanding the scope and magnitude of economic losses from sargassum events can assist policy makers in designing appropriate and efficient policy responses.

Our review of economic value and economic impacts highlights the notion that value is best measured by economic surplus. Neither costs nor revenues alone are an accurate measure of economic value. Understanding the change in economic value associated with sargassum events that harm or degrade ecosystem services therefore requires estimating the loss in economic surplus and economic impacts that result from those events. As is the case with any assessment of change, an essential prerequisite to estimating lost economic value from sargassum events is the establishment (measurement) of baseline levels of economic activity against which to measure economic losses. Our review highlights the importance of accounting for seasonal and annual variations when establishing these baselines.

Another important takeaway is that economic value can include economic surplus derived in the absence of any direct use or interaction with the natural environment. This is clearly the case for economic value losses from sargassum events – non-market and non-use values are expected to comprise a significant portion of total economic impacts. Baseline assessments of non-market activities coupled with applications of non-market valuation methods are therefore necessary for proper measurement of value

losses. Importantly, valuation efforts should include assessments of non-use values, which are commonly found to be at least as large as use values.

Our review also points to the importance of measuring resource substitution and establishing geographical and temporal boundaries for defining impacts. Suppliers' ability to substitute toward other sources of income or employment during sargassum events and consumers' and tourists' willingness to substitute toward other markets, destinations or sources of economic surplus will decrease the magnitude and duration of economic losses caused by sargassum. Hence, in addition to estimating lost use and non-use values through directed valuation studies, these substitution possibilities should be measured and used to infer the magnitude of changes in economic activity in substitute, complementary and proximate markets. Defining the spatial scale of sargassum impacts (i.e., the physical area in which value losses will be estimated) and measuring the spatial scale of substitution will be critical components of the assessment.

Our review of the economic valuation literature associated with coastal and marine ecosystems suggests that residents and tourists are willing to pay for beach width, access, and cleanliness, and numerous aspects of coral reef quality including coral cover, biodiversity and encounters with sea turtles. Mangroves and seagrasses also provide numerous valuable ecosystem services, but values are less associated with direct use by people than beaches and reefs. Our review suggests that the primary sources of economic value from beaches, seawater and coral reefs are associated with recreation, tourism, and coastal defense. The primary sources of economic value from mangroves are associated with coastal defense and carbon sequestration. The main sources of value from seagrasses appear to be associated with fisheries production, though it should be recognized that seagrass valuations are relatively scarce in the literature.

Understanding the value of degradations to these ecosystem services is therefore paramount for estimating the economic losses from sargassum events. However, our review makes clear that value losses will be highly sensitive to location, due to spatial heterogeneity in both sargassum impacts and ecosystem service values. Our review suggests that the magnitude of sargassum impacts will vary spatially according to physical features and position of affected coastlines, nearshore coastal dynamics, and the proximity of vulnerable ecosystems, resources, and economic activities. Per-unit values for ecosystem goods and services tend to be positively correlated with per capita GDP, population density and the level of coastal development.

In part 2 of this report, we create a series of sargassum event scenarios and approximate the potential range of economic losses at five locations in the Lesser Antilles using results from our review of the literature and exposure mapping. These scenarios are composed of hypothesized events impacting specific locations and described in terms of magnitude, timing, and duration of sargassum influx. Part 2 also provides a series of recommendations for data collection and directed valuation efforts to estimate the economic losses from sargassum events more accurately.

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