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Conservation status, research, and knowledge of seagrass habitats in World Heritage properties

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Abstract

Climate change is increasingly threatening World Heritage (WH) properties and their Outstanding Universal Value (OUV). Climate change impacts the attributes that collectively contribute to the OUV; these attributes can be natural (e.g., seagrass) or cultural (e.g., monuments). A recent UNESCO report showed that seagrass habitats within WH properties are estimated to hold 25% of the global seagrass blue carbon asset. Globally, seagrass habitats provide a wide range of benefits to adjacent ecosystems and coastal human communities, yet they have been declining due to direct anthropogenic and climate change stressors. However, the UNESCO report did not provide any information about the relative importance of the attribute "seagrass habitats" toward the OUV and associated communities of WH properties, nor about their conservation status. This study builds upon this previous work by assessing the relative importance of seagrass habitats toward the values of WH properties and by reviewing the current knowledge about the conservation status, threats, monitoring, and management of seagrass habitats within WH properties. Seagrass was identified as an attribute of Very High or High importance to 9 of 28 WH properties. Through analysis of UNESCO documents and scientific literature, we highlight the lack of research, monitoring, and management instruments addressing the protection of seagrass from climate change impacts within these 28 WH properties. Notably, climate change threats to WH seagrass habitats are poorly addressed within WH documentation. The insufficient analysis and reporting of climate impacts on seagrass within WH properties point to an underestimation of the value of this marine ecosystem broadly.

KEYWORDS

climate change, environmental management, marine protected area, monitoring, State of Conservation, UNESCO

1 | INTRODUCTION

World Heritage (WH) properties represent society's highest heritage designation, promoting the conservation of outstanding examples of natural and cultural values for future generations (UNESCO n.d.). As of May 2022, there were 252 WH properties inscribed for their exceptional natural beauty, significant geological, ecological or biological processes, and/or significant biodiversity (UNESCO, 2019; UNESCO n.d.). However, almost all natural WH properties are threatened by anthropogenic and climate pressures (Osipova et al., 2020). The latest WH Outlook report has identified that climate change is the greatest and fastest-growing threat to natural WH properties, being a High or Very High threat for 83 properties (Osipova et al., 2020). Many WH coral reefs have experienced repeated bleaching events due to the increased frequency of marine heatwaves (Heron et al., 2017, 2018) and 21 WH glaciers are projected to disappear this century (Bosson et al., 2019). Climate change impacts can exacerbate the effect of anthropogenic pressures (Day et al., 2020); together, these threats have the potential to impact the Outstanding Universal Value (OUV), which is the basis for which these properties are listed as WH.

A recent UNESCO report showed that coastal blue carbon ecosystems across WH properties (which include mangroves, saltmarshes, and seagrasses) account for 15% of the coastal blue carbon asset (UNESCO, 2020). The proportion of sedimentary oceanic carbon in coastal areas is 12% of the total marine sediments carbon stock, while 79% is stored in abyssal/basin zones (Atwood et al., 2020). However, the protection of coastal blue carbon ecosystems remains an important strategy to mitigate climate change, which has currently feasible management options (in contrast to management challenges in deeper areas; Hilmi et al., 2021). Furthermore, this protection also acts to preserve ecosystem services and biodiversity (Laffoley, 2020; UNEP, 2020).

Seagrass habitats across WH properties were estimated to hold 25% of the world's seagrass carbon assets (UNESCO, 2020). Other than being one of the most efficient coastal natural carbon sinks (Fourqurean et al., 2012), seagrasses are also one of the most valuable coastal ecosystems in terms of ecosystem services (Costanza et al., 2014). They support biodiversity through the provision of food for iconic grazers, and shelter for many fish and crustaceans species (Burkholder et al., 2012; Guannel et al., 2016; Thomson et al., 2015). Other coastal marine ecosystems, such as coral reefs and mangroves, benefit from the ability of seagrasses to improve water quality, reduce turbidity, and buffer ocean acidification (Berke, 2010; Hemminga & Duarte, 2000; Hendriks et al., 2014). Seagrass habitats are also considered to be socio-ecological systems, furnishing human coastal communities with a wide range of provisioning, cultural, regulatory, and supporting ecosystem services (Cullen-Unsworth et al., 2014). These include the provision of food, by functioning as nursery habitats for 20% of the world's largest fisheries (Unsworth et al., 2019); coastal protection, through sediment stabilization, reduction of wave action, and carbonate sediment provision (Boudouresque et al., 2016; De Falco et al., 2017); and water quality improvement, through absorption of human pathogen and excess nutrients (Hemminga & Duarte, 2000; Lamb et al., 2017). Moreover, the cultural heritage of several communities around the world relies on seagrass health. Seagrass rhizomes in Southeast Asia are used in traditional medicine and as an emergency food source (UNEP, 2004). In the Balearic Islands (Mediterranean), house rooftops are made from *Posidonia oceanica*, rendering the seagrass habitat a “manufacturing asset” (Carmona et al., 2018). In the UNESCO report, the areal extent of seagrass habitats was unknown for 19 WH properties, no consideration was given to the importance of seagrass habitats toward the OUV and the associated community of each WH property, and information about their status, trend, and major threats were not provided (UNESCO, 2020).

On a global scale, based on the best available estimation, the documented area of seagrass has declined by 19% since the start of the second industrial revolution (ca. 1870), due to the cumulative impacts of direct anthropogenic and climate change stressors (Dunic et al., 2021). The loss of seagrass will expose the soil to aerobic conditions, favoring remineralization of organic carbon, substantially increasing net CO_2 emissions (Salinas et al., 2020; Serrano et al., 2019).

Seagrasses have received substantially less research effort compared to other coastal ecosystems (Unsworth et al., 2019) and the distribution of seagrass research has a high geographical, species, and depth bias. Most studies have been conducted on intertidal seagrass meadows in Europe, the east coast of the USA, and Australia, leaving many gaps in knowledge in many parts of the world (Dunic et al., 2021; Waycott et al., 2009). Therefore, there is an urgent need to provide State Parties and site managers of WH properties with information to prioritize conservation actions and adaptation strategies.

The first aim of this study was to assess the relative importance of seagrass habitats toward the values of WH properties. Then, the scientific literature related to the threats, status, and trends of seagrass within identified WH properties was reviewed. Monitoring programs and management plans for WH seagrass habitats were also explored, with special attention given to climate change impacts and existing adaptation strategies. Lastly, we evaluate how threats to seagrass habitats are considered within the UNESCO-WH State of Conservation (SOC) reporting system. This study will highlight knowledge gaps and research needs within seagrass habitats across WH properties.

2 | METHODS

2.1 | Assessing the relative importance of seagrass for WH properties

An assessment system was developed to evaluate the relative importance of an identified attribute (in this case, seagrass habitat) for WH properties (Table 1). As of May 2022, there were 50 Marine and Coastal properties (46 natural, four mixed natural/cultural) on the WH List (UNESCO n.d.). Information on these was sourced from their Statement of Outstanding Universal Value (SOUV, the foundational description of a WH property), Nomination documents (for WH inscription), and Advisory Body evaluations (an important part of the nomination process). Using these, seagrass habitats were categorized from Very High to Low importance (Score 5–2, Table 1). Score 2 (Low) recognizes that, while not explicitly mentioned in the SOUV, seagrass is foundational for marine fauna that may be attributes of OUV, indicating a degree of dependency on seagrass habitats.

Properties for which seagrass and seagrass-dependent species were not mentioned in the source information, seagrass presence was evaluated using the latest global seagrass distribution map (UNEP-WCMC & Short 2021) and the World Database on Protected Areas (WDPA) (UNEP-WCMC, 2017). Seagrass habitat was assessed to have potential importance for these WH properties (Score 1). To ensure that all Marine and Coastal WH properties were present in the database, the WDPA was cross-referenced with the WH List (UNESCO, n.d.). Site managers and seagrass experts were contacted to confirm seagrass presence. Score 0 indicates there was no evidence of seagrass from UNESCO documents nor from the map intersection but should not conclude that seagrasses have never been present. The seagrass species assemblages for each property were presumed using established seagrass bioregions: Temperate North Atlantic, Tropical Atlantic, Mediterranean, Temperate North Pacific, Tropical Indo-Pacific, and Temperate Southern Oceans (F. Short et al., 2007).

TABLE 1 Criteria used to score the relative importance of seagrass for World Heritage properties

Score	Criteria	Importance
5	The seagrass habitat is a key attribute of the Statement of OUV	Very High
4	The seagrass habitat is mentioned in the Statement of OUV	High
3	Seagrass habitat is only mentioned in the Nomination or Advisory Body documents	Moderate
2	Species dependent on the seagrass habitat (e.g., dugongs, manatees, green turtles, brant geese) are attributes Statement of OUV	Low
1	Evidence of seagrass presence from global distribution map (UNEP-WCMC, 2020)	Potential
0	None of the above criteria is met	-

Only WH properties with a documented presence of seagrass (i.e., scored 1–5) were considered in this study and hereafter are referred to as "World Heritage seagrass habitats."

2.2 | SOC reports analysis

SOC reports provide information on conservation and protection to, and at the request of, the WH Committee; these are accessible from the UNESCO-WH website (UNESCO, n.d.). The total number of SOC reports and the date of the most recent report for WH seagrass habitats (up to 2020) were assessed. The most recent SOC report for each property was inspected for mentions of "climate change." Local threats were recorded within 14 threats/factors described in the UNESCO Guidelines (UNESCO, 2019) to indicate the most common threats across WH seagrass habitats.

2.3 | Review of the literature

A literature review was conducted to assess seagrass conservation status and population trends, direct anthropogenic and climate impacts, and the existence of monitoring programs and management plans for WH seagrass habitats. Using Scopus and Web of Science online databases, a preliminary search string containing all seagrass scientific and common names (developed in consultation with seagrass experts) was combined with the name of each WH seagrass habitat. After each search, abstracts were analyzed to verify whether the study was conducted within the WH property boundary and was related to seagrass. Seagrass research effort in each property was assessed through a count of scientific articles in each online database. For each property, search outcomes were refined for studies related specifically to climate change, monitoring, and management (Table S1).

3 | RESULTS

3.1 | WH seagrass habitats—scoring system outcomes

There are 28 WH properties associated with seagrass habitats to some degree (Table 2). Properties for which seagrass habitats are included in the SOUV were assessed as having Very High ($n = 5$; Table S2) and High ($n = 4$; Table S3) importance. These regions contain some of the largest, most diverse, and most pristine seagrass meadows globally and/or regionally (e.g., Shark Bay, Western Australia; Sanganeb Marine National Park; Aldabra Atoll; Great Barrier Reef).

TABLE 2 World Heritage properties grouped by relative importance of the attribute "seagrass habitat"

Importance	WH property	IUCN conservation assessment	Bioregion
Very High	(1) Banc D'Arguin (1989)	Significant concern	Tropical Atlantic[a]
	(2) Everglades National Park[b] (1979)	Critical	Tropical Atlantic
	(3) Ibiza Biodiversity and Culture (1999)	Significant concern	Mediterranean
	(4) Sanganeb Marine National Park and Dungonab Bay—Mukkawar Island Marine National Park (2016)	Good with some concerns	Tropical Indo-Pacific
	(5) Shark Bay, Western Australia (1991)	Good with some concerns	Tropical Indo-Pacific[a]
High	(6) Aldabra Atoll (1982)	Good with some concerns	Tropical Indo-Pacific
	(7) Belize Barrier Reef Reserve System (1996)	Significant concerns	Tropical Atlantic
	(8) Great Barrier Reef (1981)	Critical	Tropical Indo-Pacific
	(9) Lagoons of New Caledonia (2008)	Good with some concerns	Tropical Indo-Pacific
Moderate	(10) Gulf of Porto: Calanche of Piana, Gulf of Girolata, Scandola Reserve (1983)	Good with some concerns	Mediterranean
	(11) Islands and Protected Areas of the Gulf of California[b] (2005)	Critical	Temperate North Pacific[a]
	(12) Komodo National Park (1991)	Significant concerns	Tropical Indo-Pacific
	(13) Ningaloo Reef (2011)	Good with some concerns	Tropical Indo-Pacific[a]
	(14) Puerto-Princesa Subterranean River National Park (1999)	Good with some concerns	Tropical Indo-Pacific
	(15) Rock Islands Southern Lagoon (2012)	Good with some concerns	Tropical Indo-Pacific
	(16) Socotra Archipelago (2008)	Significant concerns	Tropical Indo-Pacific
	(17) Tubbataha Reefs Natural Park (1993)	Good with some concerns	Tropical Indo-Pacific
	(18) Wadden Sea (2009)	Good	Temperate North Atlantic
Low	Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves (2001)	Significant concerns	Tropical Atlantic
	Coiba National Park and its Special Zone of Marine Protection (2005)	Significant concerns	Tropical Atlantic
	iSimangaliso Wetland Park (1999)	Good with some concerns	Temperate Southern Oceans[a]
	Sian Ka'an (1982)	Good with some concerns	Tropical Atlantic
	Whale Sanctuary of El Vizcaino (1993)	Good with some concerns	Temperate North Pacific[a]
Potential	(24) East Rennell[b] (1998)	Critical	Tropical Indo-Pacific
	(25) Ha Long Bay (1994)	Good with some concerns	Tropical Indo-Pacific[a]
	(26) Lord Howe Island Group (1982)	Good	Temperate Southern Oceans
	(27) Ujung Kulon National Park (1991)	Good with some concerns	Tropical Indo-Pacific
	(28) West Norwegian Fjords (2005)	Good	Temperate North Atlantic

Note: For each property, the year of inscription, the most recent IUCN outlook category, and seagrass bioregion (F. Short et al., 2007) are shown. Property numbers correspond to Figure 1.

[a]Seagrass habitats at their geographical limit of distribution.

[b]The World Heritage property is inscribed on the In Danger List (UNESCO, n.d.).

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Seagrass was documented in the nomination or evaluation documents (but not the SOUV) for further nine WH properties, for which the importance was categorized as Moderate (Table S4). The SOUVs of five properties describe marine fauna dependent upon seagrass for habitat without explicit mention of seagrass; these properties were assigned Low importance of seagrass (Table S5). Lastly, the potential importance of seagrass was assessed for five additional WH properties with documented seagrass presence (Table S6).

Each of the six seagrass bioregions is represented at least by one WH seagrass habitat (Figure 1). Half of the WH seagrass habitats are within the Tropical Indo-Pacific bioregion ($n = 14$), which is the major hotspot of seagrass biodiversity worldwide (F. Short et al., 2007). Seagrass importance was assessed as Very High or High for five of these, with a further three scored as Moderate. The second most represented bioregion is the Tropical Atlantic ($n = 6$), within which three properties were assessed to have Very High or High importance of seagrass. The Mediterranean bioregion, where seagrasses are the dominant benthic habitat (Hemminga & Duarte, 2000), includes two WH properties (one of which was scored as Very High importance). The remaining three bioregions each include two WH seagrass habitats, none of which were in the Very High or High categories.

3.2 | SOC report analysis

Of the 28 WH seagrass habitats, seven properties have had no SOC report since WH inscription. Of the 21 with SOC reports, the most reported threat/factor, sourced from the standard list outlined by UNESCO (UNESCO, n.d.), ($n = 14$) was "Management and institutional factors" (Figure 2), which include issues related to financial/human resources, governance, and management systems. Threats within "Climate change and severe weather events" were reported for only five properties: sea-level rise (Everglades National Park [NP] and East Rennell); increase in storm intensity (Everglades NP and Socotra Archipelago); and increase in sea surface temperature (Great Barrier Reef and Lagoons of New Caledonia). Observed impacts on seagrass were specifically stated in only two SOC reports: from Hurricane Irma (2017) in Everglades NP; and from boat wastewater in Ibiza Biodiversity and Culture. The impact of tourism was documented in six recent SOC reports though without specific

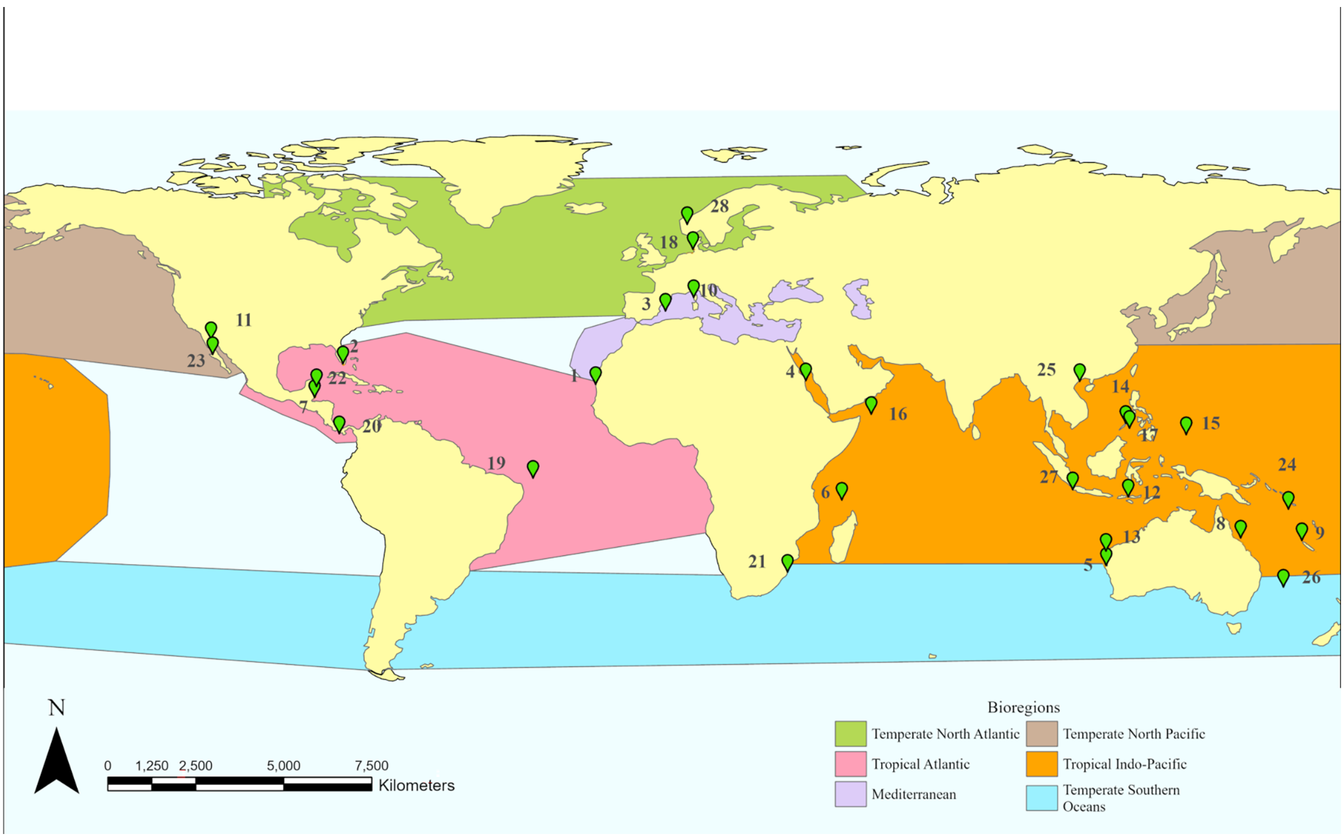

FIGURE 1 Map of the 28 World Heritage seagrass habitats. Color represents the seagrass bioregions (F. Short et al., 2007). Numbers correspond to the order of WH seagrass habitats in Tables S2–S7. The map was created with the software ArcGIS Pro v 2.7.26828.

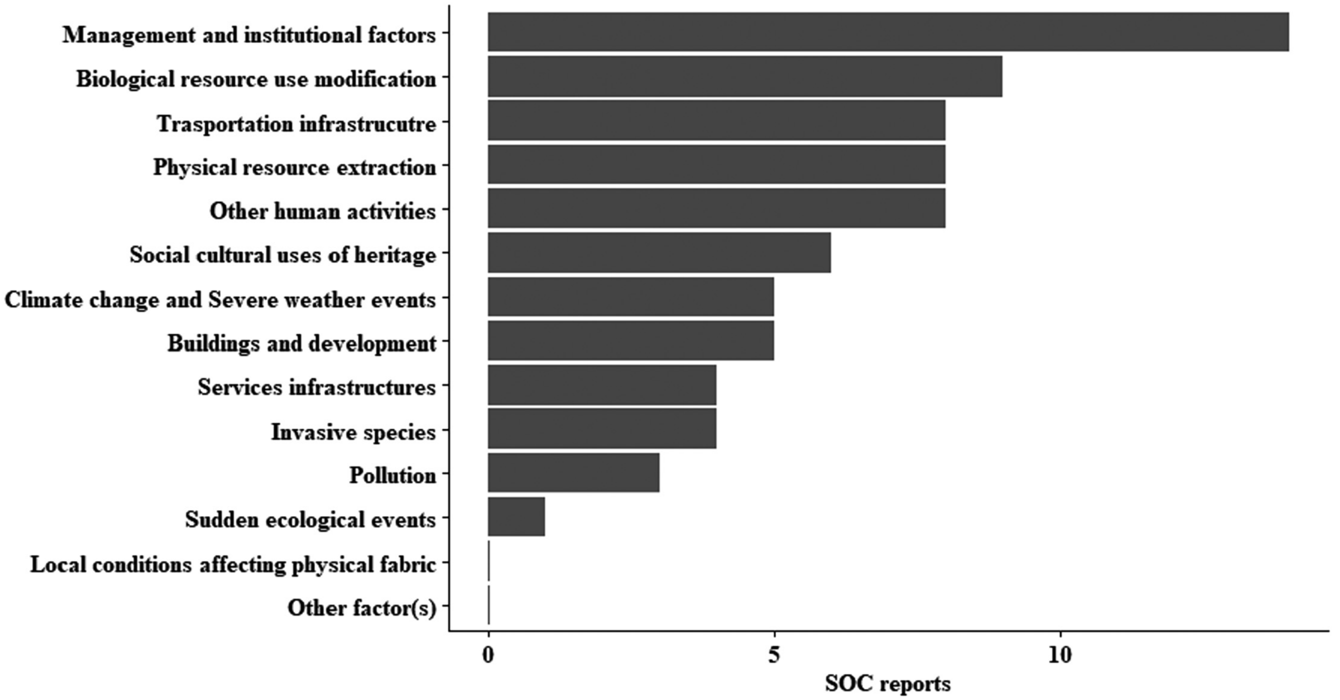

FIGURE 2 Number of State of Conservation (SOC) reports indicating each threat for World Heritage seagrass habitats. Data were sourced from (UNESCO n.d.).

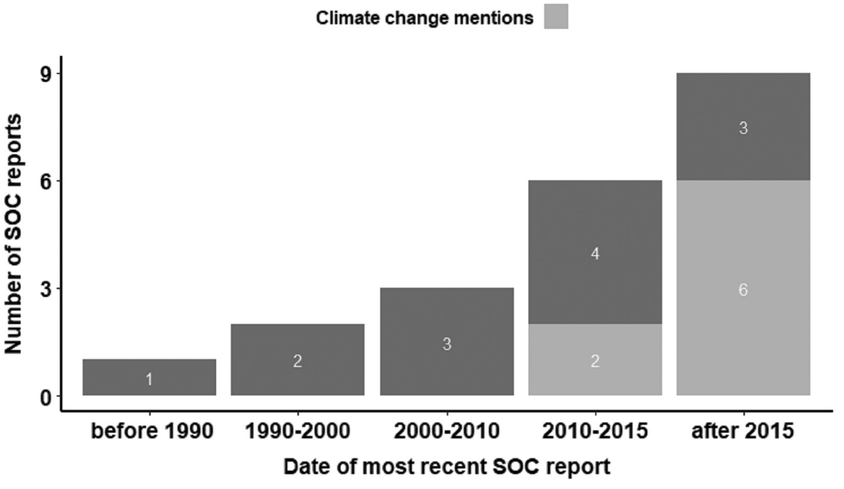

FIGURE 3 Mentions of "climate change" among the most recent State of Conservation (SOC) reports for WH seagrass habitats, sorted by date. Numbers within dark gray bars indicate SOC reports without mentions of climate change. Data were sourced from UNESCO (n.d.).

mention of impacts on seagrass meadows within the property boundary. Other common threats likely to affect seagrass are physical resource extraction (mining, water, and oil extraction), coastal development, and pollution (Figure 2).

The most recent SOC report for 29% of the WH seagrass habitats (6/21) was issued more than a decade ago (Figure 3). Within those, the term "climate change" never appears. Mentions of climate change within SOC reports ($n = 8$) first occur after 2010, of which six were after 2015. Since 2010, climate change was mentioned relating to ascertained or potential threats to the OUV ($n = 5$), concern of the WH Committee about a lack of development of adaptation measures ($n = 2$), and acknowledgement of implementation of a management plan addressing climate change ($n = 1$) (Table S7).

3.3 | Analysis of seagrass literature

The 28 Web of Science and Scopus preliminary searches returned totals of 380 and 453 articles, respectively, including less than 10 articles for 75% of WH seagrass habitats (21/28) (Figure 4). Among them, no articles were

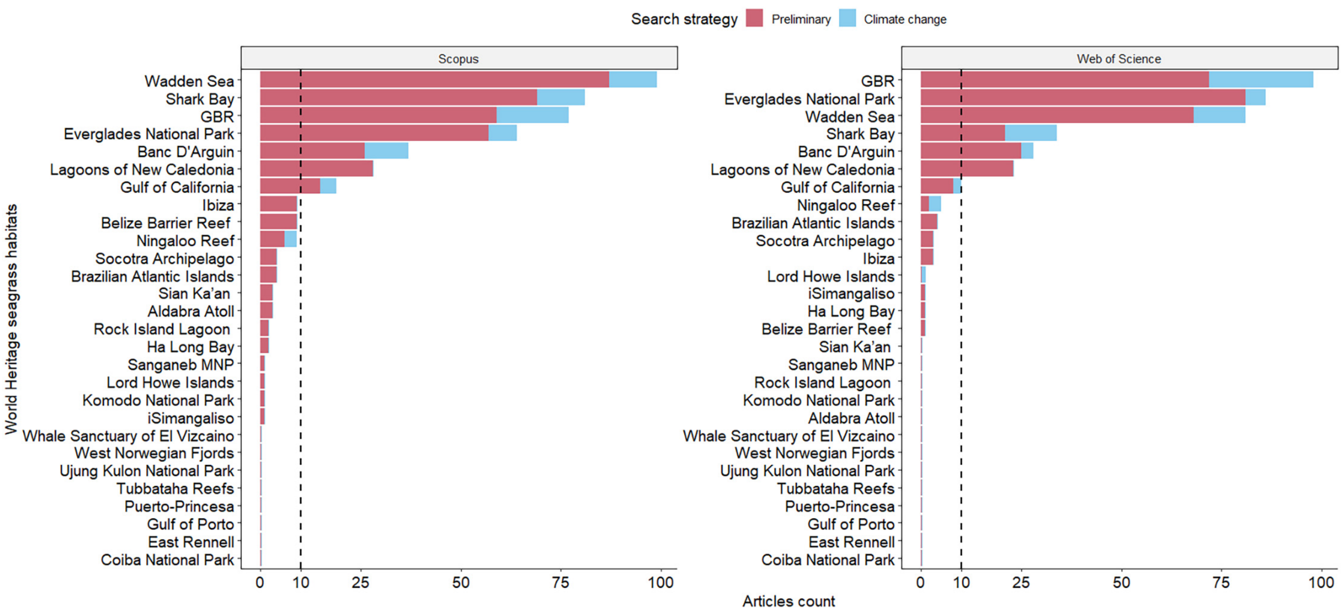

FIGURE 4 The number of scientific articles returned by Scopus and WoS after the two search strategies for each of the 28 WH seagrass habitats. The dashed line shows the 21 WH seagrass habitats (75%) with less than 10 scientific articles returned by the searches.

TABLE 3 Monitoring activities within WH seagrass habitats sourced from the scientific literature (Scopus and WoS)

WH property	Last monitoring	Program	Reference
Everglades	Ongoing	RECOVER Program	RECOVER (2019)
Shark Bay, Western Australia	Ongoing	Marine Monitoring Program (DCBA)	Holmes et al. (2019)
Great Barrier Reef	Ongoing	Marine Monitoring Program	McKenzie et al. (2019)
Ningaloo Reef	Ongoing	Marine Monitoring Program (DCBA)	Holmes et al. (2017)
Wadden Sea	Ongoing	Trilateral Monitoring and Assessment Programme	Dolch et al. (2017)
Gulf of Porto: Calanche of Piana, Gulf of Girolata, Scandola Reserve	2013	Posidonia Monitoring Network	Pergent et al. (2015)
Belize Barrier Reef Reserve System	2012	CARICOMP	Van Tussenbroek et al., 2014
Lagoons of New Caledonia	2007	Seagrass-Watch	SeagrassWatch (n.d.)
Belize Barrier Reef Reserve System	2005	SeagrassNet	F. T. Short et al. (2006)
Komodo National Park	2003	Seagrass-Watch	SeagrassWatch (n.d.)
Rock Islands Southern Lagoon	2002	Seagrass-Watch	SeagrassWatch (n.d.)

found for eight properties and two other properties included only articles examining seagrass-associated fauna. For two properties, the only result was the Coastal World Heritage Site book (Claudino-Sales, 2018). The highest number of articles returned by Scopus and Web of Science preliminary searches were for the Wadden Sea ($n = 99$) and the Great Barrier Reef ($n = 98$), respectively (Figure 4). Articles reporting climate change impacts were found for 14% of WH seagrass habitats (4/28)—a marine heatwave in Western Australia (Shark Bay and Ningaloo Coast) (Strydom et al., 2020); drought in Banc D'Arguin (De Fouw et al., 2016); and severe tropical cyclone Yasi in the Great Barrier Reef (McKenna et al., 2015). Articles describing seagrass monitoring were found for 10 properties, only half of which had ongoing long-term monitoring programs (Table 3). Lastly, the searches revealed evidence of management plans and climate change adaptation strategies addressing seagrass in only 14% of properties (4/28; Everglades NP, Ibiza, GBR, Belize).

It is worth noting that monitoring programs and management plans of many WH properties might not be available in English and/or may reside in the gray literature (Haddaway & Bayliss, 2015). However, to ensure a systematic approach to set a baseline of research effort across WH seagrass habitats, this study only considered evidence from the scientific literature. Future research could further investigate evidence of monitoring and management from different sources, including unpublished or practitioner-generated research.

4 | DISCUSSION

In addition to its inherent value, the assessed importance of seagrass reflects its wide-ranging and significant roles including providing habitat and food for vulnerable iconic species and supporting adjacent coastal ecosystems across 28 WH properties. WH seagrass habitats are also important for the human communities associated with those properties. Here, we discuss the conservation status, threats, and the available evidence within the scientific literature regarding monitoring and management of the WH seagrass habitats. Through this analysis, relevant knowledge gaps and research needs are identified.

4.1 | The importance of seagrass to WH properties and associated communities

WH seagrass habitats are key feeding grounds for many iconic species that are attributes of OUV in many WH properties. In tropical bioregions, seagrasses are the primary food source for key populations of dugongs (*Dugong dugon)*, manatees (*Trichecus manatus*), and green turtles (*Chelonia midas*) (Burkholder et al., 2012). Dugongs and manatees are long-lived mega-herbivores considered globally vulnerable to extinction due to seagrass loss, incidental bycatch in fishing gears, hunting, and watercraft collision (Marsh et al., 2002). Dugong populations are an important OUV attribute for nine WH seagrass habitats within the Tropical Indo-Pacific bioregion, which are key feeding grounds for the world's most significant dugong populations (Great Barrier Reef, Lagoons of New Caledonia, and Sanganeb MNP) and most isolated dugong population (Rock Islands Southern Lagoon) (Marsh et al., 2002). Recent sightings in Aldabra Atoll confirmed the presence of a dugong population previously thought extinct (Hamylton et al., 2012). In the Tropical Atlantic bioregion, WH seagrass habitats of Sian Ka'an and Belize Barrier Reef are key conservation areas for vulnerable populations of manatees (Burkholder et al., 2012).

WH seagrass habitats are also key wintering grounds for many migratory bird species. In temperate regions, meadows of *Zostera marina* and *Zostera noltii* are the primary food source for brant geese (*Branta berincla*) and widgeon species (*Mareca* spp.) during non-breeding seasons (Dolch et al., 2017). The Wadden Sea and the Banc D'Arguin are designated as Important Bird Areas on the East Atlantic Flyway, which links breeding grounds from East Canada to Central Siberia (Bird Life International n.d.). In Baja California along the Pacific Americas Flyway, the lagoons of the Whale Sanctuary El Vizcaino function as wintering grounds for 63% of Mexico's population of brant geese (IUCN n.d.).

Many WH seagrass habitats also contain globally significant coral reefs ($n = 21$), mangroves ($n = 10$), and three of the world's largest salt marshes. Coral reefs and mangroves in the tropics and salt marshes in temperate regions are highly interconnected with seagrass habitats (Guannel et al., 2016). Seagrasses act as nurseries for many species that move to adjacent habitats (Berke, 2010; Rutherford et al., 1989). Additionally, seagrasses help reduce nutrient concentrations in the water column, limiting macroalgal growth, and favoring the growth of crustose coralline algae onto which coral larvae are known to settle (Koester et al., 2020). Some seagrass species leach ultra-violet absorbing substances that mitigate impacts on coral reefs during heat stress; in Aldabra Atoll during the 1998 El Niño event, corals near meadows of the genus *Thalassodendron* suffered significantly less bleaching (Iluz et al., 2008).

Seagrass also benefits human communities associated with WH properties through the provision of ecosystem services (Cullen-Unsworth et al., 2014). However, studies that quantify site-specific or local seagrass' ecosystem services are absent in most WH seagrass habitats, hence, here we provide the best available evidence from studies conducted at a broader scale (i.e., regional or national). In many tropical countries, seagrasses are crucial for people's livelihoods and food security and are also part of the cultural heritage and spiritual fulfillment (Unsworth et al., 2014). For many families, daily nutrition depends on the availability of crustaceans, bivalves, sea urchins and cephalopods collected within seagrass meadows at low tide. Seagrass habitats in Indonesia account for around 5% of the world's total seagrass area, providing readily accessible fishing grounds for millions of people (Unsworth et al., 2018). Coastal communities in New Caledonia, Palau, and the Solomon Islands rely on seagrass habitats for subsistence and commercial fisheries (Unsworth et al., 2014).

WH seagrass habitats are also important for many associated economic sectors. Globally, seagrasses provide nursery habitats for over one-fifth of the largest commercial fisheries (UNEP, 2020). In the GBR, seagrass provides nursery habitats for penaeid prawns, one of Australia's major target species (Coles & Lee Long, 1985). In Queensland, the value of the prawn fishery was recently estimated at $79.2 million (AUD) in 2017 (Australian Prawn Fisheries, 2017), with 90% of the harvest coming from the coastal waters of the GBR. In the Mediterranean, *P. oceanica* meadows have a direct contribution of 4% to the total annual fish landings (Ruiz-Frau et al., 2019). Seagrass ecosystem services are also highly valuable for the tourism and recreational industry (UNEP, 2020). In the Everglades NP, recreational fishing is worth approximately US$1.2 billion in annual economic activity, with mixed seagrass meadows considered Essential Nursery Habitats for many target species such as sea trout, groupers, and snappers (Rutherford et al., 1989). In Ibiza, tourism is one of the major economic sectors, hosting 19.5 million tourists in 2017. Many tourists to Ibiza are attracted by the presence of clear water and beautiful sandy beaches (Ruiz-Frau et al., 2019), linked to *P. oceanica* meadows that act as water filters and carbonate sediment sources (De Falco et al., 2017).

4.2 | Threats to WH seagrass habitats

WH seagrass habitats are threatened by direct anthropogenic and climate pressures to varying degrees. Globally, major anthropogenic pressures that directly damage seagrass habitats are anchoring, dredging, destructive fishing practices, and seaweed aquaculture (Duarte, 2002). The active removal of seagrass shoots by unregulated anchoring (Ibiza) and propellers (Everglades NP) of tourists' boats and unsustainable fishing practices (Banc D'Arguin) are among the major direct anthropogenic threats to WH seagrass habitats (Marcial Bardolet pers. comm.) (Hallac et al., 2012; Trégarot et al., 2020).

However, most impacts on seagrass meadows occur indirectly as a result of anthropogenic activities, such as urban and agricultural development (Grech et al., 2012). These activities are the major drivers of coastal water quality degradation through changes in salinity, reduction in light and oxygen availability, and increase in pollutants. WH seagrass die-offs due to anthropogenic changes in hydrology have been documented. In Everglades NP, a significant reduction of freshwater inflow into Florida Bay caused two major *Thalassia testudinum* mortality events in 1987 and 1991 (Durako et al., 2002; Recover 2019). In iSimangaliso, reduced flow into the St. Lucia estuary system, due to anthropogenic modification of the estuary mouth, was compounded by further flow reduction from the 2002 drought, resulting in the extinction of *Z. capensis* (Cyrus et al., 2010). WH seagrass habitats have also been impacted by the reduction in light availability due to reduced water quality. Eutrophication in the southwestern and central part of the Wadden Sea impacted intertidal meadows of *Z. marina* and *Z. noltii* during the 1970–1980s (Dolch et al., 2017). Poor water quality, driven by the rapid coastal development and nutrient inputs from shrimp farms and live-a-board boats, has impacted seagrass within Belize Barrier Reef and Gulf of California (Cortés et al., 2019; Páez-Osuna et al., 2017). A significant decrease in shoot density and percent cover was observed in short-term (2003–2005) and long-term (1993–2012) studies across three locations in Belize Barrier Reef (F. T. Short et al., 2006) (CARICOMP). In Gulf of California, a high level of pesticides, metals, and nutrients in the water column are the likely causes of *Z. marina* decline (Páez-Osuna et al., 2017).

WH seagrass habitats are also threatened by a range of climate-related pressures, including increases in intensity and frequency of storms, marine heatwaves, and droughts (El-Hacen et al., 2018; Preen et al., 1995; Strydom et al., 2020). How seagrasses respond to climate change is still unclear; however, there is evidence of large-scale die-off events following extreme climate events.

Storms can have dramatic impacts on seagrass meadows through light deprivation and direct uprooting. In 1992, floods and tropical cyclone Betsy impacted seagrass meadows in Hervey Bay, south of the GBR. The cumulative impact, together with poor catchment management and intensive prawn trawling, resulted in a loss of around 1000 km^2 of seagrass (Preen et al., 1995). Three major cyclones in 2010–2011 caused flood plumes across 39% of the GBR; intertidal seagrass meadows in regions affected by cyclone Yasi (2011, Category 5) declined by 98% (McKenzie et al., 2019). In Western Australia, cyclone Nicholas (2008) caused the disappearance of many patches of *Amphibolis antartica* in Ningaloo Coast and Shark Bay (van Keulen, 2019). Recovery of shoots was observed until 2011 when a prolonged marine heatwave impacted the region. Marine heatwaves negatively impact seagrasses by reducing their photosynthetic yield and increasing photochemical quenching (Campbell et al., 2006). In Western Australia, sea surface temperature anomalies exceeded 4°C for 2 months causing widespread mortality of *A. antartica* meadows and seed abortion in *P. australis* (Strydom et al., 2020). In the Balearic islands (at Cabrera, near Ibiza), anomalously high sea-surface temperatures recorded in 2003 and 2006 resulted in a 40% loss of *P. oceanica* meadows and

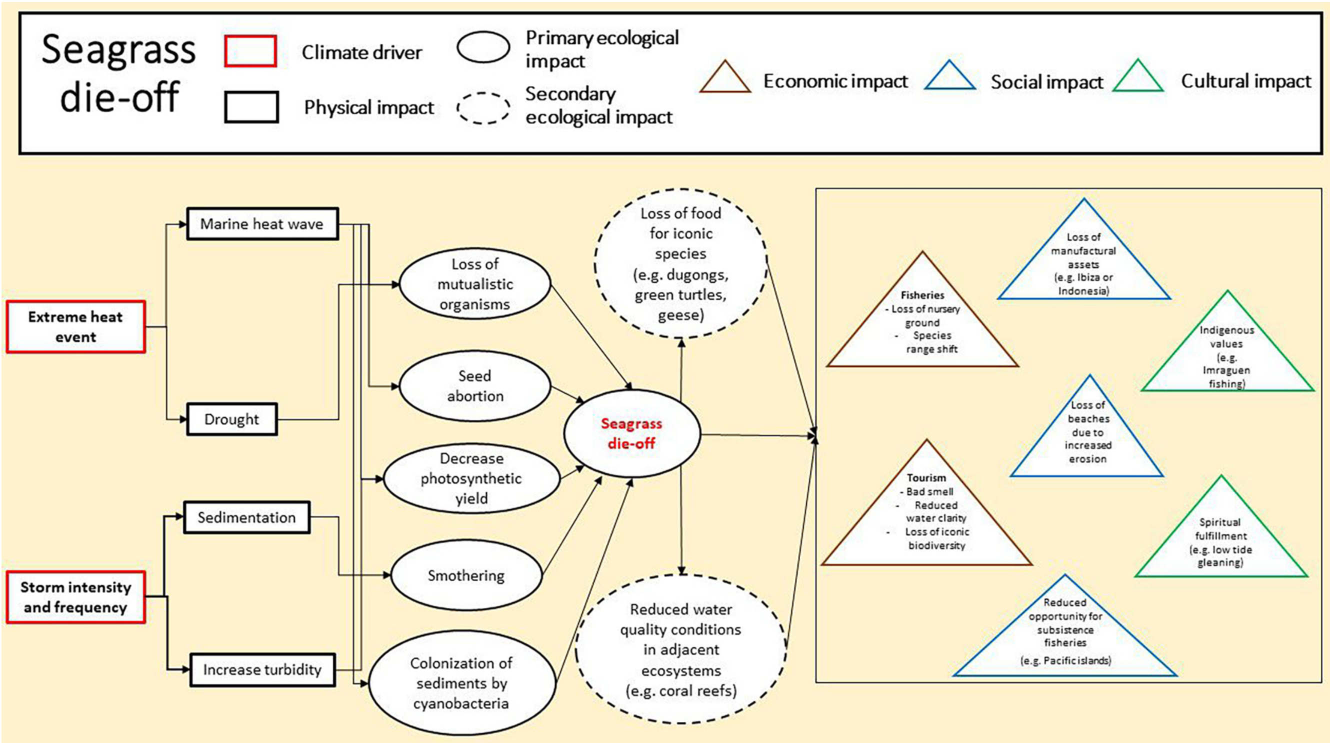

FIGURE 5 Schematic diagram showing examples of climate change-driven pathways leading to seagrass die-off and associated ecological, economic, social, cultural consequences

reduced recruitment rates (Marbà & Duarte, 2010). However, there is no record of seagrass observations at Ibiza to evaluate if impacts occurred there. Additionally, significant die-offs caused by droughts were recorded in Banc D'Arguin in 2011 and Everglades NP in 2015 (De Fouw et al., 2016; Mcginnis 2017).

Climate pressures are likely to exacerbate the effect of anthropogenic stressors, though the cumulative impact is still not well understood (Stockbridge et al., 2020). Nevertheless, there is evidence that cumulative impacts can have catastrophic consequences on organisms occupying different levels in the food web and can favor the spread of invasive species (Nowicki et al., 2019; Perissinotto et al., 2014; RECOVER, 2019). The loss of mutualistic organisms, living within seagrass sediments, can change the sediment biochemistry further slowing down seagrass recovery and favoring colonization by cyanobacteria and diatoms (De Fouw et al., 2016). Future projections predict that climate change impacts could cause the collapse of many key seagrass habitats around the world and trigger a distributional shift away from the tropics, leading to the possible extinction of populations living at their thermal limits (Jordà et al., 2012; Strydom et al., 2020).

Here we provide a visual diagram showing examples of pathways on how the climate drivers discussed in this section lead to seagrass die-off. We also highlight how seagrass die-off can cause impacts on other natural attributes contributing to WH properties' OUV and associated community (economic, social, and cultural impacts) (Figure 5).

4.3 | Status, trend, and protection of WH seagrass habitats

There is a lack of long-term monitoring programs within WH seagrass habitats. Monitoring activities have been performed in nine WH seagrass habitats. Among them, ongoing long-term monitoring programs only exist in Shark Bay, Everglades NP, GBR, and Wadden Sea (Table 3). However, even some of these might not provide a comprehensive picture of seagrass status and trends due to some key limitations. In the GBR, one of the best-resourced MPAs in the world, only shallow water seagrasses (<15 m), which account for only 10% of the potential seagrass area within the GBR, are monitored (McKenzie et al., 2020). Hence, the condition of deep-water seagrasses, which are important habitats for many fish species of socio-economic value, and for their carbon storage potential (Hayes et al., 2020; Rasheed et al., 2008; York et al., 2015), is largely unknown. Other monitoring activities, mainly conducted through citizen science projects (F. T. Short et al., 2006; Van Tussenbroek et al., 2014), did not provide enough information to determine the status and trends of these seagrass habitats.

This lack of monitoring programs leads to a general gap in knowledge about the status and trends of most WH seagrass habitats. The current status and the recent trends of the five WH seagrass habitats within the South-East Asia region, a global hotspot for seagrass diversity, are unknown. This is due to the absence of time series within individual meadows in many countries, including Indonesia and the Philippines (Sudo et al., 2021). Seagrass meadows across South-East Asia have been declining in the past two decades and are highly threatened by the cumulative impacts of multiple anthropogenic and climate stressors (i.e., coastal development, typhoons) (Sudo et al., 2021; UNEP, 2004; Unsworth et al., 2018). Hence, there is an urgent need to develop monitoring programs across those WH properties to assess the conditions of their seagrass habitats. The status of WH seagrass habitats in Central America is also largely unknown. The seagrass habitats of Belize Barrier Reef and Sian Ka'an were not included in the Mesoamerican report card of 2020, despite a commitment to include them from 2019 (McField et al., 2020; Nilipour, 2018). Up to 21% of Belize's seagrass meadows were under high threat from human activities, mainly in the Central region (CZMAI 2014). The status of seagrass habitat has not been reported since 2012 (Table 3). In the Gulf of California, seagrasses have been found recently in only five of 23 historical locations (Lopez-Calderon et al., 2016). A comparison of aerial photography from 2000 and 2010 showed no significant difference in seagrass cover in two of these locations (Lopez-Calderon et al., 2010). Quantitative information about the status and trends of Ibiza seagrass habitat is not available; however, the overall status of seagrass meadows in the Mediterranean has been assessed as poor (Marbà et al., 2014). During the last 50 years, increasing human pressures on the coastlines have caused a sharp decline in *P. oceanica* aerial extent by up to 38%. The remaining meadows have thinned over recent decades, with a 50% average decline in shoot density since 1990 (Marbà et al., 2014).

There is some evidence of WH seagrass habitats in good condition or that have recovered from past stressors. Seagrasses in Aldabra Atoll and the Gulf of Porto are stable and in good condition; in each of these locations, there is no major source of pollution and anthropogenic impacts (Güreşen et al., 2020; SIF 2016). Significant reductions in riverine nutrient input (see below) into the Wadden Sea in the last 25–30 years resulted in seagrass recovery in the Schleswig-Holstein region (Table 4), which reached the predicted ecological potential maximum for the first time since a 1930 wasting disease-driven die-off (Dolch et al., 2017).

Some species of seagrass can recover faster and therefore be more resilient to climate change impacts. In the GBR, the fast-growing deep-water *Halophila decipiens* was the only species showing rapid recovery after the impact of tropical cyclones, likely due to their production of dormant seeds that sprout when optimal conditions return (Rasheed et al., 2014). In the Gulf of California, the range of the opportunistic species *Ruppia maritima* has expanded since 2007, which is attributed to its higher temperature and salinity tolerance and suggesting a lower climate vulnerability compared to other taxa (e.g., *Z. marina*; Lopez-Calderon et al., 2010). However, it is unclear whether the colonizing *R. maritima* can provide the same ecosystem services as the opportunistic *Z. marina*.

The lack of information in SOC reports related to seagrass may be a result of the lack of monitoring programs and research efforts. A further outcome of this is that current and potential threats to seagrass may be underrepresented in SOC reports. For example, the cyclone and marine heatwave impacts in Shark Bay and Ningaloo

TABLE 4 Status and trends of seagrass within World Heritage seagrass habitats based on ongoing long-term monitoring programs

WH property	Status[a]	Trend	Monitoring timespan	Monitoring program	Reference
Everglades National Park	Fair	↘	2012–2017	RECOVER program	RECOVER (2019)
Shark Bay, Western Australia	Poor	↘	2002–2016	Marine Monitoring Program (DCBA)	Holmes et al. (2019)
Great Barrier Reef	Poor	→	2013 - present	Marine Monitoring Program	McKenzie et al. (2019)
Wadden Sea				Trilateral Monitoring and Assessment Programme	Dolch et al. (2017)
Dutch	Poor	↘	2000–2015		
Lower Saxony/Hamburg	Poor	↘	2008–2015		
Danish	Fair	↘	2010–2015		
Schleswig-Holstein	Good	↗	1994–2015		

[a]The status of seagrass habitats is on a five-point scale (Very poor, Poor, Fair, Good, Very good).

Coast, previously noted, occurred after the most recent SOC report for Shark Bay (2000) and there are no SOC reports for Ningaloo Coast. Periodic Reports are another reporting mechanism within WH processes and could provide additional information; however, for these properties, the latest was in 2003 for Shark Bay (with no information on seagrass status, nor climate change) and there has been no PR for Ningaloo Coast. This illustrates a potential under-reporting of climate change impacts within WH reporting processes.

Among WH seagrass habitats, management activities have, to date, resulted in variable outcomes. Most conservation actions among WH seagrass habitats focus on the reduction of direct human impacts from tourism pressures and coastal run-off. In the Balearic islands, the Posidonia Decree actively protects *P. oceanica* meadows from anchoring, sewage discharge, and beach cleaning (BOIB, 2018). In Everglades NP, as a response to increasing damage to seagrass from shallow-water boating, protective measures were implemented through the Seagrass Habitat Restoration Management Plan (Hallac et al., 2012). Since 2011, specific areas have been closed to recreational boaters, non-motorized zones established, improved signage installed, and public education on the importance of seagrass resources enhanced. Most importantly, these regulations are being enforced. In addition, active restoration options have been proposed, including seagrass transplantation and sediment placement (Hallac et al., 2012). A more detailed discussion of active seagrass restoration is beyond the scope of this paper; however, there are numerous publications addressing this emerging focus (e.g., Bastyan & Cambridge, 2008; Paling et al., 2009; Tan et al., 2020). In Belize, a National Integrated Coastal Zone Management Plan provides national guidelines to ensure sustainable coastal development. The scheme seeks to reduce the area of seagrass at high risk by 75% by limiting dredging, oil exploration, and agriculture in key areas (CZMAI 2014). The most comprehensive seagrass management plan is in the GBR and includes policies and legislation to protect seagrass from fishing, port development, dredging, and land-based run-off (Coles et al., 2015). Among 10 key management instruments, the 2004 re-zoning of the entire Marine Park included around 86,000 km^2 of non-reef areas as "no-take" zones. Approximately 2000 km^2 of seagrass habitat is now in zones with a high level of protection (Coles et al., 2015). Despite the above-average protection of the seagrass habitat and substantial investment by Australian governments into seagrass conservation, the condition of GBR seagrasses is still considered poor (McKenzie et al., 2021). In contrast, management of industrial water discharge improved water quality in the Wadden Sea and aided seagrass recovery. *Z. noltii* in this region accounted for the largest increase in seagrass area in Europe during the 21st century (De los Santos et al., 2019). However, the protection of seagrass from the growing threat of climate change is absent from all management plans analyzed.

4.4 | Knowledge gaps and future directions

Seagrass conservation has the potential to maintain existing levels of CO_2 sequestration and avoid further CO_2 emissions, helping mitigate climate change (Salinas et al., 2020; UNEP, 2020). As individual nations are the custodians of these key blue carbon assets, seagrass protection actions have the potential to be included in nationally determined contributions that will help achieve the targets of the Paris Agreement (UNEP, 2020). However, the future of WH seagrass habitats is not "secure" (Hind-Ozan & Jones, 2018). Increased understanding of seagrass dynamics through research and long-term monitoring programs can provide managers with tools to develop effective management plans. WH properties are the "flagship" of marine protected areas globally and so should lead seagrass conservation efforts (UNESCO, 2020). To achieve that, research funding, public awareness, and monitoring efforts need to increase (van Keulen et al., 2018). Research should focus on improving mapping techniques, developing models of future seagrass distribution under climate change, and providing accurate quantitative information on cumulative impacts of anthropogenic and climate pressures (York et al., 2017). Enhanced education and the implementation of citizen science projects can help raise public awareness (Jones et al., 2018). Improved standardization of seagrass monitoring methodologies within WH seagrass habitats will enable comparisons between locations and time frames to better inform management plans.

Moreover, grouping WH properties with common attribute/s (i.e., seagrass habitats) is the first step for a thematic vulnerability assessment. Thematic approaches have been previously employed to assess the vulnerability of WH coral reefs, glaciers, and low-lying cultural properties to climate change (Bosson et al., 2019; Heron et al., 2018; Reimann et al., 2018). Benefits include contextual understanding of climate impacts, networking opportunities within the thematic group, and shared strategies for adaptive management (UNESCO World Heritage Committee 2020). Assessing the climate vulnerability of the WH seagrass habitats thematic group would provide generic information for constituent WH properties, which can be customized by the relative importance of the common attribute to individual properties evaluated in this study.

5 | CONCLUSION

This study identified that seagrass habitats are, to varying degrees, important for the value of 28 WH properties. Our analysis of research effort and monitoring in these properties indicated it is scarce or absent within most, resulting in a lack of knowledge of seagrass status and trends. WH seagrass habitats are exposed to a combination of direct anthropogenic and climate pressures, which are not adequately reported to the WH Committee within SOC reports. Management plans addressing the protection of seagrass are few in number and do not consider the cumulative impact of anthropogenic and climate change pressures. The outcome of this study is the first step of a climate vulnerability assessment of these WH seagrass habitats, currently being undertaken through consultations with seagrass experts and site managers. This study also offers a summary to researchers about knowledge gaps and research needs for seagrass habitats across WH properties and can enable the development of networks of WH site managers to promote collaboration and strategic management.

In combination, insufficient research, monitoring, and management of seagrass within WH properties point to an underestimation of the value of this marine ecosystem broadly. Given the vulnerability of seagrass under climate change, its value in mitigating climate change causes, and impacts on adjacent ecosystems and dependent communities, there is a need for greater recognition of and investment in seagrass research and conservation.

AUTHOR CONTRIBUTIONS

All authors conceived the study and contributed to the editing of the manuscript. Riccardo Losciale performed the data collection, ran the analysis, and designed the figures, under the supervision of Jon Day and Scott Heron. Riccardo Losciale wrote the original manuscript draft.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data will be made accessible from the authors on request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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