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Ranking the risk of CO_2 emissions from seagrass soil carbon stocks under global change threats

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ABSTRACT

Seagrass meadows are natural carbon storage hotspots at risk from global change threats, and their loss can result in the remineralization of soil carbon stocks and CO_2 emissions fueling climate change. Here we used expert elicitation and empirical evidence to assess the risk of CO_2 emissions from seagrass soils caused by multiple human-induced, biological and climate change threats. Judgments from 41 experts were synthesized into a seagrass CO_2 emission risk score based on vulnerability factors (i.e., spatial scale, frequency, magnitude, resistance and recovery) to seagrass soil organic carbon stocks. Experts perceived that climate change threats (e.g., gradual ocean warming and increased storminess) have the highest risk for CO_2 emissions at global spatial scales, while direct threats (i.e., dredging and building of a marina or jetty) have the largest CO_2 emission risks at local spatial scales. A review of existing peer-reviewed literature showed a scarcity of studies assessing CO_2 emissions following seagrass disturbance, but the limited empirical evidence partly confirmed the opinion of experts. The literature review indicated that direct and long-term disturbances have the greatest negative impact on soil carbon stocks per unit area, highlighting that immediate management actions after disturbances to recover the seagrass canopy can significantly reduce soil CO_2 emissions. We conclude that further empirical evidence assessing global change threats on the seagrass carbon sink capacity is required to aid broader uptake of seagrass into blue carbon policy frameworks. The preliminary findings from this study can be used to estimate the potential risk of CO_2 emissions from seagrass habitats under threat and guide nature-based solutions for climate change mitigation.

1. Introduction

Seagrasses are recognised for their globally significant role in long-term sequestration of carbon dioxide (CO_2) (Fourqurean et al. 2012; Macreadie et al. 2021). Despite occupying just 0.1% of the ocean surface, they contribute about 15% of the carbon burial in marine sediments (Duarte et al., 2013), with almost all of the organic carbon (C_{org}) deposited in the underlying soils (Fourqurean et al. 2012). Despite the recognised value of seagrass ecosystems for C_{org} sequestration, they remain at risk and their global area has declined by about 20% since the earliest recordings in the late 1800s (Dunic et al. 2021), and experienced an accelerated loss during the last decades (Waycott et al. 2009). However, recent trends in seagrass recovery have also been observed in some regions, including Europe (de los Santos et al. 2019; Dunic et al. 2021). The loss of seagrass extent reduces their C_{org} sequestration capacity, but also exposes the underlying soil C_{org} to erosion, resuspension and remineralisation, which can result in CO_2 emissions (Marbà et al., 2015). In 2009, the United Nations identified the opportunity to promote seagrass conservation and restoration to offset CO_2 emissions, and named the carbon stored in marine habitats (including seagrass meadows, mangrove forests and salt marshes) as “blue carbon” (Nellemann et al. 2009). To date, 71 countries have embraced blue carbon strategies to abate climate change impacts (Lecerf et al. 2021), while some countries, such as Colombia, India (Sunderban), Indonesia

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(Sumatra), Kenya, Madagascar and Senegal have already implemented blue carbon credits for mangrove forest conservation and restoration (Jones 2021; Kuwae et al. 2022).

Although data on seagrass C_{org} stocks and sequestration rates together with the uptake of seagrass blue carbon projects by industry and governments are increasing exponentially (e.g., Fourqurean et al. 2012; Röhr et al. 2018; Fu et al. 2021), there is very little information on the greenhouse gas emissions associated with disturbance and loss of seagrass ecosystems (Macreadie et al. 2019). The information gap includes the proportion of soil C_{org} stocks eroded, and the fate of the eroded C_{org} stocks (i.e., remineralization, consumption or sequestration elsewhere; Duarte and Krause-Jensen 2017). Studies have reported that 0 to 90% of soil C_{org} stocks within the top 50 to 100 cm were eroded following disturbance (Macreadie et al., 2014, 2015; Salinas et al. 2020; Serrano et al. 2021), while others assume 50 to 90% erosion of soil C_{org} stocks (Githaiga et al. 2019; Carnell et al. 2020). Estimates of potential CO_2 emissions following erosion of seagrass soils relied on the assumption that 25–100% of soil C_{org} stocks within the top meter are remineralized (Pendleton et al. 2012; Arias-Ortiz et al. 2018). The large variability in the percentages of eroded and remineralized soil C_{org} stocks following seagrass disturbance is likely driven by the type, duration, magnitude and spatial scale of the disturbance, as well as the seagrass meadows' resilience and recovery capacity, and time span since the disturbance. Determining the fate of eroded C_{org} is complex owing to the large spatial and temporal scales involved, and remains uncertain (Duarte and Krause-Jensen 2017).

The types of disturbances that can impact seagrass meadows and their soil C_{org} stocks are numerous and cover a range of mechanisms acting on different spatial and temporal scales (Fig. 1). These activities include direct disturbances that typically impact at small spatial scales and with short time spans (e.g., dredging and boat moorings), physically disturbing the seagrass meadows and their soil C_{org} stocks (Lefcheck et al. 2017; Arney et al. 2021). On the other hand, indirect disturbances, for example storms and marine heat waves act on larger spatial scales and short time spans (Serrano et al. 2021). Additionally, some local biological disturbances, such as intensified grazing on seagrasses, typically affect the canopy but can also directly impact the soils underneath the meadows (Christianen et al. 2014). However, impacts on the aboveground biomass can lead to erosion and resuspension of the soil C_{org} stocks following the loss of the protective canopy and degradation of the stabilizing root-rhizome system (Marbà et al. 2015; Dahl et al. 2021).

The risk of CO_2 emissions from seagrass soil C_{org} stocks vary with the spatial distribution and intensity of the threats, and the vulnerability of the seagrass soil C_{org} stocks following disturbance (Zacharias and Gregr 2005; Stelzenmüller et al. 2010). Evaluation of the vulnerability and potential risk of CO_2 emissions from seagrass soils following different types and intensities of disturbances is critical to providing estimates of avoided CO_2 emissions linked to conservation and restoration activities. Such information could be used to underpin estimates of emission reductions in seagrass-focussed blue carbon projects, for example with carbon credits or other policy mechanisms (Kelleway et al. 2020; Kuwae et al. 2022). When there is a deficiency of empirical data, risk assessment frameworks (best expert judgment) provide a transparent process to assess the consequences of activities in risk assessments. Expert elicitation has been used to resolve critical but complex research questions in marine habitats (e.g., Halpern et al. 2007). For example, in global ecosystem assessments (Halpern et al. 2008) as well as global to local scale evaluations of risks to seagrass ecosystems associated with multiple threats (Grech et al. 2011, Grech et al. 2012; McMahon et al. 2022). Here we used both expert elicitation and peer-reviewed studies to assess the risk of seagrass CO_2 emissions linked to key threats (i.e., climate change, human-induced and biological processes) and vulnerability factors (i.e., spatial scale, frequency, magnitude, resistance and recovery) to seagrass soil C_{org} stocks. Based on best expert judgement, the risk of potential CO_2 emission from different threats on soil C_{org} losses and CO_2 emissions were ranked using the summarized scores of the vulnerability factors. This ranking and vulnerability scores summarize the main threats to seagrass blue carbon, and can aid management initiatives for climate change mitigation.

2. Methods

2.1. Expert elicitation

Based on peer-reviewed literature, we identified 20 threats that may

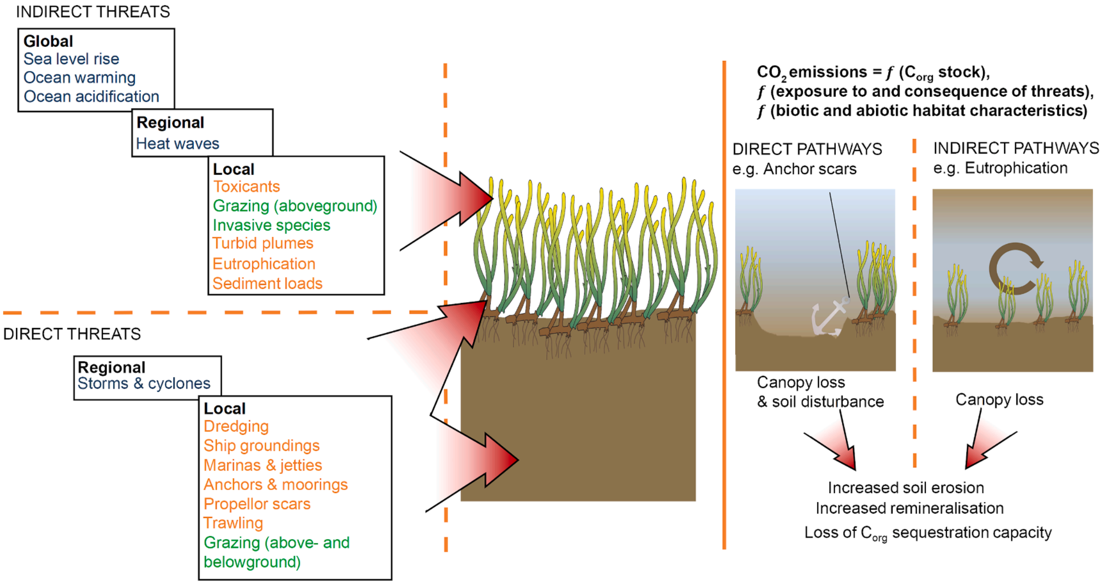

Fig. 1. Conceptual diagram showing direct and indirect threats resulting in CO_2 emissions from seagrass soil organic carbon (C_{org}) stocks. Direct threats result in seagrass loss and soil disturbance, while indirect threats only affect the living seagrass canopy. Threats are categorized based on the global, regional and local scale of impact, and include climate change (dark blue), human-induced (orange) and biological (green) impacts. The effects of direct and indirect threats to the canopy and/or soil are indicated with red arrows and the level of CO_2 emissions is a function of initial C_{org} stock, exposure to a threat, and the consequence of the threat and biotic and abiotic habitat characteristics (e.g., seagrass species and hydrodynamic exposure).

result in CO_2 emissions from seagrass meadows. The threats identified include human-induced, biological and climate change processes, e.g., physical threats (dredging and boating activities; Badalamenti et al. 2006; Unsworth et al. 2017), land-use change within the catchment (e.g., sediment run-off and pollution) (Serrano et al. 2016a; Thorhaug et al. 2017); grazing, bioturbation and invasive species (Rose et al. 1999; Thomson et al. 2019; James et al. 2020); and storms, sea level rise, global warming and ocean acidification (Jordà et al. 2012; Koch et al. 2013; Wilson et al. 2020) that occur at local ($<$10 km^2), regional (10–1,000 km^2) and global ($>$1,000 km^2) spatial scales (Fig. 1). An online survey was developed to collect information from research experts on the risk of CO_2 emissions from seagrass soil C_{org} stocks from these various threats (See S1 for the survey template). The research experts for this study were identified by a survey of literature on seagrass ecology, blue carbon and biogeochemistry in particular, and those with $>$ 2 published manuscripts related to seagrass blue carbon were approached to complete the survey. The research experts approached encompassed different career-stages (i.e., early stage: $<$5 years after PhD, mid-stage: 5–10 years, and late-stage: $>$10 years), gender and biogeographical regions (i.e., Indo-Pacific, Mediterranean, North Atlantic, North Pacific, Southern Ocean, and Tropical Atlantic) in order to assess potential biases in the experts' opinion that could be associated with research experience, gender and geographical location. The worldwide search for experts in seagrass blue carbon identified 142 individuals, all of whom were invited via email to participate in the online survey. We received a positive response rate of 29% (n = 41) who participated in the survey, which is typical for online surveys (Cook et al. 2000). The survey protocol followed the approach used by Halpern et al. (2007) and Grech et al. (2011) who examined the vulnerability of marine ecosystems and seagrass bioregions, respectively, to anthropogenic activities using expert opinion. In this present study expert elicitation involved an assessment of five vulnerability factors: the frequency of the threat; the magnitude of CO_2 emissions from the threat; the capacity of seagrass to recover from the disturbance; the capacity of seagrass to resist the threat; and the spatial scale of the threat, to assess the vulnarabiltiy of seagrass soil C_{org} stocks to be emitted as CO_2 (Table 1). The CO_2 emissions from seagrass soils (i.e., the potential impact) following disturbance can be considered a function of two aspects: the initial soil C_{org} stock, with higher stocks equating to higher potential emissions; and the nature of the threats and their consequences, with some types likely to result in greater soil C_{org} erosion (and remineralisation) than others. The abiotic characteristics of the seagrass habitat, including geomorphology and exposure to hydrodynamic energy, which have also been shown to influence the degree of soil C_{org} erosion following disturbances (Salinas et al. 2020), were not included in the survey owing to the large variability of geomorphological settings at small spatial scales. The experts were provided with information on the aims and objectives of the study and a description of the 20 threats, the five vulnerability factors, and the scoring approach. The scores were ranked from 0 to 3 where 3 was the highest value (Table 1; S1). Respondents also evaluated the certainty of their responses for each threat and these certainty values were applied equally to each vulnerability factor associated with the threat.

Table 1
Definition of vulnerability factors assessed for each threat (for more details see S1).

Vulnerability factors	Definition	Range of scores (0–3)
Frequency	The occurrence of the threat causing CO_2 emissions	Never – Persistent
Magnitude	Magnitude of CO_2 emissions from the threat	None – High
Recovery	Recovery of CO_2 sequestration capacity after a disturbance (in years)	No impact – >10 years
Resistance	The level of threat required to cause CO_2 emissions	No impact – Low
Spatial scale	The scale of the threat (in km^2)	No impact – >1,000 km^2

3. Assessment of survey results

Recognising the varying expertise among participants, including in the range of threats examined, we weighted each participant's score based on their self-assessed certainty scores. The calculation of the final vulnerability score followed Halpern et al. (2007). Weighted values for each respondent for a given vulnerability factor associated with a particular threat were calculated by multiplying their 0–3 scores by their respective certainty scores for that threat, then dividing this number by the sum of certainty scores from all respondents for the given vulnerability factor measure. The sum of the weighted values from all respondents gives the weighted average for each particular threat-vulnerability factor combination. This calculation was repeated for each vulnerability factor for a particular threat. An overall vulnerability score was calculated for each threat, by taking the mean value of the weighted averages of the five corresponding vulnerability factors. Each threat was subsequently ranked (1 to 20) in accordance with this score. The overall vulnerability scores were also calculated with and without the inclusion of spatial scale scores. This was because global scale threats would always have a higher score than local scale threats in the spatial scale ranking, so by excluding spatial scale scores, the threats to CO_2 emissions are scored based on a risk per unit area, removing the spatial bias. To assess the consensus among the responses, a coefficient of variance (CV) value was calculated for the five different vulnerability factors within each of the 20 types of threats. It was not possible to account for cumulative impacts of multiple threats on CO_2 emissions from seagrass soil C_{org} stocks, owing to the complexity associated with their assessment and the scarcity of empirical data.

4. Literature review for impacts of disturbances on seagrass C_{org} stocks and CO_2 emissions

In order to assess empirical work addressing the impact of disturbances on seagrass soil C_{org} stocks, we performed a systematic review on peer-reviewed literature in English using the Web of Science database in August 2022 with the search string: (seagrass OR *Zostera* OR *Posidonia* OR *Thalassia* OR *Cymodocea* OR *Phyllospadix* OR *Enhalus* OR *Halophila* OR *Amphibolis* OR *Halodule* OR *Syringodium* OR *Thalassodendron*) AND ("blue carbon" OR "carbon storage" OR "carbon stock" OR "carbon erosion" OR "carbon loss" OR "CO2 emission") AND (impact* OR anthropogenic activ* OR eutroph* OR "climate change" OR invasive* OR mooring* OR propeller OR bioturbation OR dredg* OR pollut* OR ship* OR jetty OR graz*). We followed the procedure of Moher et al. (2009) in order to identify, screen and include relevant studies. The time interval for the literature search was 2013 to present (August 2022), and was set in relation to Greiner et al. (2013), which was the first publication addressing the topic. We found 249 published articles in total from which 66 were selected after screening of title and abstract (see S2 for the review flow diagram). In order to be included in this review, the following criteria needed to be fulfilled: data should be published in peer-reviewed journals and attributed to one or several specific disturbances, time since the occurrence of impact reported, and measured or estimated initial C_{org} stocks and losses due to disturbance. The disturbances reported in the literature were embedded into the same disturbance categories as requested in the expert survey, i.e., climate change, human-induced and biological threats and direct and indirect impacts. The data extracted from the literature was used to assess C_{org} stock losses and the potential CO_2 emissions in relation to initial C_{org} stocks prior to disturbance (i.e., baseline) for the soil depths reported in the studies, and differences explored based on the type of disturbance, and the time period since disturbance. For estimating potential CO_2 emissions, we converted the soil C_{org} stock loss to CO_2 by multiplying by 3.67 (the molecular ratio of CO_2 to C). For the purpose of standardization, we assumed that all of the soil C_{org} stock loss measured was remineralized and released as CO_2. While this assumption is arguable, it does not affect the relative weighting of different risks to CO_2 emissions, only the absolute magnitude of emissions; a topic that is not addressed in this study.

4.1. Statistical analysis

All statistical analyses were performed in R (version 3.6.1). Chi squared analyses were used to assess whether experts responded differently based on either their career stage or the biogeographic region in which they reside. Based on the individual expert responses, one-way ANOVA models were used to compare categories of threats (i.e., climate change, human-induced and biological processes) for each of the vulnerability factors (i.e., spatial scale; frequency; magnitude; resistance, recovery), as well as the overall vulnerability score of threats (with and without spatial scale). If significant differences were found, Tukey HSD post-hoc tests with Bonferroni adjustment were used to distinguish significant differences among threat categories. Student t-tests were used when comparing the direct and indirect threat categories, both for the expert survey and literature review results as well as comparing the survey responses from male and female experts. For establishing relationships among the vulnerability factors, linear regression models were used. Furthermore, linear regressions models were also used to assess the relationships between potential CO_2 emissions and initial C_{org} stocks for short– (0 – 6 years) and long–term (30 – 60 years) impacts extracted from the literature review data.

5. Results

5.1. Respondent demographics and assessment of survey results

The raw but de-identified data collected in this study are available in S3. Among the respondent experts there was a rather even distribution among career-stages with mid-stage researchers being slightly underrepresented (Table 2), and with 51% being male and 49% being female. There was no significant difference in response based on gender for any of the vulnerability factors ($p > 0.05$) while there were some differences among respondents from different career stages regarding certainty and frequency, with early career researchers expressing lower certainty than late career researchers ($\chi^2 = 64.54$, $p < 0.0001$). Early career researchers also tended to score lower frequency values representing the occurrence of the threat causing CO_2 emissions ($\chi^2 = 20.89$, $p < 0.01$). Mid-career researchers estimated relatively higher magnitudes of CO_2 emissions ($\chi^2 = 20.89$, $p < 0.01$) and higher resistance scores for CO_2 emissions ($\chi^2 = 16.61$, $p < 0.05$). As most respondents were from either the Indo-Pacific ($n = 11$) and the Southern Ocean ($n = 19$) biogeographic regions (Table 2), we compared responses from these two regions. There were no differences in the opinions of experts from these two regions in the magnitude, resistance and certainty of CO_2 emissions over all threats. However, those from the Indo-Pacific estimated relatively smaller spatial scales of impact ($\chi^2 = 8.42$, $p < 0.05$) and lower frequency of events ($\chi^2 = 16.37$, $p < 0.01$), while the Southern Oceania respondents reported slower recovery rates ($\chi^2 = 8.15$, $p < 0.05$).

6. Expert elicitation of seagrass threats to CO_2 emissions

The overall vulnerability score for the biological threats (average ± SD 1.41 ± 0.26), which took into account spatial scale, was significantly lower ($p < 0.05$) than for human-induced (1.71 ± 0.28) and climate change (2.02 ± 0.35) threats, however no significant differences among threat categories were observed when spatial scale was excluded (Fig. 2a). The recovery scores of biological threats were significantly lower (i.e., a quicker recovery of CO_2 sequestration capacity) compared to the other categories of threats ($p < 0.05$), while climate change threats were considered by the experts to impact larger spatial scales (>1,000 km^2) than biological or human-induced threats ($p < 0.05$; Fig, 2a). This indicates that biological and human-induced threats tended to be small-scaled, and there is a greater potential for recovery from impacts associated with biological threats (Fig. 2). In the expert responses there were higher levels of certainty about human-induced threats. The greatest mean (±SD) certainty score was for mooring (2.07 ± 0.75), followed by anchoring (2.02 ± 0.82), propeller scars (2.02 ± 0.76) and marina/jetty development (2.00 ± 0.84). The experts were least certain about the threat to CO_2 emissions from invasive species (1.03 ± 0.66), ocean acidification (1.20 ± 0.81) and sea level rise (1.25 ± 0.78) (Fig. S1). There seemed to be more agreement among experts on the impacts of building of marinas or jetties, dredging events and heat waves (CV ranging from 23 to 56%) on the potential CO_2 emissions from seagrass soil Corg stocks, while the impacts of grazing (above- and belowground), ocean acidification and invasive species on CO_2 emissions had the lowest agreement among experts (CV ranging from 42 to 120%; Table S1). The comparison of direct and indirect threats affecting seagrass soil C_{org} stocks and CO_2 emissions (see Fig. 1 for the classification of threats involving direct and indirect disturbance pathways) by experts, showed that direct threats act at lower spatial scales ($p < 0.001$) but can result in greater CO_2 emissions at lower magnitudes due to the lower resistance by seagrasses ($p < 0.05$). However, there was no difference in the overall vulnerability score between direct and indirect effects regardless of spatial scale inclusion (Fig. 2b). The magnitude scores were positively correlated with the recovery ($p < 0.0001$; $R^2 = 0.68$), resistance ($p < 0.0001$; $R^2 = 0.49$) and spatial scale ($p < 0.001$; $R^2 = 0.29$) scores, and recovery was positively correlated to resistance ($p < 0.001$; $R^2 = 0.48$) and spatial scale ($p < 0.001$; $R^2 = 0.29$) (Fig. 3).

The expert perception of how threats can result in potential CO_2 emissions from seagrass soils showed that threats related to climate change (i.e., sea level rise, storms and cyclones, heat waves and gradual ocean warming), as well as sediment run-off entailed the highest ranking and thus largest risks of CO_2 emissions (i.e., ranked numbers 1–5 when including the spatial scale; Table 3). The threats that result in higher risk of CO_2 emissions per unit area (excluding the spatial scale), were direct and local threats, such as dredging and building of a marina or jetty, but also sedimentation and climate change threats (i.e., sea level rise and gradual ocean warming) (Table 3). In addition, biological threats such as grazing of the aboveground biomass (both with and without considering the spatial scale) and bioturbation were also perceived to have a low impact on soil C_{org} stocks, despite having a high frequency of occurrence. Other threats considering to be low risk were anchor damage and ocean acidification.

Table 2
Number of participants based on their biogeographic region and career stage.

Career-stage	Biogeographic region						
	Indo-Pacific	Mediterranean	North Atlantic	North Pacific	Southern Ocean	Tropical Atlantic	Total
Early	2	3	1		8		14
Mid	1	2	1		4	2	10
Late	8	1		1	7		17
Total	11	6	2	1	19	2	41

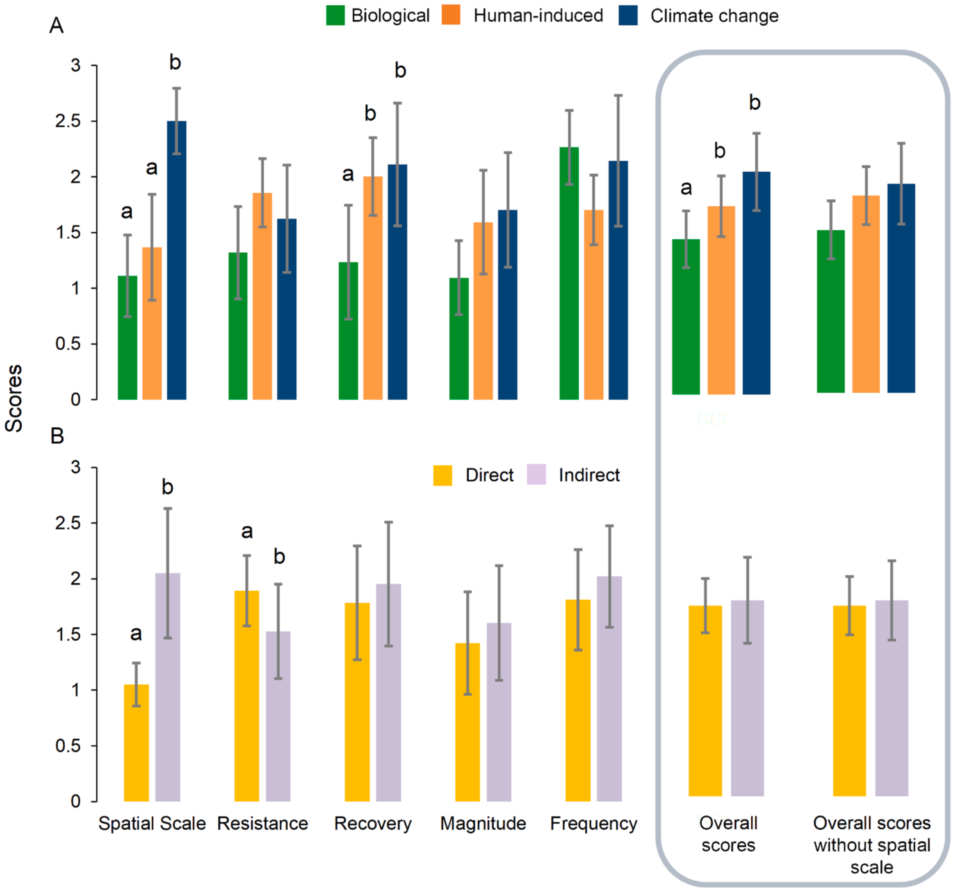

Fig. 2. Mean ± SD scores of vulnerability factors categorized by type of threats (A) biological, human-induced and climate change threats, and (B) direct and indirect threats. The values are weighted for certainty. The letters above the bars (a, b) show significant differences, while the absence of letters (or shared letters) indicate no significant differences among the categories.

7. Findings from the literature review

A total of 13 peer-reviewed studies that estimated soil C_{org} stock loss or CO_2 emissions following seagrass disturbance were identified, and in several of these studies there were assessments of multiple disturbances (see S4 for the literature review data) resulting in 22 different data entries for disturbances. The studies assessed change in soil C_{org} stocks within a certain soil depth, averaging (±SE) 24 ± 6 cm across the 13 studies compiled. One study assessed change in the top 1 cm soil thickness, whereas another one in the top 100 cm; however, the soil thickness assessed in the rest of studies ranged from 5 to 50 cm. A clear majority of these studies investigated indirect impacts (71%) and on local scales (59%) compared to regional and global scale assessments (23 and 18%, respectively). Most of the studies focused on human-induced disturbances (55%) compared to biological (23%) and climate change impacts (23%). The average loss of soil C_{org} stock from direct impacts (59 ± 29%) was up to 2-fold higher than for indirect impacts (20 ± 22%; Fig. 4a); although these differences were not statistically significant. The low number of studies and the high variability among studies resulted in high levels of uncertainty in estimates of soil C_{org} loss (Fig. 4). The time since impact (0–6 years compared to 30–60 years) had a significant effect on the % soil C_{org} loss ($p < 0.001$; Fig. 4b) and from this, we inferred a proportional difference in the potential CO_2 emission of short- ($p < 0.001$; $R^2 = 0.46$) and long-term ($p < 0.05$; $R^2 = 0.43$) impacts, assuming 100% remineralization of the soil C_{org} stock lost in all cases (Fig. 5).

8. Discussion

The findings from the expert survey highlighted differences in the risks of CO_2 emissions from seagrass soils based on the nature of threats. The expert's ranking of threats indicated that indirect threats acting at large scales (such as gradual ocean warming, heatwaves and sea level rise) and direct threats linked to low resistance to the disturbance (e.g., dredging and building of marina or jetty) have a higher potential risk for CO_2 emissions (Fig. 6). In addition, threats causing larger CO_2 emissions were perceived to result in longer-time periods for seagrass to recover their carbon sequestration capacity. The compilation of empirical data showed a clear lack of studies assessing seagrass soil C_{org} stock loss and/or CO_2 emissions associated with seagrass ecosystem disturbances (13 peer-reviewed studies in total). The findings from the literature data showed increasing CO_2 emissions with higher soil C_{org} stocks prior to disturbances, and with longer time span since the disturbance event. Owing to the scarcity of robust, empirically-derived emission factors, the experts elicitation and ranking of threats provides an indicator (relative ranking) of the potential for CO_2 emissions from seagrass habitat from a range of disturbances. This can aid conservation and restoration actions by managers, policy makers and entrepreneurs aimed at managing seagrass ecosystems for climate change mitigation.

The expert assessment, provided by respondents with a wide regional and career-stage distribution and gender-balance, captured a diversity of opinions on how threats to seagrass ecosystems can result in potential CO_2 emissions. There were differences in the rating of the vulnerability factors among regions, with experts from the Indo-Pacific envisaging smaller spatial scale of impact by disturbances and lower frequency of disturbance events, while the Southern Ocean experts highlighted

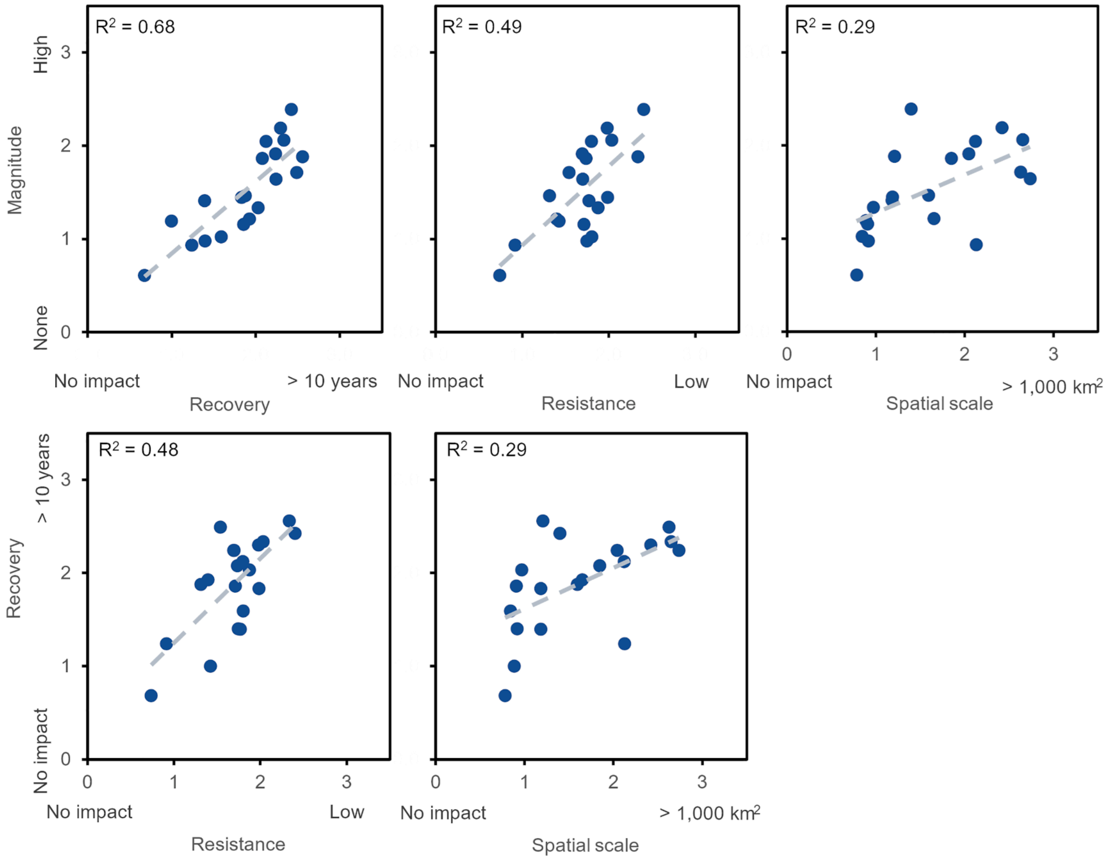

Fig. 3. Correlations between vulnerability factors that showed significant relationships. For details on the ranking scores (0–3) see Table 1.

relatively slower recovery rates after disturbance. Differences in seagrass life-history strategies and their distribution worldwide (Short et al. 2007; Kilminster et al. 2015), together with differences in the main threats affecting seagrass meadows across regions (Waycott et al. 2009; Dunic et al. 2021), could be an explanation of these differences in opinion. Tropical meadows are typically formed by opportunistic and colonising species that have a fast shoot turnover rate, low physiological resistance and rapid ability to recover compared to dominant species found in temperate and subtropical regions that form persistent meadows that are more resistant to pressures. Indeed, experts from the Indo-Pacific rated small-scale threats (i.e., mooring and anchoring damage) with the highest certainty, which reflects a common observation of damage to seagrasses in tropical regions (Macreadie et al. 2014; Serrano et al. 2016b). In contrast, Southern Ocean seagrass systems are dominated by large, slow-growing and perennial species (e.g., *Posidonia* spp. and *Amphibolis* spp.) which typically are very slow to recover (Kilminster et al. 2015). Different career-stages among the respondents from the Indo-Pacific and Southern Ocean regions also contribute to differences in certainty and frequency scores. Overall, the early career-stage researchers tended to reply with relatively lower certainty and higher frequency scores, which might be associated with less experience within this group compared to mid- and late-career experts, and mid-career experts envisaged higher CO_2 emissions (i.e., magnitude) but also higher resistance to disturbance. Despite the inherent ability of seagrasses to withstand disturbances (Vergés et al. 2008; O'Brien et al. 2018), increasing scientific evidence support the hypothesis that crossing ecological thresholds will impact soil C_{org} stocks and result in high potential CO_2 emissions (Carnell et al. 2020): Owing to the multiple factors influencing potential CO_2 emissions from seagrass soils, which include the type of threat and biotic and abiotic variables, and the internationalization of seagrass research, it is complex to establish cause-effect relationships between scores and career stages and/or bioregions of residence.

The higher overall scores (2.1–2.3) reported for climate change threats (apart from ocean acidification) reflect the view that threats acting at large spatial scales have the highest likelihood of larger CO_2 emissions owing to the greater seagrass area impacted and slower recovery. Biogeochemical and ecological processes following large losses in seagrass extent, including changes in hydrodynamic patterns, sediment destabilization and erosion, re-oxygenation of soil C_{org} stocks and CO_2 emissions, and loss of recovery potential (through sexual and asexual reproduction) (Lovelock et al. 2017; Dahl et al. 2018, Dahl et al. 2021; James et al. 2020), likely cause long-term impacts on seagrass soil C_{org} stocks and sequestration capacity. For instance, the reports of massive seagrass loss of$>$1,000 km^2 after a marine heat wave in Shark Bay, Australia in 2010–11 (Arias-Ortiz et al. 2018; Strydom et al. 2020; Serrano et al. 2021), together with the almost complete loss of seagrass area (decreased from about 10 to 0.1 km^2) following a typhoon in 2019 in the Yellow River Delta, China (Yue et al. 2021) entailed soil C_{org} stock losses, and support the growing concern around climate change threatening seagrass ecosystems. Ocean acidification was the only climate change-related threat with a low ranking to cause CO_2 emissions, matching the general view that the capacity of seagrasses to modify seawater pH through photosynthesis and respiration can counteract the impacts of ocean acidification (Ricart et al. 2021). The experts indicated that seagrasses have a low resistance to sea level rise, gradual ocean warming and heat waves. Indeed, increased rates of greenhouse gas emissions (i.e., carbon dioxide and methane) are expected with ocean warming (Pedersen et al. 2011; Thorhaug et al. 2017; Burkholz et al. 2020; George et al. 2020), and regions where climate change is more prevalent will likely experience higher CO_2 emissions from these threats. Increasing ocean warming and heat wave events will also likely affect species that already grow close to their thermal limit (George et al. 2018), including seagrass meadows in the shallow upper tidal zone or

Table 3

The weighted mean scores of the vulnerability factors (from 0 to 3) for the different threats, and the overall scores for the seagrass CO_2 emissions and the ranking of threats with and without considering the spatial scale factor are shown. The overall scores were weighted based on the certainty scores provided by the experts. Ag = aboveground, bg = belowground.

	Vulnerability Factors					**Overall Scores and Ranking**			
Threats	Frequency	Magnitude	Recovery	Resistance	Spatial Scale	Including spatial scale	Rank	Without spatial scale	Rank
Biological									
Grazing (Ag)	2.3	0.6	0.7	0.8	0.8	1.0	20	1.1	20
Bioturbation	2.6	1.2	1.0	1.4	0.9	1.4	16	1.6	16
Grazing (Ag and Bg)	2.3	1.4	1.4	1.7	1.2	1.6	11	1.7	11
Invasive species	1.8	1.2	1.9	1.4	1.6	1.6	12	1.6	14
Human-induced									
Anchor damage	1.8	1.0	1.4	1.7	0.9	1.4	19	1.5	18
Propeller scar	1.8	1.0	1.6	1.8	0.8	1.4	17	1.6	15
Mooring	1.7	1.2	1.9	1.7	0.9	1.5	14	1.6	12
Ship grounding	1.0	1.3	2.0	1.9	1.0	1.4	15	1.6	13
Trawling	1.8	1.4	1.8	2.0	1.2	1.6	10	1.8	10
Building marina/jetty	1.7	1.9	2.6	2.3	1.2	1.9	8	2.1	3
Dredging event	1.5	2.4	2.5	2.4	1.4	2.1	6	2.2	1
Turbid plumes	1.6	1.9	2.1	1.7	1.8	1.8	9	1.8	9
Sedimentation	2.2	2.0	2.1	1.8	2.1	2.1	5	2.0	5
Toxicant pollution	1.5	1.5	1.9	1.3	1.6	1.6	13	1.5	17
Eutrophication	2.0	1.9	2.3	1.7	2.1	2.0	7	2.0	7
Climate change									
Heat waves	1.7	2.1	2.3	2.0	2.7	2.1	3	2.0	6
Storms	1.5	2.2	2.3	2.0	2.4	2.1	4	2.0	8
Ocean warming	2.7	1.6	2.2	1.7	2.7	2.2	2	2.1	4
Ocean acidification	2.1	0.9	1.1	0.8	2.0	1.4	18	1.3	19
Sea level rise	2.7	1.8	2.5	1.6	2.7	2.3	1	2.1	2

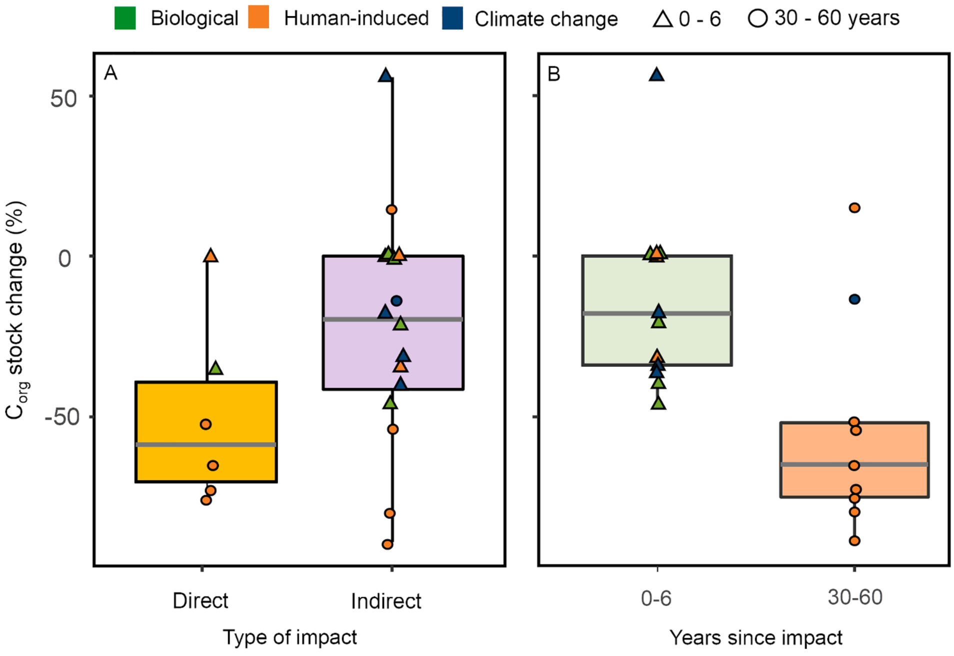

Fig. 4. Summary of peer-reviewed literature on the effects of seagrass disturbance on soil C_{org} stocks. The data compiled were categorized into direct and indirect disturbances. (A) Soil C_{org} stock change (%) according to direct and indirect disturbances. (B) Soil C_{org} stock change (%) according to time since impact (0 to 6 years, and 30 to 60 years). The colours indicate the nature of the threat: biological (green), human-induced (orange) and climate change (dark blue) impacts. The black line in the middle of the boxplots show the median, 75% and 25% percentiles create the top and bottom of the box and the error bars indicate the 95% confidence interval.

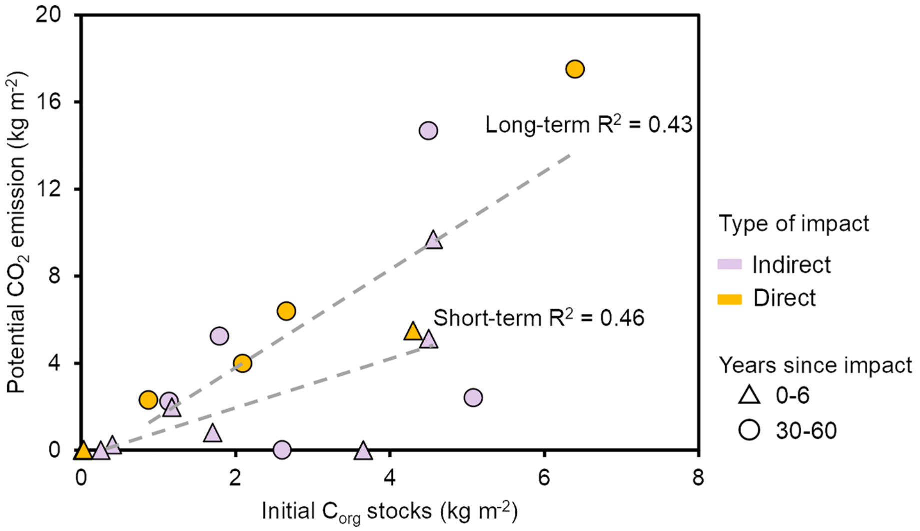

Fig. 5. Correlations between seagrass initial soil C_{org} stocks and estimated potential CO_2 emissions for two categories of time since impact (short-term = 0 to 6 years, triangles; and long-term = 30 to 60 years, circles). The colours indicate the nature of disturbances: indirect (purple) and direct (orange). Data extracted from Macreadie et al., 2014, 2015; Dahl et al., 2016; Serrano et al. 2016b; Thorhaug et al. 2017; Trevathan-Tackett et al., 2018; Githaiga et al.,2019; Carnell et al. 2020; Salinas et al. 2020; Aoki et al. 2021; Yue et al. 2021; Gangal et al. 2021; Serrano et al. 2021).

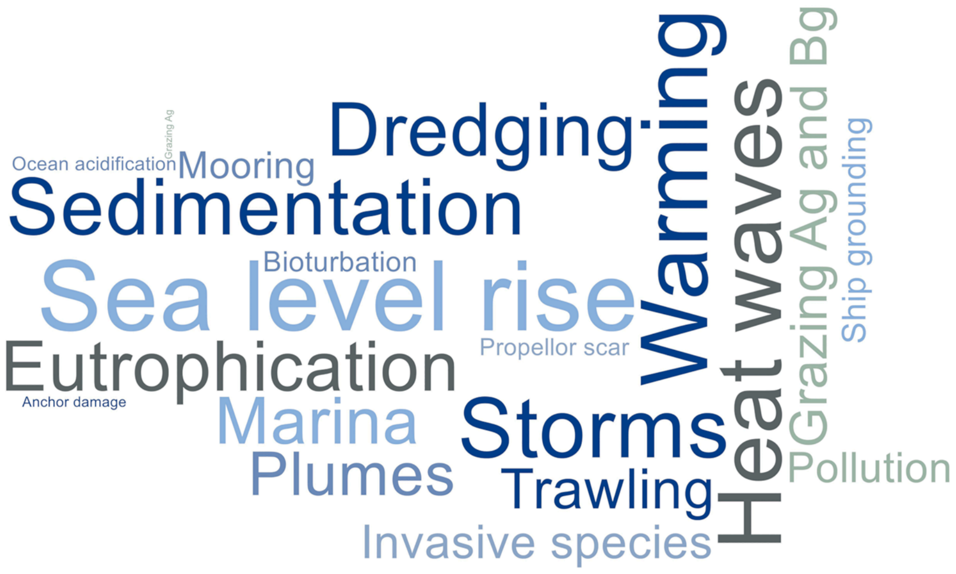

Fig. 6. The ranking of threats with inclusion of the spatial scale as relative size of the word. Ag = aboveground, Bg = Belowground, Marina = building of marina or jetty, Dredging = dredging event, Plumes = turbid plumes, Pollution = Toxicant pollution, Warming = Ocean warming.

temperate species that reside close to tropical regions (Hyndes et al. 2017). The seagrass response to sea level rise depends on the accretion rate of the soil and the possibility of a landward shift (and potential coastal squeeze) of the meadow (Saunders et al. 2013; Valle et al. 2014; Albert et al. 2017), as well as the coastal slope as water depth regulates the depth distribution of seagrass due to decreasing light irradiance with increasing water depth (Duarte 1991). Through the literature review it was also clear that climate change impacts on seagrass C_{org} storage have recently been addressed in blue carbon research, in particular the potential impacts of heat waves (Arias-Ortiz et al. 2018; Aoki et al. 2021; Serrano et al. 2021). Although only 23% of the peer-reviewed literature (5 out of 22 data entries in our literature review) related to climate change threats, the results of this survey together with the scientific evidence indicate the importance of climate change threats to seagrass soil C_{org} stocks and resultant potential CO_2 emissions. This could indicate a current shift of perspective within the expert community towards focusing research on global scale threats, although previous expert surveys on coastal habitat threats (i.e., seagrass meadows and coral reefs) ranked local to regional scales threats higher than climate change threats (Grech et al. 2012; Wear 2016).

The inclusion of spatial scale had a strong influence on the ranking of human-induced threats to CO_2 emissions. When spatial scale was included, sedimentation, eutrophication and dredging events were ranked among the highest (numbers 5 to 7) within the human-induced threats (with overall vulnerability scores of 2.0 – 2.1). When considering risk per unit area (i.e., spatial scale excluded), dredging events and building of a marina or jetty had the highest ranks (1 and 3) with overall vulnerability scores of 2.1 and 2.4, respectively. This was mainly because these threats were given low recovery scores after the disturbance as coastal constructions lead to permanent loss of the habitat, while eutrophication can result in long-term water quality degradation, which limits seagrass recovery and generally occurs over larger spatial scales than dredging and the construction of a marina or jetty (Boström et al. 2002). Both sedimentation and eutrophication had high spatial scale scores (Schmidt et al. 2012), which is supported by the increasing evidence showcasing the severity of these threats triggering high CO_2 emissions (Trevathan-Tackett et al., 2018; Salinas et al. 2020). Sedimentation and eutrophication together with coastal development are generally considered to be key causes of seagrass decline worldwide (Waycott et al. 2009; Dunic et al. 2021). This was supported with a strong certainty around human-induced threats including sedimentation and eutrophication and there was a clear consensus among experts on the effects of several of the local-scale threats, including mooring, anchoring and propeller scares, and construction of marinas and jetties on CO_2 emissions from soil C_{org} stocks, and much empirical work has been focused on assessing these type of disturbances (e.g., Macreadie et al., 2014, 2015; Serrano et al. 2016; Thorhaug et al. 2017). However, many threats that operate at local scales were ranked low for the risk of CO_2 emissions from seagrass habitats owing to the relatively low extent of impact. Although the cumulative impacts from multiple threats that operate from local to global scales were not assessed in this study, the influence of these interactions will likely exacerbate CO_2 emissions from seagrass soils.

Biological disturbances were generally given a low ranking (ranking numbers 11, 12, 16 and 20 out of 20). Although several of the threats (i.e., grazing and bioturbation) were considered to occur on a high frequency, the rapid recovery and limited spatial scale of impact rendered a low overall score (1–1.6). Grazing (of both above- and belowground biomass) is a natural and intrinsic process in many seagrass ecosystems (Valentine et al. 1997; Moran and Bjorndal 2007), so the recovery potential is considered to be high. However, outbreaks of sea urchins or increasing populations of sea turtles can lead to substantial loss of seagrass soil C_{org} stocks and potential CO_2 emissions (Carnell et al. 2020; Gangal et al. 2021). Nowadays, however, these events are rare from a global perspective and less pressing when compared to the threats imposed by climate change. Other biological threats, such as invasive species and bioturbation, had low certainty scores, indicating a poor understanding by experts and that very little or no empirical data exists (but see Thomson et al. 2019). In addition, the low certainty may also be explained by variation in soil C_{org} impacts depending on what invasive species is considered. Bioturbation was also ranked 16 out of 20, indicting the low potential for CO_2 emission from this threat, although the role of bioturbating organisms for re-oxidation of the seagrass soil and hence the degradation rate of organic matter is important (Aller, 1994; Thomson et al. 2019) but oxygenation of the rhizosphere (through bioturbation) can also stimulate plant growth (Smith et al. 2009).

Most of the reviewed literature of direct impacts on seagrass soil C_{org} were related to human activities on a local scale, while the origin of indirect impacts was more diverse and related to either climate change, human-induced or biological disturbances, and although not statistically significant, there was an indication that direct impacts have up to 2.5-fold larger impact on soil C_{org} stock losses than indirect impacts. On small spatial–temporal scales, threats directly impacting soil C_{org} stocks are likely to immediately result in soil erosion and potential CO_2 emissions, and may be less influenced by environmental characteristics (such as hydrodynamic energy) compared to indirect disturbances. The level of CO_2 emissions from seagrass disturbance can therefore vary depending on the type and intensity of disturbance, the environmental conditions as well as the morphology of the seagrass species. For instance, the disappearance of the living seagrass habitat for the Mediterranean species *Posidonia oceanica* was found to have little effect on soil C_{org} erosion due to the intact belowground root and rhizome system stabilizing the soil (Piñeiro-Juncal et al. 2021), while the local hydrodynamic activity within a seagrass meadow can cause large differences in the degree of soil C_{org} erosion (Salinas et al. 2020). Interestingly, potential CO_2 emissions following seagrass disturbance might even be underestimated, as it does not consider the emission of other more potent greenhouse gases (i.e., methane and nitrous oxide) (Lyimo et al. 2018; Al-Haj and Fulweiler 2020; Murray et al. 2020; Rosentreter et al. 2021), or the continued erosion and remineralization of organic matter in seagrass soils that occur below the top 5–50 cm benchmark typically reported in the existing literature. A continued erosion of soil C_{org} stocks after a disturbance (given that the seagrass meadow cannot recover) could therefore yield higher CO_2 emissions, which is indicated by the limited empirical evidence showing increasing emissions with increasing time span since disturbance. This highlights the need for immediate management actions such as restoration after disturbance, and for long-term management actions and monitoring to prevent prolonged and enhanced CO_2 emissions. The differences in the soil thickness assessed for change in soil C_{org} stocks is an important parameter to consider. Among the literature reviewed, the range of assessed soil depth was large (from top 1 cm to top 100 cm) but the average soil depth (24 ± 6 cm) was overall similar across studies, and the normalization of change in soil C_{org} as percentage of initial stock levels allowed establishing comparisons among studies. However, the publication of raw dataset for being able to standardize soil C_{org} losses across studies together with more research on the topic could result in more comprehensive estimates in the future.

The results from the expert survey can be used as a roadmap to prioritise blue carbon management actions aimed at mitigating climate change, and to guide future empirical studies to support blue carbon activities. Based on expert opinions, it seems that not all threats to seagrass soil CO_2 emissions are of equal concern (Fig. 6). In particular, climate change threats (i.e., sea level rise, heat waves and gradual ocean warming) was thought to compromise the resilience of seagrass meadows and cause large scale seagrass losses and CO_2 emissions, which stresses the necessity to implement conservation actions and prevent irreversible, climate change-driven tipping points in ecosystem functioning. Current management is mostly focused on the local scale (Cullen-Unsworth and Unsworth 2016), and to our knowledge strategies to effectively mitigate climate change-driven impacts besides reducing greenhouse gas emissions are challenging. This should be developed through collaboration of governments, industry, research institutes and local communities (Serrano et al. 2021) to reduce anthropogenic CO_2 emissions, increase research efforts to fill knowledge gaps and execute restoration projects. In the light of ongoing climate change threats, various management efforts to improve seagrass recovery potential have been suggested, including removing of dead seagrass biomass after a large die-off to avoid toxic sulfide production in the soil and blooms of phytoplankton and bacteria from heightened releases of nutrients linked to high in situ degradation of organic matter (Arias-Ortiz et al. 2018), keeping herbivory at natural levels to circumvent overgrazing (Atwood et al., 2015) and initiating seed and seedling restoration programs using genotypes of species assemblages that are more resilient to global warming (Serrano et al. 2021). We found some indications in the published literature that there has been a shift of focus towards climate change impacts in recent years, showing the increased awareness within the seagrass research community for the severity and potential magnitude of these impacts (Arias-Ortiz et al. 2018; Serrano et al. 2021; Yue et al. 2021), although still most studies are on small scale disturbances. Based on the expert survey and empirical evidence we suggest that future perspectives for research on CO_2 emission and management to mitigate soil C_{org} stock erosion following blue carbon habitat loss should focus on:

1. Increasing the scientific evidence on the impacts of specific disturbances to better understand the effects on soil C_{org} and CO_2 emissions, especially for climate change impacts.
2. Improving the understanding on the fate of the eroded soil C_{org} stocks to more accurately estimate CO_2 emissions (as well as other greenhouse gases, i.e., methane and nitrous oxide); and
3. Assessing the spatial and temporal scales relevant for soil C_{org} losses and resultant CO_2 emissions.

This will lead to a greater understanding on CO_2 emissions from disturbances of seagrass and especially on the impacts of climate change threats, which according to the expert survey were highlighted as the most important threat globally to seagrass C_{org} stocks and CO_2 emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is presented in the text, figures and supplementary information

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2022.102632.

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