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Linking threat maps with management to guide conservation investment

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ABSTRACT

Stressors to marine ecosystems are increasing, driven by human activities in the sea and on land, and climate change. Cumulative impact maps highlight regions affected by multiple human activities, but efficient conservation investment requires linking dominant pressures to management actions that best address the particular drivers of impacts. We rebuild cumulative impact maps by stressor type (climate change, marine and land) at a global scale to evaluate the expected effectiveness of various management strategies for all coastal territories. Average cumulative impact from non-marine stressors (climate and land) was double those of marine impacts at a national level. The greatest climate impacts by country were in the waters of Pacific Island and Antarctic territories; in the Caspian Sea region and East-Asia for land impacts; and in the waters of European, East-Asian and Caribbean countries for marine impacts. We developed a conservation-effectiveness indicator for the 10 worst-impacted countries in each of the three stressor categories. The indicator considered common management tools for each stressor category: ecosystem-based adaptation and disaster risk reduction (climate), marine protected areas (marine) and integrated coastal management (land). Key disparities were found between broad-scale management of marine ecosystems and the dominant stressors, with existing management in tropical island nations likely insufficient to address intense impacts from climate change. These countries also typically had low performance on governance indicators, suggesting challenges in implementing new mitigation. We highlight trade-offs in making decisions for stressor mitigation and offer strategic guidance on identifying locations to target management of marine, land, or climate impacts.

1. Introduction

Marine ecosystems are threatened by multiple stressors driven by direct human activities in the ocean, but also indirectly from global climate change and, in the case of coastal ecosystems, from human activities on land. The coastal zone is particularly vulnerable, with research showing these ecosystems are undergoing the most rapid increase in human pressures globally (Halpern et al., 2019). Cumulative human impact maps (e.g., Halpern et al., 2015) describe spatial variation in the multiple stressors that ecosystems face and their combined impacts given associated ecosystem vulnerability. Such maps are often used to guide international conservation investment (Allan et al., 2019b), and inform spatial plans (e.g., see review by Stelzenmüller et al. (2014)). To maximise the effectiveness of these maps in guiding conservation funding and action, information on the distribution and intensity of stressors and their impacts must be explicitly paired with the consequences of targeted management actions (Tulloch et al., 2015). For actions to have maximum effectiveness at mitigating cumulative impacts they should address the dominant threats faced by ecosystems.

Marine conservation is commonly approached by managing the impacts of ocean-based activities such as fishing and shipping. marine protected areas (MPAs) address local marine stressors, but the challenge of managing stressors generated by activities outside of the local marine environment remains (Brown et al., 2019; Selkoe et al., 2008). For example, MPAs provide little direct protection from global climate drivers that have resulted in extensive marine ecological impacts, such as coral bleaching and sea-level rise (Hoegh-Guldberg and Bruno, 2010), but can enhance resilience of some ecosystems to climate impacts. MPAs also cannot directly mitigate the downstream impacts of

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Table 1
Stressors and their assigned category (marine, land or climate), with asterisks indicating which studies the data was derived from * = Halpern et al. (2015), ** = Halpern et al. (2019).

Stressor category	Feasibility of management	Stressors	Number of stressors used
Marine	Can be managed through action in the ocean (e.g., MPAs)	Fishing – artisanal, demersal destructive, demersal non-destructive (high and low bycatch), pelagic (high and low bycatch)** Invasive species* Light** Ocean pollution* Benthic structures (e.g., oil rigs)* Shipping (commercial)**	11
Land	Cannot be managed by action in the ocean – requires action on the land in connected catchments	Nutrient pollution ** Organic pollution ** Inorganic pollution * Population (human density) **	4
Climate	Cannot be managed through land or sea action alone – requires global action (i.e., reduce carbon emissions)	Sea-surface temperature ** Ultraviolet light* Sea-level rise ** Ocean acidification **	4

land-use and altered runoff regimes on coastal marine ecosystems (Fabricius, 2005). Climate and land-based stressors operate across different jurisdictions at vastly different scales from marine stressors, and their impacts are displaced from the stressor's origin, so both require cross- or multi-jurisdictional action (Boersma and Parrish, 1999; Klein et al., 2010). Management of most stressors by individual countries is largely restricted, however, to the boundaries of their national waters.

Effective marine conservation requires an understanding of how dominant stressors and their impacts vary across countries and ecosystems and then identifying the specific management actions, as well as the scale of action (e.g., marine, land, or global in the case of climate change), required to address the dominant stressors. Without this information, gaps in marine protection are inevitable, even in areas with active marine management (Devillers et al., 2015). Past efforts have highlighted gaps in marine protection from fishing stressors (Kuempel et al., 2019) and hotspots of land-based impact (Halpern et al., 2009). Extending these to a global analysis of where gaps in current threat management exist relative to the impacts caused by activities across oceans, on the land or from climate change could help inform new global conservation targets (e.g., Sala et al., 2018; Visconti et al., 2019). Many countries are signatories to the United Nations' Convention on Biological Diversity (CBD), with the central goal of ensuring 10% of oceans are conserved through networks of MPAs by 2020 ('Aichi Target 11'). Targets that consider human pressures and impacts across jurisdictions are necessary to direct conservation efforts towards actions where they can have the greatest benefits to ecosystems, as well as highlight transboundary issues where multinational actions are needed.

Although identification of gaps in management of marine environments are needed, there are additional challenges to implementing the best management. Local governance, for instance, can be inadequate to deal with impacts resulting from activities within their own jurisdiction. Although governance effectiveness has previously been linked to social resilience of marine environments to stressors (Halpern et al., 2012), there is little guidance on how issues of scale mismatch between stressors and impacts, and associated issues of governance capacity, may be affecting the ability of individual countries to mitigate human stressors. Information on expected management feasibility is crucial for guiding conservation investment and preventing perverse outcomes (Tulloch et al., 2014).

Here, we re-evaluate the cumulative impacts on marine ecosystems (Halpern et al., 2019) to identify differences in impacts from three stressor categories – land, marine, and climate - and evaluate this information through a management lens to better guide conservation investment. We compare the spatial distribution of marine, land and global climate impacts at a national level, and then explore where potential targeted mitigation towards impacts stemming from each stressor category would result in reduced impacts to marine ecosystems. Given the increases in stressors upon the coastal zone in particular (Halpern et al., 2019), we also compare impacts for offshore versus coastal ecosystems, exploring intensity and distribution of impacts at a country-level scale to help identify priorities for management. These outputs provide valuable information on where management action at different scales (land, marine, or global in the case of climate change) will give the best biodiversity outcomes at a national level.

We then demonstrate an approach to linking impact maps with actions at a national level. In this demonstration, we aimed to identify where existing policies and management may or may not be sufficient for mitigating impacts at the national scale. We rank the worst affected countries and evaluate three commonly used tools to mitigate marine, land or climate impacts (MPAs, integrated coastal management (ICM), climate hazard reduction respectively) in these countries. We develop a simple index that can be used to highlight countries where potential mismatches in existing management or policy exist to address the intensity of impacts from different stressors. Finally, we compare relative indices of governance and regulatory effectiveness to identify countries where barriers to effective management may exist and inform potential for implementing new conservation actions.

2. Methods

To explore cumulative impacts of human stressors in the sea, on adjacent land, and from climate change – and the feasibility of managing these impacts – we used four stressor categories (*D*) (Table 1):

1. Marine-based, requiring marine action locally or regionally – these impacts can be managed through direct marine action
2. Land-based, requiring action on the land for mitigation – cannot be managed through direct marine action
3. Global climate change, requiring multi-jurisdictional action around the world for mitigation – cannot be managed through direct marine action alone
4. Non-marine, consisting of the sum of impacts from land and global stressors (2 & 3, above).

To map the impacts of these different stressor categories on marine ecosystems we utilized data on the intensity and cumulative impact (cumulative stressor intensity x ecosystem vulnerability across all ecosystems) of 19 different anthropogenic stressors to marine environments globally from 2013 (Halpern et al., 2015, 2019, Table 1). These data represent the finest resolution (1km^2 cells), most up-to-date maps of marine stressors available, as well as the most comprehensive, including data on marine stressors (e.g., fishing), land-based stressors (e.g., nutrient runoff), and global stressors (climate change). We evaluated 19 ecosystems, excluding deepwater and surface water used in previous cumulative impact analyses.

2.1. Cumulative impacts by stressor category

To assess cumulative impacts by stressor category for our chosen ecosystems, we built on previous methods by Halpern et al. (2015, 2019). Fourteen of the stressors were recently updated for 2013 (Halpern et al., 2019), but five were not updated, because they lacked adequate data over time (Table 1). We therefore substituted data from Halpern et al. (2015) for the five stressors not updated in Halpern et al. (2019) to undertake our cumulative impact analyses. For the updated stressors (Table 1), we obtained stressor-by-ecosystem vulnerability combinations from Halpern et al. (2019), which are estimates of the impact on each ecosystem (E_j), calculated by multiplying the stressor's intensity rescaled to a value between 0 and 1 (P_i) by an ecosystem vulnerability (V_{ij}) for every cell 'i' where the ecosystem 'j' occurs (Halpern et al., 2007). For the stressors that were not updated, we recalculated the stressor-by-ecosystem vulnerability combinations for our 19 ecosystems from rescaled stressor data, vulnerability indices and ecosystem data (Halpern et al., 2015). We modified previous cumulative impact methods by combining the resulting 19 stressor-by-ecosystem vulnerability combinations according to their respective category (D = land "L", marine "O", climate "C", Table 1), rather than as a whole cumulative total. The cumulative impact score (I_{Di}) of each stressor category, across all ecosystems, was thus estimated by summing the stressor-by-ecosystem vulnerability combinations and dividing by the number of ecosystems (m) within each cell, as follows:

$$I_{Di} = \frac{\left(\sum_{i=1}^{n}\sum_{j=1}^{m} P_i * E_j * V_{ij}\right)_D}{m}$$

As such, I_{Di} represents the cumulative impact of each stressor category averaged across all the ecosystems rather than the summed impact for all ecosystems (Halpern et al., 2009). Although the average scoring method may underestimate true impacts on some coastal regions where there are multiple overlapping ecosystem, this accounts for possible bias from using coarse maps of intertidal ecosystems (beach, rocky intertidal, intertidal mud, and saltmarsh), which previous studies assume to exist in all coastline cells (Halpern et al., 2019).

2.2. Analysis of impacts by stressor category

We calculated total cumulative impacts for every cell, and calculated average impacts for every country's exclusive economic zone (EEZ). We then calculated average impacts across all cells in every EEZ for each stressor category to identify the primary drivers at a national scale. We mapped stressor impacts by EEZ globally (Fig. A1), and plotted impacts by EEZ for pair-wise comparison. To calculate the relative contribution of different stressor categories to total cumulative impact (termed "percent" impacts), we divided cumulative scores for each category by the total cumulative impact score in each cell to produce a percent ranging from 0 to 100. We also created cumulative impact maps by stressor category for coastal and offshore zones, summing impact combinations for each of the 11 nearshore coastal ecosystems versus the 8 offshore ecosystems (Table 2). We compared outputs for the primary drivers of impacts in these zones by EEZ. We tested the sensitivity of our results to using different metrics when ranking the worst-affected countries (Appendix 1).

We conducted a secondary classification to identify the highest (90th percentile) cumulative impacts globally (hereafter 'intense impacts') in each grid call for each of the stressor categories independently (Côté et al., 2016). We calculated the proportion of grid cells within each EEZ that were in the top 90th percentile for each stressor category, as a national index of 'intense impacts'.

2.3. Conservation effectiveness indicator

We then conducted an analysis exploring synergies and possible gaps in existing conservation measures for marine, land and global climate change stressor impacts in highly-impacted countries. We first ranked the top 10 worst-ranked nations for each stressor category globally (where cumulative impacts from each stressor category in national waters (EEZ) were the greatest). For climate and marine stressors, we ranked countries by their average score. For land stressors, we aggregated the impact scores at a coarser scale (10km^2) to identify local hotspots (based on the maximum value in each EEZ), to reduce bias from averaging impacts across large EEZs (due to the point-source nature of land-based stressor impacts and narrow distribution along the coastline). We then developed a stressor conservation index ("C_D") for each worst-ranked country to represent national marine, land, and climate stressor management. We chose common management strategies for each stressor category used by conservation agencies globally as a proxy for management: MPAs for marine stressors, ICM policies and practices for land stressors, and climate hazard reduction strategies (ecosystem-based adaptation (EbA) and ecosystem-based disaster risk reduction (Eco-DRR) for climate stressors (see Appendix 1 for detail). We also identified whether each worst-ranked nation was a signatory to any treaties with the objective of managing the impacts of each stressor category (e.g., Paris Agreement adopted under the United Nations Framework Convention on Climate Change (UNFCCC, 2015)), which were incorporated in the calculation of each index (whereby more policies correlate with higher governance values, see Supplementary methods). For the marine conservation index, we used the World Database on Protected Areas (WDPA) (UNEP-WCMC and IUCN, 2019) and calculated the areal extent of MPAs proportional to each countries' EEZ with the appropriate high level of protection to stop human activities in the marine realm, deemed to be those MPAs with IUCN Category Status I-IV. MPAs listed under Category V-VI permit human uses and resource extraction, whilst other categories such as the UNESCO-Biosphere Reserves and Ramsar Wetlands listings typically cannot prevent certain levels of resource use and extraction, and so these were not considered adequate protection against marine stressors. For the land management index, we performed literature searches to identify whether there is any active ICM in effect for the worst-ranked countries, calculated the average of the total number of local, national and international policies for each nation, and then divided this score by the maximum total value across all countries to obtain a relative score for each country (Appendix 1). For the climate stressor management index, we reviewed the

Table 2
Ecosystems aggregated into each zone (coastal or offshore) for comparative analyses.

Ecosystem zone	Definition	Ecosystems included	Notes
Coastal	Vegetated or non-vegetated ecosystems distributed predominantly at shallow depths in the nearshore subtidal, intertidal, and supratidal	Beach, coral reef, intertidal mud, kelp, mangroves, rocky intertidal, rocky reef, saltmarsh, seagrass, shellfish reef and subtidal soft bottom	Some of these habitats also may be found at deeper depths in offshore areas.
Offshore	Deeper offshore and oceanic ecosystems	Pelagic demersal habitats, deep hard bottom, deep soft benthic, hard shelf, hard slope, soft shelf, soft slope, seamounts	

EbA and Eco-DRR literature to obtain the number of ecosystem-based projects for climate change adaptation (Giffin et al. unpublished data) and disaster risk reduction strategies for our selected countries (Appendix 1). We calculated a relative climate hazard reduction management metric by dividing the number of climate hazard reduction strategies for each country by the maximum number of measures for all countries. We normalised each index score for the worst-ranked countries relative to the maximum score for that stressor category (transforming the maximum value to 1, and the minimum to 0), so that scores were comparable between countries.

These levers represent the primary tools used by conservation agencies to manage coastal stressors at ecosystem scales (Agardy, 2000; Jupiter et al., 2014), and conservation agencies are key users of global threat maps (Tulloch et al., 2015). Furthermore, data for each of these levers exist at a global scale, allowing them to be directly comparable between countries. We acknowledge that there may be other mechanisms in place at a national level used to manage local impacts of stressors (e.g., fisheries management and regulations), and that each tool can indirectly provide conservation benefits for non-primary stressors (e.g., EbA can help with non-climate stressors), but their primary purpose is to address the impacts from each of the respective stressors.

We provided conservation indices for every stressor category for all 30 countries regardless of which category drove the initial top 10 ranking, for ease of comparison. We then created a simple conservation effectiveness index (CE_D) for each country and stressor category (in terms of their policies and conservation tools, C_D, addressed above) relative to average EEZ impacts for each category (I_D), as follows:

$$\mathrm{CE}_D = C_D - I_D,$$

whereby higher values of the CE metric indicate countries are potentially more equipped to deal with impacts for the respective stressor category due to the management in place when compared to lower values. Finally, we explored the relative feasibility of countries to implement effective conservation action mitigating marine, land or climate stressors, using the World Governance Indicator data (WGI, Kaufmann et al., 2011) from 2013 (to match stressor data). We performed regressions of indices of government effectiveness and regulatory quality against the cumulative impact by stressor category to visualize the relationship between stressor impacts and the WGI.

3. Results

The greatest total cumulative impacts in 2013 were spread across the northern hemisphere, with the top 10 impacted countries from Europe (Slovenia, Bosnia and Herzegovina, Bulgaria, Romania, Greece) and Asia/Middle East (Singapore, Jordan, Georgia, Turkey, Iraq) (Fig. A2, Table A1). These high total impact scores were driven largely by a high percentage (> 50%) of non-marine (land and climate) impacts, which were on average double (1.11) those of marine stressors (0.60) across all 232 countries and territories evaluated. For > 85% of countries globally (N = 202), non-marine stressor impacts made up more than half of the cumulative impact score, largely due to the high contribution of climate impacts (Fig. 2, Table A1). More than 51 million km^2 of the world's oceans are experiencing intense impacts (≥90th percentile) from non-marine stressors (global and land-based) on marine ecosystems, largely driven by global climate impacts (Fig. A3). These impacts, by definition, cannot be managed by actions in the marine realm alone. In some cases over 90% of the total impact score came from climate impacts alone (e.g., southern hemisphere polar regions, Figs. 2, A1). Beyond the Antarctic region, the contribution of globally-driven climate impacts to cumulative impacts were highest for tropical countries such as Kenya and Tanzania (> 85%); developing island countries in the Pacific such as Niue, Samoa, Solomon Islands, Tonga and Tuvalu (> 90%); and high-latitude countries of Canada, Greenland and Iceland (> 90%, Figs. 1, 2).

Land-based impacts on all marine ecosystems made up, on average, < 4% of the total score by country. A land-impacts hotspot was found in the land-locked Caspian Sea from surrounding Azerbaijan, Kazakhstan, and Turkmenistan, where over 60% of impacts were from land stressors alone (Figs. 1, 2b, Table A1), though total impact scores for these countries were in the bottom 1% overall (Figs. A1, A4). Countries in the middle-east had some of the highest levels of land-based impacts including Israel, Lebanon and Palestine (Fig. 2b–c), which were also in the top 20 worst-ranked nations for total cumulative impacts (Table A1). Our analysis of local land-based impact hotspots (aggregated at 10km^2) also ranked Singapore in the worst 10 countries for maximum land impacts, along with Australia, Brazil, Mexico and Russia (Table A2). Singapore also had the highest marine impacts globally (Table A1).

Impacts of marine stressors on all ecosystems were spread predominantly across the northern hemisphere (Fig. 1 blue regions, Figs. A1–A2). Only 15% (n = 32) of countries worldwide have more than half of their total cumulative score stemming from marine stressors, despite the predominance of marine-based stressors within the cumulative impact index (Table A1). Nations with the highest percentage of marine impacts include Belgium, Denmark, Germany and the Netherlands, as well as east-Asian countries of North Korea and Singapore, and middle-eastern countries including Israel and Lebanon (Fig. 2a,b). For the coastal zone alone, the highest marine impacts were found in Caribbean countries such as Bermuda, Saint Barthélemy and Saint-Maarten, African countries of Cameroon and Nigeria, Guernsey, and Johnston Atoll (an unincorporated territory of USA) (Fig. 2a,b) with negligible land-based impacts in these regions.

Disaggregation of impacts by ecosystem zones found total cumulative impact scores for coastal ecosystems were on average twice those of offshore ecosystems, driven in large part by the addition of land-based impacts (Fig. 3a). The greatest impacts on coastal ecosystems were found in countries across Asia, the Caribbean, Europe and North America, whilst several European countries including Sweden and the UK were found to have the greatest impacts on offshore ecosystems, in addition to Antarctic territories and some Pacific island countries (Fig. 3a). More than 11 million km^2 of coastal ecosystems were found to be currently affected by intense levels (top percentile) of land-based impacts. Mangrove ecosystems were the worst affected, with land impacts on average almost half the total cumulative score (I_c = 2.9) (Fig. A5). Sensitivity tests of individual impact of stressors within each stressor category found land impacts were on average three times greater for coastal ecosystems than the averaged sum of all fishing impacts (mean I_c 0.1). For most countries, land impacts were greater on coastal ecosystems than offshore, which were more heavily impacted by climate and marine stressors (Fig. 2c). There were several exceptions to this, including Iraq, Jordan, Kuwait, Slovenia, Singapore and Spain (Fig. 3), which had relatively high land-based impacts in offshore ecosystems (largely slope and shelf). Climate impacts made up 60% of the total impact score across all ecosystems on average. For coastal ecosystems, climate impacts were greater in general in countries in Oceania and South America than impacts from marine and land stressors. In contrast, marine stressors dominated impacts in offshore ecosystems of several European countries, including Denmark, Germany, the Netherlands, and Poland (Fig. 3, Table A1).

Our identification of worst-ranked countries by stressor category revealed no country was in more than one stressor 'top 10', resulting in 30 worst-ranked countries in total. Of the 10 top-ranked countries for climate change impacts (C_C), only four have existing climate hazard reduction projects (Fig. 4, Table A3). The Solomon Islands had the highest number of climate hazard reduction projects relative to the other worst-ranked countries (Fig. 4, Table A3), whilst several countries with substantially lower climate impacts have more mitigation projects (Brazil, India, Mexico, the Netherlands). Mismatches between climate impact management (C_C) and stressor impact intensity (I_C) were identified for several worst-ranked nations including Marshall Islands,

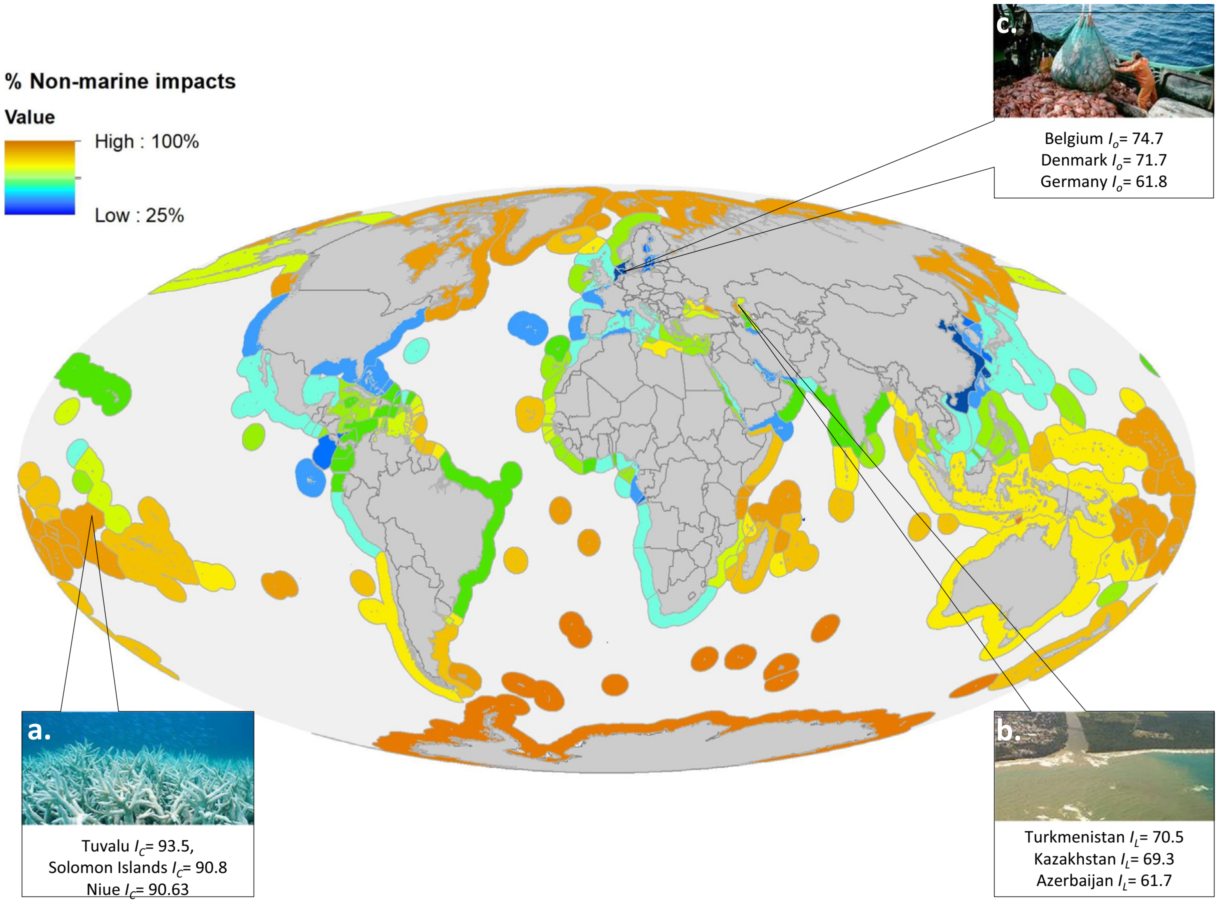

Fig. 1. Percentage cumulative impact by stressor category within national waters (EEZ), showing relative contribution to overall impact score from local marine stressors (blue) versus combined global and land- based stressors (orange), with territories where impacts are roughly 50/50 highlighted in light blue. Insets point to those areas with some of the highest percent impacts of particular stressors: a) Climate impacts in Pacific Island countries, b) Runoff from poor agricultural practices in the Caspian Sea and b) Marine stressors such as overfishing in European countries. We show impact scores for the top three hotspots and their highest stressor (I_C = climate, I_L = land, I_O = sea). Image copyright for a) https://www.fishforward.eu/; b) https://reefresilience.org/; c) HANDOUT/Reuters. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

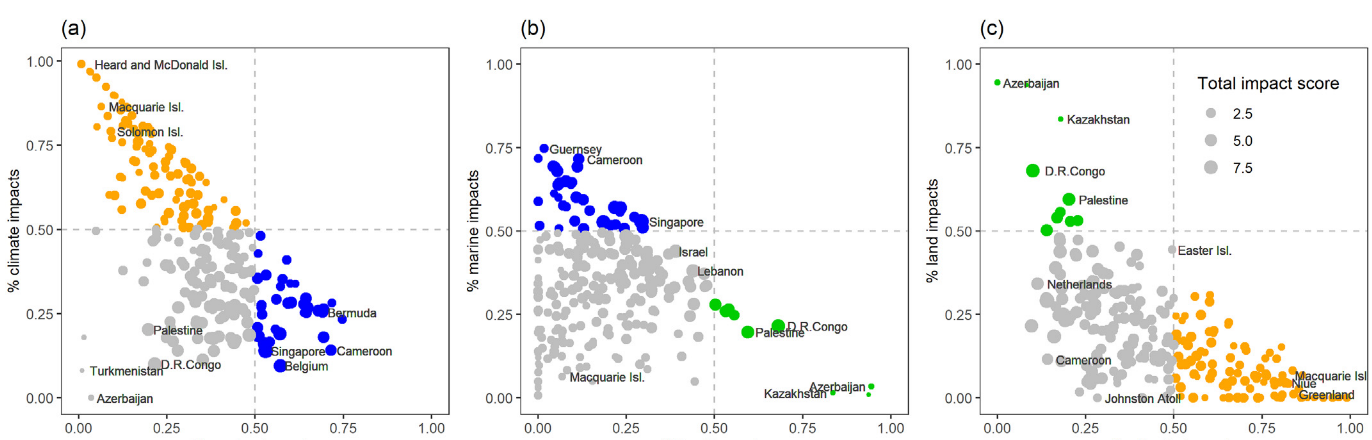

Fig. 2. Percent cumulative marine, land, or climate impacts for each nation for the coastal zone, shown by pairwise comparisons of stressor categories - a) climate and marine, b) land and marine, and c) climate and land (for all ecosystems see Fig. A4). Dominant impacts by stressor (> 50% of total cumulative impact score) are highlighted as follows: orange = climate impacts dominate, blue = marine impacts dominate, green = land impacts dominate. Grey indicates neither of the respective two stressor categories dominate in that particular EEZ. The quadrants highlight where reduction in cumulative impacts for respective stressor categories can potentially provide the biggest impact by nation – above the horizontal line = manage y-axis stressor category, to the right of the vertical line = manage x-axis stressor category. The size of the point indicates the total impact score for all cumulative impacts. E.g., for Bermuda (Panel a, to the right of the vertical line), marine impacts make up a higher percentage of the total cumulative score than climate impacts, so management for this region should focus on mitigating marine stressors to most effectively reduce cumulative impacts. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

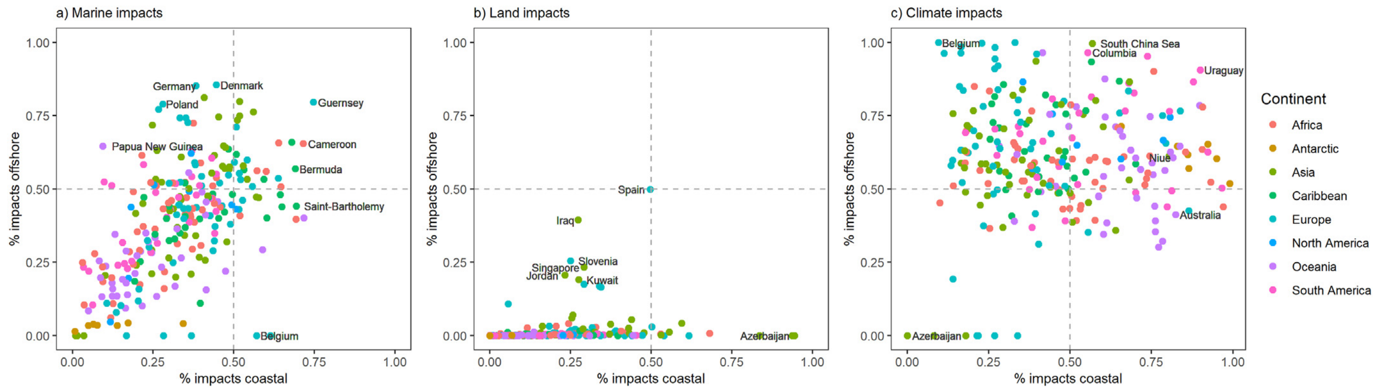

Fig. 3. Pair-wise comparison of cumulative impact scores by stressor category for coastal ecosystems (x-axis) and offshore ecosystems (y-axis) for a) marine, b) land, or c) climate impacts for all EEZs, coloured by contitent. Dashed lines identify the 50th percent impact point for each ecosystem zone. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

Nauru and Tonga (Fig. 4), where there are no or few existing climate hazard reduction projects in place (Table A3).

Of the highest-ranked countries from percent land-driven impacts, all are parties to international or multi-national treaties or policies that consider integrated coastal management within their guidelines (Table A2). All have national ICM policies in place, but four are lacking sub-national regional-scale ICM projects, including the top three hotspots (Azerbaijan, Kazakhstan, Turkmenistan). Despite high numbers of established MPAs in waters of the top-ranked countries for marine stressors impacts (in some cases > 200, Table A4), on average only 11% of these MPAs are listed under strict IUCN categories, although > 80% of MPAs in Germany are listed under strict categories. The average area of EEZ protected under strict categories is < 12% (Table A4). Three of the highest-ranked countries for marine impacts have no 'strict category' MPAs (Bahrain, North Korea, China Table A4, Fig. 4), and others have very little area with strict IUCN protection (Denmark, Poland, Singapore). In contrast, several European countries (Belgium, Germany, Netherlands) have high coverage of strict MPAs (up to 32%, Table A4).

Countries in Africa and Oceania generally have the lowest regulatory quality and government effectiveness indices (< 0), well below those of most European countries (regulatory quality mean = 0.53 and government effectiveness mean = 0.97, Fig. 5a, Table A5). When governance indices were compared with 90th percentile impact scores, countries in Africa and Oceania were found to have some of the most intense climate change impacts (mean = 0.23) (Fig. 5), and lowest scores for existing policy and management measures to mitigate climate

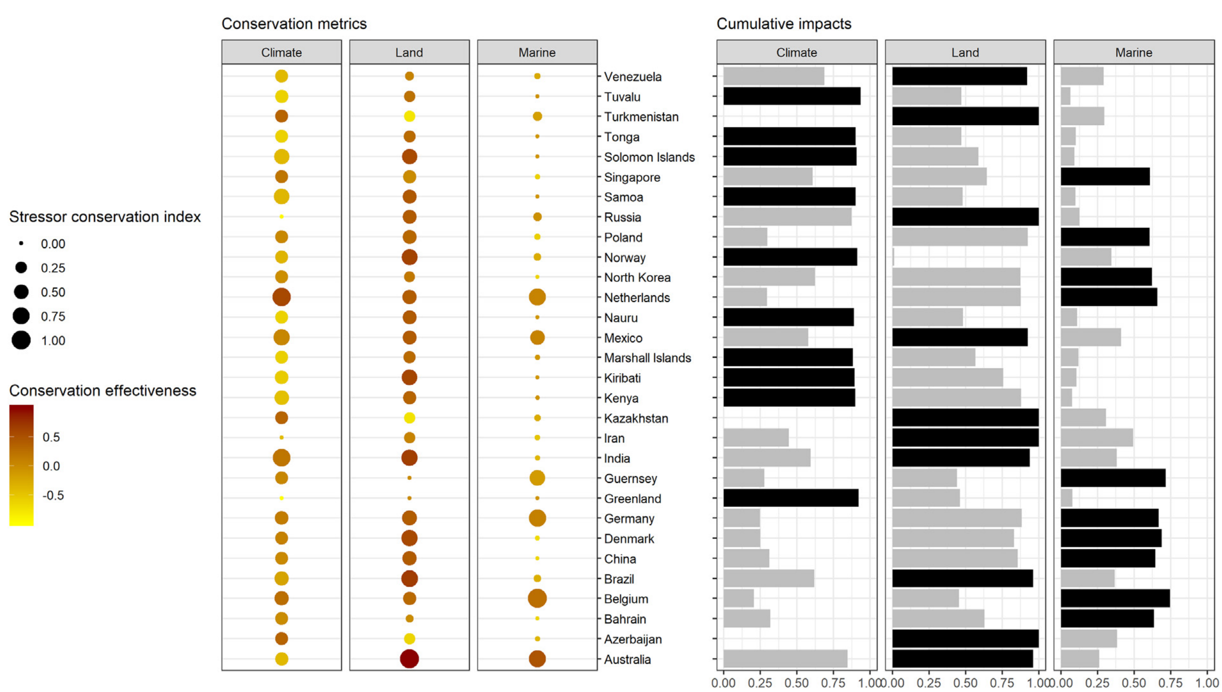

Fig. 4. Stressor conservation and management effectiveness indices (left) calculated for each worst-ranked country based on tools that are able to address impacts from climate, land and marine stressors. Relative values for the conservation index (C_D) are shown in size of dots (from small = few policies and/or management addressing that specific stressor category, to large = good policies and/or management) and the relative match (conservation effectiveness index, CE_D) between existing policies and/or management and impacts for each stressor category shown by colour (from poor match = yellow to good match = red). The right graph shows percent impacts of total cumulative impact for each stressor category for the top 10 ranked countries for each stressor category (black bar indicates that country was in the top 10 for that category). Note: for land stressors only, the maximum impact hotspot was used rather than the average to identify worst-ranked nation, but we show average impact values here. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

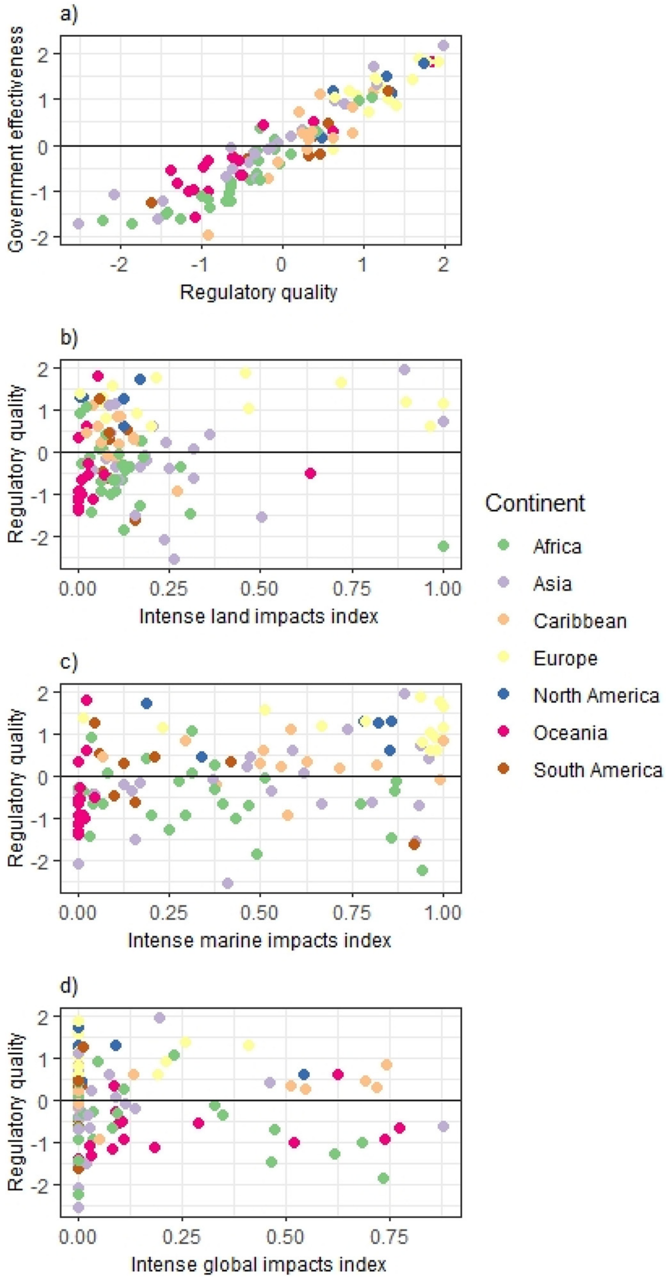

Fig. 5. a) Comparison of regulatory quality and government effectiveness by nation (World Governance Indicators 2013 data), showing high correlation between regulatory quality and government effectiveness; and evaluation of nations regulatory quality and index of intense impacts (90th percentile scores) from b) land, c) marine or d) global stressors by nation. For b–d, those countries above the line are considered to have increasingly high regulatory quality, and below the line, increasingly poor regulatory quality.

impacts (Fig. 4). African countries also had some of the highest levels of intense marine and land-based impacts. Although Caribbean countries have high levels of intense marine impacts occurring in their national waters, regulatory quality is also generally quite high in comparison to the African and Oceanic regions (and so they may be better placed to manage their local stressors) (Fig. 5). Similarly, European countries with the highest land impacts concomitantly have good indices of regulatory quality, along with relatively good existing management in place to mitigate these impacts (Fig. 5). The highest intense climate indices were also found in the waters of Caribbean countries (mean = 0.23), compared to low climate indices for South American (mean ≤0.01) and European (mean = 0.09) countries.

4. Discussion

Effective conservation decision-making relies both on understanding the drivers of different stressors and their impacts, but also being able to use this information effectively to guide management (Tulloch et al., 2015). We highlight some relatively simple approaches to linking cumulative stressor maps with management actions at different scales, and across different realms. By identifying the dominant drivers of impacts by country, we were able to estimate where local marine spatial management measures may be more effective, versus where alternative management in other jurisdictions (e.g., on the land, or addressing climate change) might be needed. Countries with the greatest proportion of climate impacts within their EEZ such as the Antarctic territories, Greenland, Pacific island countries such as Niue and low latitude tropical countries such as Kenya and Tanzania, could see considerable reductions in total cumulative impacts within their EEZs if global climate stressors were reduced (Fig. 2). In contrast, our analyses show considerable reductions in total cumulative impacts could be achieved by managing land-based stressors in middle-east countries surrounding the Caspian Sea, due to the high proportion of land impacts in the region, whilst marine impacts would be the most effective management choice for Caribbean countries such as Bermuda, Saint Barthélemy and Saint-Maarten, and African countries such as Cameroon and Nigeria. This information can help agencies seeking to invest in conservation both globally, and at national scales, to identify where targeted marine, land, or climate management will result in the greatest reduction in threats to biodiversity.

MPAs are often the most common management tool used by agencies to manage human activities in oceans (Agardy, 2000). We found some of the worst impacted regions by marine impacts currently have very low coverage of strict MPAs within their national waters (Fig. 4, Table A4). This finding is consistent with previous research (Kuempel et al., 2019), which found protection covered < 2% of high-threat areas. The average number of established MPAs under strict categories in worst-impacted countries is also low (11%). Some of these are developed countries or territories (Denmark, Singapore), which are much better resourced to establish and enforce MPAs, but may be restricted by political or regulatory power, or otherwise inadequate management capacity (Gill et al., 2017). Strategic placement of protected areas under strict IUCN categories (Ia-II) to stop manageable marine stressors in these regions (e.g., fishing, shipping, other extractive uses) could be an important step in improving outcomes for marine biodiversity, particularly in regions with very high total cumulative impacts such as Singapore. We note that in some cases countries had high numbers of protected areas not listed under IUCN categories (e.g., Denmark, with 253 MPAs) that may have been listed under other multi-national agreements (e.g., OSPAR, HELCOM) and may afford considerable protective measures at the local scale. For consistency across countries, however, we chose to focus our metric of effectiveness using IUCN category listing alone. In such cases our policy effectiveness metric for marine impacts likely underestimates the true protective capacity of existing management, but is a useful tool for global comparison between countries.

Effort to prevent the local impacts of different stressors on marine ecosystems through a number of targeted conservation strategies (ICM, MPA, climate hazard reduction) is currently not homogeneous across highly impacted countries (Fig. 4). For instance, local EbA and Eco-DRR measures to reduce globally-driven climate impacts varied across the island countries most affected by climate change impacts, with moderate climate hazard reduction coverage in some highly-impacted island countries (e.g., Samoa, Solomon Island, Tonga, Fig. 4), versus very low coverage in others (e.g., Tuvalu, Kiribati, Marshall Islands). These islands are highly vulnerable to climate change due to their relatively small land mass and high dependence on coastal ecosystem services

(Chape et al., 2005; Selig et al., 2019). Our climate hazard reduction index assesses two strategies (EbA and Eco-DRR) that can address the local impacts of climate change, but we acknowledge there are others (e.g., hard engineering) (Spalding et al., 2014) or actions that may not have been explicitly termed EbA or Eco-DRR. Further work could extend this analysis to more comprehensively review how marine conservation actions are addressing climate change, in particular addressing the multi-faceted conservation benefits that can be achieved using each lever (MPA, ICM, climate hazard reduction), or combinations of these levers. For instance, ICM and MPA efforts are increasingly designed to take into account cross-realm conservation benefits (Cicin-Sain and Belfiore, 2005). Similarly, MPAs can help marine biodiversity be more resilient to climate impacts (Bates et al., 2019), particularly when used within an EbA framework (Groves et al., 2012), but the explicit integration of climate change into general biodiversity legislation is still not common (e.g., Frost et al., 2016). Our approach of mapping global climate impacts could be used to guide priorities for establishing national climate-ready marine biodiversity legislation and policies (e.g., in Pacific island nations). We recognise that climate hazard reduction strategies cannot directly reduce the drivers of climate change, but instead focuses on preventing damage (in the case of Eco-DRR) or promoting ecosystem and associated human resilience (in the case of EbA) in the face of global change.

The indirect nature of both climate and land-based impacts on marine ecosystems requires management outside the marine realm that indirectly benefits marine species and ecosystems, such as through the global reduction of emissions or improved catchment management. All 30 worst-ranked countries are signatories to the Paris Agreement (UNFCCC, 2015), and other than Iran, Russia and Greenland, all have ratified the agreement and set Nationally Determined Contributions (NDCs) to reduce carbon emissions. In most cases, however, direct emission reduction by these smaller highly-impacted countries will do little to reduce the larger global impacts of climate stressors (Du Pont et al., 2017), reinforcing issues of inequities in the countries that are major emitters versus those that will see the greatest impacts (Hoad, 2015; Mcleod et al., 2019). Importantly, our pair-wise approach of mapping dominant cumulative impacts by driver (e.g., land/marine, or marine/climate, Fig. 2) can be used to identify countries where combinations of strategies (such as ICM and MPA) are most appropriate.

Our analyses highlighted regions where management of land-based stressors could substantially reduce impacts to coastal marine ecosystems, such as the Caspian Sea, Mediterranean Sea, and eastern Europe. Countries in this region also generally lacked sub-national ICM plans. This is consistent with earlier studies that found insufficient recognition of the impacts of land-based stressors in policy and legislation (Griffiths et al., 2020; Sorensen, 2002). Although information on the relative importance of land impacts and management is crucial at a regional scale to help guide local action, we note the importance of taking into account the relative magnitude of total cumulative impacts to effectively guide global action. For instance, countries in the Caspian Sea region had very low total cumulative impact scores, compared with other nations such as Palestine, Iraq, and Lebanon, which had both high percentages of land-driven impacts and were also in the top 20 worst-ranked nations for total cumulative impacts overall. By combining this information our approach can be used to guide where more effective land management might be needed at a global scale. We also note many of the worst-affected countries by land-driven impacts (e.g., Azerbaijan, Iraq, Iran, Palestine) have poor regulatory quality and ineffective governance (Kaufmann et al., 2011), and are facing high conflict, which can have negative consequences for biodiversity conservation (Gaynor et al., 2016). Therefore, whilst our analyses suggest a high need for management of land-based stressors in these regions, conservation actions may have a low chance of success.

Our analysis of regulatory and governance capacity versus cumulative impacts highlights where management of land- and marine-driven impacts is most feasible. For instance, low climate impacts combined with high regulatory capacity in regions such as Europe suggests greater success of both implementation and direct mitigation of local impacts from land and marine activities (Borja et al., 2010). In contrast, Oceania countries face high climate impacts combined with poor governance capacity, with top-down centralised governance potentially hindering adaptation and implementation of national actions (Adger, 2001; Nunn, 2009). Many of these countries, however, have relatively low locally-placed stressor impacts from marine and land activities combined to climate impacts, concurring with the multitude of calls for immediate global action to reduce carbon emissions versus improved local management (Côté and Darling, 2010). In contrast, African countries not only have some of the weakest governance capacity (Fig. 5a), but also some of the highest levels of intense marine and land-based impacts. Existing poor governance and lack of targeted policies, combined with high level corruption across sectors such as fisheries (Standing, 2008) may prevent effective cumulative impact management in this region.

Countries will need to manage inshore and offshore ecosystems differently, because impacts across these zones from each stressor category were weakly correlated (Fig. 3). Some of the worst impacts from non-marine stressors are to coastal wetland ecosystems such as saltmarsh and mangroves. Given that these are some of the most efficient natural carbon storage environments, maintenance of these habitats is crucial for slowing the impacts of carbon emissions (Atwood et al., 2017). There is a need for improving catchment management to address high sediment and nutrient loads that threaten coastal wetlands. These intertidal habitats could change significantly over the coming century due to global sea-level rise, suggesting immediate investment in mitigation, restoration, or even managed retreat of the shoreline to remove impervious surfaces will be key to prevent mangrove or seagrass loss (Saunders et al., 2013). Our driver-based framework could be used with new finer-resolution maps of individual coastal habitats (e.g., Mcowen et al., 2017) to inform such management at a global scale. Although marine activities have the highest number of stressors, with more than twice the number of stressors compared to non-marine stressors, we show that average impacts on most coastal ecosystems are considerably lower than those from displaced stressors from the land or global climate change. This may suggest that actions to mitigate or prevent marine-based human activities at the coastal interface are working, but also highlights the serious threat posed by land-based activities that may be jeopardising conservation measures in the coastal marine realm.

There are several caveats and assumptions in this analysis. Firstly, we do not consider all management and policy measures across countries. If these outputs were to be used to guide decision-making in impact hotspots, a more thorough review of management locally may be necessary (e.g., Griffiths et al., 2020; Portman et al., 2012; Sorensen, 2002). Such local studies should also consider the area in need of management. Secondly, our focus in the management analysis on Top 10 worst-ranked nations means we give little attention to countries just outside Top 10. Potentially a country can be just outside top 10 in more than one category but will not be highlighted here (e.g., Lithuania, ranked 11th and 13th worst for marine and land impacts respectively). Finally, although other cumulative impact studies tend to consider Caspian Sea as a pseudo-marine environment and exclude it when summarizing global ocean results (e.g., Halpern et al. 2008), we include it here given the disproportionally high impacts from land-based activities. Further global scale models are needed to link actions and their costs to prioritise specific actions for their effectiveness at reducing stressors and their impacts (Allan et al., 2019a).

4.1. Conclusion

Our method allows identification of regions and ecosystems where existing marine management may be insufficient in the face of global climate change or land-based human activities. The high proportion of climate impacts on marine ecosystems shown in this study relative to other stressor drivers globally reinforces the ubiquitous impacts of climate change that cannot be stopped by local action alone. Although ecosystem resilience to these impacts may be enhanced through local action (Knowlton and Jackson, 2008; Shaver et al., 2018), this is a continuing subject of debate (Côté and Darling, 2010), and attention should continue to be directed towards global action to reduce carbon emissions. Our approach can be used to easily identify those countries, regions or ecosystems more severely impacted by different stressors, where biodiversity is under intense human pressures and action is urgently needed. We demonstrate the urgent need for countries to undertake assessments of both local and displaced human stressors within national waters when planning for spatial marine management, or biodiversity objectives may be compromised. These efforts must be combined with better land management practices and enhanced efforts to reduce global carbon emissions, to ensure that nature conservation goals can be more fully achieved in the long term.

CRediT authorship contribution statement

VJDT: conceptualization, methodology, investigation, data curation, writing - original draft, review & editing, visualization. **MPT**: methodology, investigation, writing - review & editing, visualization. **ALG**: methodology, investigation, writing - review & editing. **BSH**: conceptualization, resources, writing - review & editing. **RC**: funding acquisition, writing - review & editing. **LG**: methodology, writing - review & editing. **MF**: data curation, writing - review & editing. **CJB**: supervision, conceptualization, writing - original draft, writing - review & editing, visualization.

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.

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Appendix A. Supplementary material

Supplementary methods and data to this article can be found online at https://doi.org/10.1016/j.biocon.2020.108527.

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