Manuscript ESD-2023-35
Considerations for determining warm-water coral reef tipping points.
Paul Pearce-Kelly, Andrew H. Altier, John F. Bruno, Christopher E. Cornwall, Melanie McField, Aarón Israel Muñiz-Castillo, Juan Rocha, Renee O. Setter, Charles Sheppard, Rosa Maria Roman-Cuesta, and Chris Yesson

Editor comments

While both Reviewers are positive on the merits of your submission, they also suggest a number of modifications and edits that may improve its reach and usefulness for the community. One of the Reviewers questions the subjectivity of the paper and the lack of a systematic review. I believe that this is perfectly acceptable in the context of a perspective piece. I would nonetheless ask you to provide a reasoned reply to those comments, since if your paper is published the reviews and replies will become openly accessible.

Authors response: We thank the editor for the positive response. We have included responses to all reviewer comments below.

As part of your revisions, try to avoid lengthening the text (or even try to shorten it if possible), as perspective pieces benefit from a concise and focused presentation. One of the Reviewers also highlights this point, and provides some specific suggestions of passages that could be cut or reduced.

Authors response: We have revised the text and the manuscript we have cut some text where possible and added where we needed to directly address reviewer comments, the net result is the length is consistent with the previous submission.

I am contacting you since, in making my decision on your manuscript yesterday, I forgot to attach a comment that I received from a potential reviewer, who ultimately did not accept to review your study. They based this comment purely on reading the paper abstract but I do agree that, since one typically reads the abstract to decide whether a paper is worth reading further, it is an important point to clarify. Some clarifications to this effect may also be necessary at other points in the paper, e.g. in the conclusions. I would therefore be grateful if you could include a reply to this comment too in your replies to reviewers when you submit a revised version of your manuscript.

Authors response: We have pasted these comments and our responses below

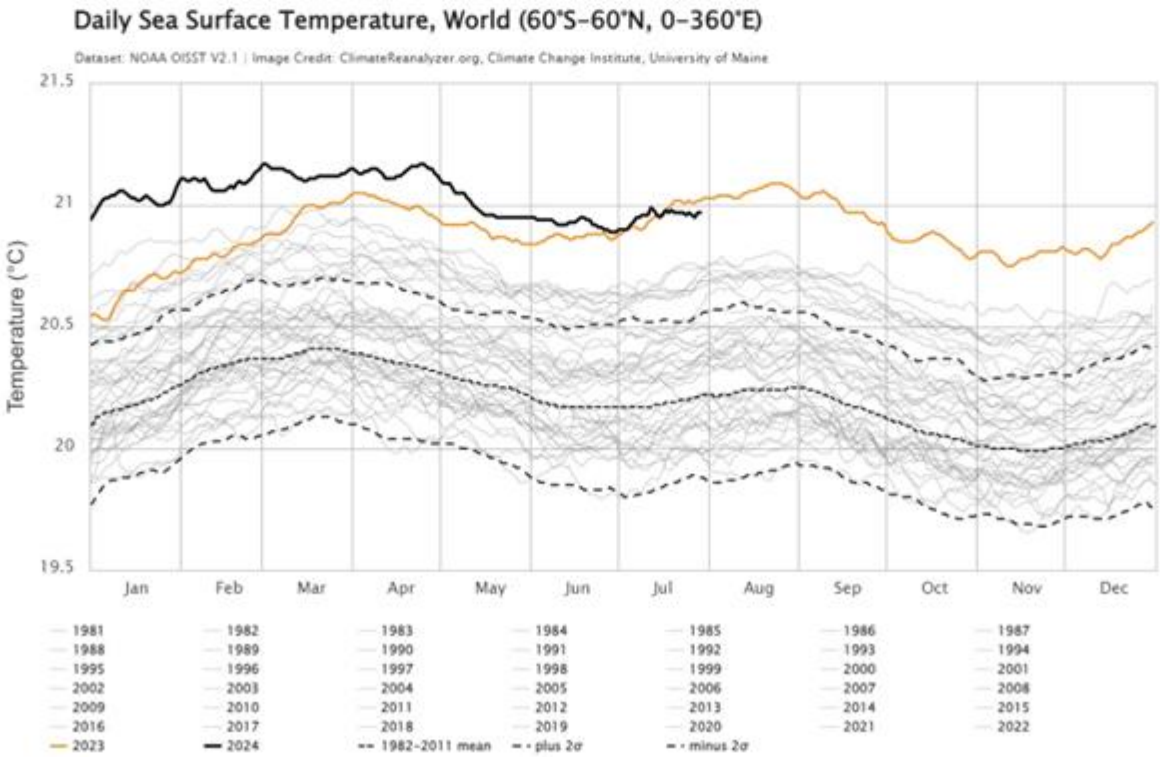
I see a real problem with the publication, in that we have already exceeded the thresholds that they conclude are the tipping points:
As of May 2022, we were already at a CO2 level of 421ppm, and in 2023, the temperature mean was 1.52C above pre-industrial levels, with 2024 running at about 1.7C. We are now in the midst of a thermal regime not expected until after 2050! See the below graph of mean ocean temperature: we clearly went over the tipping point in March of 2023. This new reality overshadows the publication and needs to be addressed.

The following statement is not based on our present reality:
"Uncertainties around tipping point sensitivities for such crucially important ecosystems underlines the imperative of robust assessment and, in the case of knowledge gaps, employing a precautionary principle favouring lower range tipping point values."

But perhaps the issue is that the abstract does not convey enough information?

More in detail: While can not be sure that we have gone over a tipping point before several years pass, in order for this paper to be relevant, it must discuss the elephant in the room: that everything is already over the predicted tipping points of the study. The study determined that the tipping point for CO2 is 350ppm, so the authors must mention that we are already at 421ppm and rapidly climbing! Assuming their study is relevant, the tipping point should already have occurred, which real-world observations confirm, despite many trying to hem and haw themselves out of accepting this new reality!

Based on scientific consensus, the IPCC reports clearly state that if nothing was done, that the planet would reach 1.5C above pre-industrial conditions by 2050. With the planet already exceeding 1.5C for both 2023 and 2024, we are in effect living in a thermal reality not expected until 2050. At this level of stress, the consensus is that >90% of all coral reefs would be dead. So based on what happened in 2023-24, we have already entered the great dying. To have this paper not acknowledge the present anomaly, even if not proven permanent, the paper loses most or all relevance. It gives the illusion that we are still under the thresholds if they don't clearly state what happened in 2023/24 and continues.



Author response: We have added text to acknowledge that some of the tipping points that we refer to have been crossed and others will be breached in the future. We talk in the manuscript about the inherent lag in the ocean system as well as lags within reef system response times which means there is not an instantaneous cause and effect, we hope there is still time for meaningful action to avoid some of the worst case scenarios. One open question is the extent to which crossing tipping point thresholds leads to irreversible change, or whether effective measures can mitigate or reverse the tipping points. We have made edits to highlight this. We feel this issue reinforces the urgency of this message.

Reviewer 1 - Lyndon DeVantier

General comments:
The manuscript is a very useful contribution outlining the potential tipping points arising from the many faceted issues, and interactions therein, that impact and increasingly threaten coral reefs. More information on the rationale for selection of 1.2 C and 350 ppt CO2 , as per the Veron et al. (2009) paper, would be useful. The paper could benefit from an expanded Section 13 on Chagos, to include more of the history, given it is one of the best studied, remote reef systems. The paper could also benefit from additional case-studies from Caribbean (nutrient enrichment, over-fishing, heat-waves, diseases, invasive species) and Great Barrier Reef (COTS, storms, run-off, heat waves, etc.), with summary noting differences in resilience among the three systems in respect to oceanographic connectivity and variability therein, coral population sizes, habitat heterogeneity, depth ranges etc. The paper would benefit from a hard edit to shorten some sections that appear repetitive; and with shifting of some text that may fit better in other sections. The Interactions sections may be better combined into one section following all those dealing specifically with the various stressors. This would help to minimize repetition. Eg. Ocean acidification section also presently includes comments on heat waves – those could be covered solely in the Interactions section. I have suggested shuffling and shifting some text accordingly (see below Lines 196-210). Similarly in Disruptions section, some text seems to fit better in Pollution section.

Author comments: In reference to including a separate interaction section. We had such a section in an earlier draft of the manuscript, but we chose to remove it. We felt that the separate section required a lot of repetition to reintroduce concepts. We felt it an important point to show the interactions alongside each stressor to create a more integrated whole.
In reference to the request for additional case studies. We note the editor guidelines that the manuscript in its current form requires trimming, so we don't have the space to make significant additions. We do provide a wide set of references that would allow readers to delve deeper into the Chagos and other regions if desired.

Specific comments:
References could be improved by including more of the primary sources. Some examples are provided. Citations in text need to be standardized as per journal requirements.

Author comments: We already provide an extensive reference list that includes many primary sources, but we feel the review-type publications that we cite are important to include as they are particularly relevant to tipping point considerations and act as gateways to more studies that we cannot individually cite due to space constraints. References have been checked for standardisation.

Lines 39-42:
"They are also among the most sensitive ecosystems to anthropogenic driven stressors with an estimated 50% of global live coral cover having been lost over the last 50 years (Souter et al., 2021, WWF 2022), primarily due to ocean warming (and related climate change threats of ocean acidification and deoxygenation), but in some locations also due to fishing, pollution, and disease (IPCC 2022)."
LD: Loss of cover – consider noting '… albeit with significant temporal fluctuations, as on the Great Barrier Reef (see AIMS LTMP reports).
https://www.aims.gov.au/monitoring-great-barrier-reef/gbr-condition-summary-2023-24
Also, Crown-of-thorns seastar (Acanthaster spp., COTS) outbreaks have caused sig. loss of coral cover across the Indo-Pacific since at least the 1960s. Heat-wave driven bleaching mortalities are increasing rapidly, since 1998. However, to date, loss of significant cover from ocean acidification

and deoxygenation is not well established (at least as far as I am aware), although these are serious looming threats. Nutrient enrichment (as a specific form of pollution) has had sig. impacts in the Caribbean and in parts of the Coral Triangle (eg. Areas of Java Sea).

Author response: This section is a broad-brush introduction so there is a limit to how much detail we can provide in this section, especially when we give details on each threat later in the document. We have amended this sentence to list more examples and indicate these are a selection of many threats.

Line 63:
"Approximately half the live coral cover on coral reefs has been lost since the 1870s …"
LD: presumably 1970s? Also recently estimated as dropping from 36 to 19 percent from 1997 to 2018 (Tebbett et al. 2023), with decreases most severe in the Western Atlantic and Central Pacific.
Tebbett SB, Connolly SR, Bellwood DR (2023) Benthic composition changes on coral reefs at global scales. Nat Ecol Evol 7: 71–81. https://doi.org/10.1038/s41559-022-01937-2

Author response: We have removed the potentially confusing reference to 1870. We thank the reviewer for the additional information, but the percentage stats of 36-19% refers to hard coral cover measured at a wide selection coral reef sites, which is a different metric to the global declines we are reporting here. We feel the important message here is the big picture global decline, so we have stuck with what we had.

Lines 67-70:
"… regional die-offs (e.g. Western and Central Indian Ocean, Great Barrier Reef, Mesoamerican Reefs) (Le Nohaïc et al., 2017; Amir 2022; Muñiz-Castillo et al., 2019; Obura et al., 2022; Sheppard et al., 2020), with most reef regions having experienced multiple die-off events (Darling et al., 2019; Cramer et al., 2020; IPCC 2022). Coral reef bleaching tipping points have already been reached in seven ocean systems (IPCC 2022)."
LD: On GBR, Earth's largest and arguably oceanographically best-connected reef system, and elsewhere, the 'die-offs' (coral cover losses) since the 1960s (COTS mainly) have been interspersed with recovery of cover, as has again recently happened, but prior to severe 2024 mass bleaching.
https://www.aims.gov.au/monitoring-great-barrier-reef/gbr-condition-summary-2023-24
This is not to downplay the seriousness of present impacts and future risk, nor the shifts in community structure (eg. See Richards ZT, Juszkiewicz DJ, Hoggett A (2021) Spatio-temporal persistence of scleractinian coral species at Lizard Island, Great Barrier Reef. Coral Reefs 40: 1369-1378. https://doi.org/10.1007/s00338-021-02144-4), but to add some nuance to the statements.

Author response: We have amended this section to add nuance using the reference provided as an example of sites bucking the widespread negative trend.

Line 100: "…is over centennial time (IPCC 2021).

Author response: changed for clarity to "... is more than a century"

Lines 104-105:
"(IPCC 2022). Overshoot of multidecadal time spans imply severe risks and irreversible impacts in many ecosystems Meyer et al. (2022), including …

Author response: changed for clarity to "Overshoot of multiple decades implies…"

Lines 110-111:

“Increasingly warmer ocean temperatures, driven by Anthropogenic climate change, compounded by El Niño heating events, is the primary stressor of regional scale mortality of scleractinian corals,. LD: … and ocean-basin …

Author response: added “... and ocean-basin…” as suggested, to show this operates at a larger scale.

Line 113:
Primary sources would be better: Eg. Cite Barbara Brown and John Ogden, Peter Glynn, Ove Hoegh-Guldberg, among others, here.
Glynn, P.W., D’Croz, L. (1990) Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. Coral Reefs 8: 181–191. https://doi.org/10.1007/BF00265009
Brown, B.E. and Ogden, J.C. (1993) Coral Bleaching. Scientific American 268 (1): 64-70. https://doi.org/10.1038/scientificamerican0193-64
Glynn, P.W. (1996) Coral reef bleaching: facts, hypotheses and implications. Global Change Biology 2 (6): 495-509. https://doi.org/10.1111/j.1365-2486.1996.tb00063.x
Hoegh-Guldberg, O. (1999) Climate Change, Coral Bleaching and the Future of the World’s Coral Reefs. Marine and Freshwater Research 50: 839-866. http://dx.doi.org/10.1071/MF99078

Author response: We feel the most relevant references are already provided. Given the request from the editor to avoid manuscript bloat, we have not added these additional references.

Line 143: “Since the first bleaching event of 1998,…
LD: Pedantic, but this should be ‘… first global bleaching event …’ Bleaching had been documented since at least 1960s following flooding (Tom Goreau Snr).

Author response: corrected to “Since the first global bleaching event…”

Line 145-146:
“With repeated events, loss of sensitive corals and acclimation and adaptation, the DHW thresholds may change (Lenton et al., 2023)
LD: Also see and cite:
van Woesik R, Kratochwill C (2022) A global coral-bleaching database, 1980–2020. Sci Data 9: 20. https://www.nature.com/articles/s41597-022-01121-y
van Woesik R, Shlesinger T, Grottoli AG, et al. (2022) Coral-bleaching responses to climate change across biological scales. Glob Chang Biol 28: 4229-4250. https://doi.org/10.1111/gcb.16192
Donner SD, Rickbeil GJ, Heron SF (2017) A new, high-resolution global mass coral bleaching database. PLoS One 12:e0175490. https://doi.org/10.1371/journal.pone.0175490
LD: The time series suggested a possible increase in coral thermal tolerance – see Virgen-Urcelay and Donner 2023, Shlesinger and van Woesik 2023.
Shlesinger T, van Woesik R (2023) Oceanic differences in coral-bleaching responses to marine heatwaves. Sci Total Environ 871: 162113. https://doi.org/10.1016/j.scitotenv.2023.162113
Virgen-Urcelay A, Donner SD (2023) Increase in the extent of mass coral bleaching over the past half-century, based on an updated global database. PLoS ONE 18: e0281719. https://doi.org/10.1371/journal.pone.0281719

Author response: We thank the reviewer for these additional references, but we do not feel they add sufficiently important details to the information we are delivering in this section, which is focussed on the number and scale of bleaching events.

Lines 182-184:

The introduction to ocean acidification could benefit from a more detailed explanation of the process, or citations thereof. Many primary sources are provided in Kleypas, J.A., Yates, K.Y. (2009) Coral reefs and ocean acidification. Oceanography 22(4): 108-117. https://www.coris.noaa.gov/activities/oa/resources/22-4_kleypas.pdf

Author response: Thank you for these suggestions, we have substantially revised this section following reviewer recommendations.

Lines 196-210:
LD: Suggest restructuring for clarity, as below.
"OA acts to alter the internal chemistry of corals and coralline algae, slowing calcification rates. The direct metabolic impacts of OA do not manifest a tipping point, but tipping points at ecological levels are likely. Recent evidence indicates that ecological tipping points within coral reefs caused solely by ocean acidification would occur around 550 ppm, roughly the same concentration of atmospheric CO2 that would cause detectable declines in both coral and coralline algal calcification (Cornwall et al., 2024). However, ecosystem trajectories are uncertain, and much more future research is required to determine the generality of these findings.
The adverse impacts on coral and coralline algal calcification are direct negative effects, when combined with the direct positive effects on other taxa (such as opportunistic turfing algae). Susceptible species would start to give way to tolerant species over time (as generally occurs at natural analogues in the field (Fabricius et al., 2011, Comeau et al., 2022), and other non-coral taxa would start to dominate space on what once were traditional coral reefs. Species that are capable of maintaining stable internal carbonate chemistry or compensate for these changes tend to be more tolerant to OA.

Author response: We have added a paragraph following these recommendations.

LD: The following paragraph may be better placed at end of Interactions section.
"However, of greater immediate importance to the majority of corals will be successive marine heatwaves that will reduce the coral cover of less heat tolerant species, populations and genotypes over the majority of the oceans in the near future (van Hooidonk et al., 2014, Cornwall et al., 2021, Logan et al., 2021, Cornwall et al., 2023). Survivors of this human-driven evolutionary force will not necessarily be those that are tolerant to OA also, and thus numerous tipping points in time could occur."

Author response: moved to the end of the interaction paragraph of the OA section as suggested.

Lines 218-219 and elsewhere.
LD: Greenhouse gas driven climate and ocean change poses a quintuple threat: ocean warming and heat waves, OA, deoxygenation, super-storms, and sea level rise - reefs having to 'catch-up' or 'drown', esp. on their lower slopes, and esp. if sea level rises rapidly and exceeds several metres over coming centuries. These are each mentioned in later sections of the manuscript.
Deoxygenation – consider mentioning that several of the 'reef gaps' in the fossil record coincide with periods of deoxygenation. Eg. See Veron, J.E.N. (2011) Mass Extinctions, Anoxic Events and Ocean Acidification. In: Hopley, D. (eds) Encyclopedia of Modern Coral Reefs. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-2639-2_37

Author response: rather than debate whether there are 3 or 5 threats we have removed reference to triple threat and simplify to refer to this as one of several major threats

Line 278: "Moderate rates of sea level rise may potentially aid some reefs to contend with thermal stress …"

Author response: reworded to "Moderate rates of sea level rise may potentially provide cooling for some reefs contending with thermal stress… "

Line 287:
"… , with plumes in large tropical river systems travelling many km from disturbance …"

Author response: Correction made as suggested

Line 306-307 seem better placed in this Section on Pollution:
"To calculate reef change threshold exceedance, Setter et al., (2022) use an ideal value of summed proportion agricultural/urban land use <0.5 in a 50km radius around a reef."

Lines 301-309:
10. Disruption
LD: Consider a different sub-heading. The inclusion of Land use change, as a proxy for pollution, seems repetitive, as covered in section 9. Suggest focus here on Over-fishing and consider Diseases only in sub-heading 11.

Author response: We agree there is substantial overlap between the pollution and disruption sections, so much so that we have decided to merge these sections together.

Lines 320-322:
11. Diseases "Regions such as the Great Barrier Reef, the Caribbean, the Pacific Islands, and the Indian Ocean have been particularly impacted by these outbreaks, in some places surpassing the devastating impact of bleaching events by causing even greater coral mortality. Coral diseases stand out as being driven largely by a changing environment and are contributing to whole ecosystem regime shifts (Thurber et al., (2020)…."
This statement appears too broad – perhaps 'Some areas within the GBR …'

Author response: we have edited to add this caveat

Although diseases are becoming increasingly prevalent with temperature rise and pollution, these, by themselves, have had relatively little overall impact outside of the Caribbean Sea, to date. In the Caribbean SCTLD is a major present source of coral mortality, impacting more than a third of all reef-building coral species present, and potentially driving the extinction of Pillar coral Dendrogyra cylindrus (among others). The relative impact of diseases elsewhere is likely to change in future, however, becoming more prevalent, interacting with heat waves.
Two additional, relevant references.
Cavada-Blanco F, Croquer A, Vermeij M, et al. (2022) Dendrogyra cylindrus. The IUCN Red List of Threatened Species 2022: e.T133124A129721366.
https://www.iucnredlist.org/species/133124/129721366.
Estrada-Saldívar N, Quiroga-García BA, Pérez-Cervantes E, et al. (2021) Effects of the Stony Coral Tissue Loss Disease outbreak on coral communities and the benthic composition of Cozumel reefs. Front Mar Sci 8: 632777. https://doi.org/10.3389/fmars.2021.632777

Author comments: We have included this suggested text.

Diseases are also a major risk as 'invasive species', as more ornamental reef species are traded and transported, deliberately or accidently, across and between ocean basins. For example, several Indo-Pacific species of fish and coral have been released, mainly it seems by aquarium hobbyists, into the Atlantic, and shipping ballast water also poses significant risk as a transport mechanism. This aspect could be included in an Interactions section.

Author response: We have included a line in the interaction paragraph to specify the link between invasives and disease.

13. Reef impact example

Lines 350-353: Edit for clarity
"… large areas are becoming covered by the encrusting and bioeroding sponge Cliona spp (Sheppard et al., 2020 skeletons formed a very abrasive layer on the substrate and, like liquid sandpaper, almost no larvae were seen in these areas. These sponges are clearly increasing; with one reef showing over 80% Cliona cover preventing coral larvae settlement."
This case study could be expanded to include more of the history, given it is one of the best studied remote reef systems. The paper would benefit from additional case-studies from Caribbean (nutrient enrichment, over-fishing, heat-waves, diseases, invasive species) and Great Barrier Reef (COTS, storms, run-off, heat waves, etc.), with summary noting differences in
resilience and potentially tipping points among the three systems in respect to oceanographic connectivity, coral population sizes, habitat heterogeneity etc.

Author response: Unfortunately we do not have the space to expand the Chagos example, but we do provide references permitting a deeper dive into this area. We agree that there are many valuable case studies that could be incorporated here, but we are limited by the editors space constraint, but we note that other case study relevant publications are provided in some of the references cited.

15. Resilience and adaptation

Lines 390-391: Edit for clarity
"Evidence of a persistence of heat adapted genotypes at the cost of the reduction of coral diversity, i.e. the reef may survive but the biodiversity diminishes (Fox et al., (2021) Although …"

Author responses: edited to "There is Evidence of persistence of heat adapted genotypes but the loss of non-adapted corals leads to an overall loss of diversity"

Reviewer 2

The manuscript presents a valuable review of the existing literature on the determinants and sensitivities of tipping point thresholds in warm-water coral reef ecosystems. The authors have clearly put a great deal of work into compiling and synthesizing the available research on this important topic.

However, the lack of a systematic review or meta-analysis approach means the study may be more prone to potential biases, which should be acknowledged and discussed in more depth. Importantly, the specific objectives of the study are not entirely clear from the current framing.

Author response: We note that this is a perspective piece and not a systematic review. The distinction is important for the interpretation of this manuscript and an expectation of what should be included.

Rather than exploring "where localized coral reef collapse aggregate" as stated in the introduction, the manuscript seems to focus more on documenting the known impacts of various coral reef stressors and their potential interactions. To improve clarity, the authors should clearly state the actual objectives of the work and the methodological approach used.

Since this is not a systematic review, it may be more appropriate to present it as an opinion piece or narrative review, with a well-developed caveats section that transparently addresses the limitations and potential biases inherent in the chosen approach.

Author response: This is indeed a perspective piece and will be categorised as such by the journal, as agreed with the journal editor. We explicitly call this a "perspective piece" in the abstract. We have removed the line about collapse for clarity.

Additionally, the resilience and adaptation section could benefit from a more cohesive structure and flow, moving beyond a simple literature summary to draw clearer conclusions.

Author response: We have reviewed this section and made some minor edits to aid clarity.

Providing additional examples beyond the Chagos case study, which focuses on cascading effects, could further strengthen the manuscript by highlighting examples of interacting stressors that may lower tipping point thresholds.

Author response: While it would be nice to include more case studies, but we cannot do this without expanding the manuscript, please see further responses on this issue above.

Overall, the topic is highly relevant and the authors have undertaken substantial work. By addressing the points above, the manuscript could be strengthened and provide greater value to the research community.

Author response: We thank the reviewer for the kind words. We hope this will be relevant to both the academic & assessment community as well as policy makers.

Additional Comments:

• Abstract:

o L26 & l33 : the is not a robust assignement, since not a systematic review

Author response: This manuscript is calling for robust assessments, we are not claiming this is a robust assessment.

• *Introduction:*

o L60/61 : the objectives are not in line with the content of the paper. The objectives should be rephrase and clarified overall.

Author response: we agree this sentence is not aligned with the broader aims of the manuscript so we have removed this line.

o L71 : I found the title of the section confusing, do you mean « Key indicators for predicting critical shifts in coral reef health »

Author response: We have reworded this to "Considerations for assessing coral reef tipping points"

o L98 to 100 : replece pers. Com by a published reference

Author response: We have reworded this section and added published references as suggested.

o L104 : typo at Meyer

Author response: corrected

• *Resilience and adaptation*

o L381 : see « section Reef impact example »

Author response: removed as this is not required

o L390 – sentence is not finished

Author response: reworded (see reviewer comment above)

o L394 – 396 : repetition between the two sentences

Author response:

o L420 : typo

Figure 2 : the figure does not bring any information, everything seems connected - a table might work better

Author response: We feel this figure makes several points firstly that nearly all stressors are connected, secondly we show that nearly all links are synergistic, it also shows that these are not fixed and that the magnitude matters for the impact of the interaction. While these may be obvious to the reviewer we feel this is an important communication aid to the wider assessment community and policy makers who may not be as informed as the review.