Interactions between global and local stressors of ecosystems determine management effectiveness in cumulative impact mapping

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Abstract

Aim

Cumulative impact maps are used to identify the spatial distribution of multiple human impacts to species and ecosystems. Impacts can be caused by local stressors which can be managed, such as eutrophication, and global stressors that cannot be managed, such as climate change. Cumulative impact maps typically assume there are no interactive effects between stressors on biodiversity. However, the benefits of managing the ecosystem are affected by interactions between stressors. Our aim was to determine whether the assumption of no interactions in impact maps leads to incorrect identification of sites for management.

Location

General, Australasia

Methods

We used the additive effects model to incorporate the effects of interactions into an interactive impact map. Seagrass meadows in Australasia threatened by a local stressor, nutrient inputs, and a global stressor, warming, were used as a case-study. The reduction in the impacts index was quantified for reductions in the nutrient stressor. We examined the outcomes for three scenarios: no interactions, antagonistic interactions or synergistic interactions.

Results

Cumulative impact maps imply that reducing a local stressor will give equivalent reductions in the impact index everywhere, regardless of spatial variability in a global stressor. We show that reductions in the impact index were greatest in refuges from warming if there was an antagonistic interaction between stressors, and greatest in areas of high warming stress if there was a synergistic interaction. Reducing the nutrient stressor in refuges from warming always reduced the impact index, regardless of the interaction.

Main conclusions

Interactions between local and global stressors should be considered when using cumulative impact maps to identify sites where management of a local stressor will

provide the greatest impact reduction. If the interaction type is unknown, impact maps can be used to identify refuges from global stressors, as sites for management.

Keywords Synergistic threats, antagonistic threats, biodiversity prioritisation, multiple stressors, seagrass, threat mapping, ecosystem stress mapping

(A) Introduction

There is a growing appreciation that management of marine ecosystems must deal with multiple human stressors, rather than focusing on a single stressor at a time (Halpern *et al.*, 2010; Halpern *et al.*, 2012; Allan *et al.*, 2013). Generation and analysis of maps of cumulative impacts is an increasingly popular approach (Halpern *et al.*, 2008; Selkoe *et al.*, 2008; Ban *et al.*, 2010; Grech *et al.*, 2011; Allan *et al.*, 2013), which is being used to identify the extent and magnitude of human impacts on ocean ecosystems regionally and globally. In these analyses, stressors to ocean ecosystems are mapped in space and the cumulative impact of multiple stressors is summed on a relative scale. A key finding of these analyses is the prevalence of both local and global stressors (Halpern *et al.*, 2008). Stressors with local causes, including overfishing and eutrophication, can be acted on directly by managers in a region. By contrast, stressors with global causes, such as global warming, cannot be acted on directly (Brown *et al.*, 2013). It has also been argued that cumulative impact maps can be used to assist prioritisation of management actions, in part by identifying areas with the highest level of cumulative impact (e.g. Ban *et al.*, 2010; Grech *et al.*, 2011; Allan *et al.*, 2013).

There are many caveats to using impact mapping approaches in prioritisation of management actions. Key among these is that the there is no clear relationship between the cumulative impact index and ultimate management goals, which may be to avoid species extinction, recover an ecosystem's past state, or restore services such as fisheries. Cumulative impact indices imply that impacts on ocean ecosystems are additive and linear, so reducing one stress in a location will have a direct benefit for the ecosystem (Ban *et al.*, 2010; Halpern *et al.*, 2010). If this is true, impact maps can be used in a prioritisation of actions where the goal is to maximise threat abatement (Klein *et al.*, 2010). However, this may not be the case when system stressors act antagonistically, that is, they cancel each other out. Further, stressors can interact synergistically, so that reducing one stressor will have a greater than additive benefit for the ecosystem (Brown *et al.*, 2013). Management that aims to reduce indices of cumulative impact without considering stressor interactions may target the wrong stressors or the wrong locations and consequently provide fewer benefits for biodiversity or restoring ecosystem services.

It is often assumed, explicitly or implicitly, that stressors act in an additive fashion. In this case, the impacts of two stressors are simply added together. However, the chance that there is no interaction between two stressors is low; in two meta-analyses of dozens of studies, there were interactions in about three quarters of instances (Crain *et al.*, 2008; Darling & Cote, 2008). Stressors can interact synergistically, where the combination of two stressors has a greater effect on the population or ecosystem of interest than the sum of their individual effects (Folt *et al.*, 1999; Crain *et al.*, 2008). From a management perspective, synergisms mean that acting on a local stressor will provide additional benefits by also reducing the synergistic effect of the local with the global stressor (Brown *et al.*, 2013). Stressors can also interact antagonistically, so that the combination of two stressors is less than their additive effects (Folt *et al.*, 1999; Crain *et al.*, 2008). Antagonisms can be further divided into dominance and mitigative effects. Ecosystem responses to dominance antagonisms are driven by the first stressor and additional stressors have little additional effect. For instance, if coral species are either tolerant or sensitive to both fishing and climate stress, then fishing may remove the most stress-sensitive species, leaving only stress tolerant species that are not strongly affected by climate impacts (Vinebrooke *et al.*, 2004; Darling *et al.*, 2010). In a mitigative antagonism, one stressor reduces the impact of another stressor. For instance, some coral species may be less likely to bleach in response to unusually warm temperatures if water clarity is low (Anthony *et al.*, 2007). When there are antagonisms, management that reduces a single stressor will be ineffective or may even worsen the ecosystem state (Brown *et al.*, 2013).

Previous studies have examined the effects of interactions on management at single point locations using population models (Brown *et al.*, 2013) or locally in experiments (Falkenberg *et al.*, 2013; Ghedini *et al.*, 2013). However, spatial variability in global stressors across large areas may influence the effectiveness of management when there are interactions. Cumulative impact maps are a useful tool for studying impacts of multiple stressors across large areas, although interactions are not explicitly considered in cumulative impact maps. Therefore, incorporating interactions into impact maps is necessary for quantifying the benefits of reducing a local stressor at different locations, to find priority sites for management action.

Here we incorporate interactions into an impacts index. We examine how reducing a local stressor reduces the impacts index, when that local stressor has interactive impacts with a global stressor. We develop an interactive impacts index and map impacts from nutrient input and global warming stressors to Australasian seagrass ecosystems. Seagrasses are critically important ecosystems in shallow coastal seas, providing habitat for important fisheries species, water filtration, carbon sequestration, and shoreline protection services (Orth *et al.*, 2006; Unsworth & Cullen, 2010; Fourqurean *et al.*, 2012). Conserving seagrass ecosystem in Australasia is particularly important because it is the global epicentre of seagrass diversity (Short *et al.*, 2007). Yet seagrass are amongst the most threatened ecosystems on Earth, rapidly declining globally due to a suite of anthropogenic stressors (Orth *et al.*, 2006; Waycott *et al.*, 2009). We demonstrate that regions where management can make the greatest gain from reducing impacts depend both on the magnitudes of stressors and their interaction. Importantly, the regions where the greatest benefits are achieved are not necessarily the areas with the greatest cumulative impact.

(A) Methods

(B) Interactive impacts index

We used the additive effects model to examine the effect of multiple stressors on an ecosystem (Folt *et al.*, 1999). This model is similar to the cumulative impacts index used for mapping, but it has the advantage of allowing interactions between stressors. We therefore refer to the index with interactions as the 'interactive impacts index'. The interactive impact index of multiple stressors is: $E = a_1S_1 + a_2S_2 + a_3S_1S_2$ (equation 1). Where a_i coefficients are the effect sizes and S_j variables are the stressor values. The a_iS_j are direct additive impacts and $a_3S_1S_2$ is the interactive effect of two stressors. Stressor values are always positive and scaled to their maximum value, so they range from 0-1. A stressor is defined as an environmental variable that has a negative effect on the ecosystem of interest when it acts in isolation from other stressors (a_1 and $a_2 > 0$, Fig. 1A). In this model, the interactive impact could be positive or negative, where positive values imply greater ecosystem degradation (to be consistent with earlier studies) and negative values imply improvement.

We focussed on three possibilities: no interaction (a_3=0), a synergistic interaction (a_3>0) or an antagonistic interaction (a_3<0, Fig. 1A). Synergisms will increase the interactive impact beyond that expected on the basis of additive impacts (Fig. 1B, line with circles). For an antagonism, the interactive impact is either less than that expected on the basis of additive impacts (Fig 1B, dot-dash line) or, if the antagonism is mitigative, the interactive impact can be decreased (improved) for increases in stressor values (Fig. 1B, dotted line). The interactive impact improves because the positive antagonistic effect is greater than the direct negative effects. The linear model does not distinguish explicitly between mitigative and dominance antagonisms. However, the model can be parameterised to disallow strong mitigative interactions by setting $a_3 \geq -a_2/C_{max}$, so that the interactive impact value cannot decrease (improve) when the magnitude of a stressor increases. First we modelled the effect of mitigating a local stressor under different interactions in a theoretical system. We then apply this theory to a case-study.

(B) Seagrass case-study

We applied equation (1) to an impact index for a seagrass ecosystem in Australasia. Land-based nutrient inputs and global warming are major concerns in the conservation of seagrass ecosystems (Orth *et al.*, 2006; Waycott *et al.*, 2009). Accordingly, there have been calls to reduce nutrient inputs into seagrass meadows and promote their ability to adapt to climate change (Waycott *et al.*, 2007; Morgan, 2011; Saunders *et al.*, 2013). Nutrient inputs reduce light availability to seagrass by promoting growth of phytoplankton and epiphytic algal competitors (Schaffelke *et al.*, 2005), which subsequently reduces benthic irradiance necessary for photosynthesis by seagrass. Global warming can also slow seagrass growth, through heat induced mortality and by promoting growth of epiphytes (Short & Neckles, 1999; Collier *et al.*, 2011).

Here we considered the existence of antagonistic and synergistic interactions, both of which are plausible. A synergism could occur if warming and nutrient inputs increase growth of both phytoplankton and epiphytes (synergism) and, therefore worsen declines of seagrass (Orth *et al.*, 2010) or if warming increases the sensitivity of seagrass to stress from eutrophication (García *et al.*, 2013). Alternatively, antagonisms could occur if the growth of phytoplankton and epiphytes is limited by either nutrients or temperature, but not both together (Burkholder *et al.*, 2007). We predicted the relative change in the interactive impact index for seagrass in response to reduction of nutrients, when there were either synergistic or antagonistic interactions between warming and nutrient stressors.

Maps of seagrass distribution were obtained from the United Nations Environment Program databases (Green & Short, 2003). The resolution of this compilation of seagrass maps varies depending on the source map (Green & Short, 2003). Maps of present nutrient and global warming stressors (sea surface temperature, SST) were obtained from the Global Marine Impacts database (Halpern *et al.*, 2008), over the years 1993 to 2002 for nutrients and 1985 to 2005 for SST on a 1km^2 grid. Stressor values are relative and scaled from 0-1, globally (Halpern *et al.*, 2008). Stressor maps were aggregated to 100km^2 boxes for display purposes and to standardise and align the resolution of the stressor and seagrass maps. We aggregated to such a large scale because our focus was on regional variability in stressor values. Halpern *et al.* (2008) give two measurements of SST impacts. Both are strongly correlated, so we used the number of months in the year that SST exceeds one standard deviation above the regional SST anomaly for the period 1985 to 2005. Halpern *et. al*. (2008) derived the nutrient stressor map from the Food and Agricultural Organisation statistics on fertilizer use and modelled distribution of nutrient runoff from fertilizers into the oceans.

Calculating the interactive impact index requires estimates of the additive and interactive effect sizes. To represent negative additive effects of nutrient inputs and global warming, we used the same effect weightings as Halpern *et al.* (2008) for seagrass, based on expert elicitation of effect weightings for different stressor variables (Halpern *et al.*, 2007). Impacts to seagrass (E_i) in each of i 100 km^2 boxes were modelled as:

$E_i = 2.2C_i + 2.2L_i + a_3C_iL_i$, where C_i and L_i are the climate and nutrient stressors respectively, and a_3 is the interactive term.

Interactive effects are more difficult to estimate than single stressor effects. We present representative scenarios for synergistic (a_3 = 3) and antagonistic (a_3 = -2.2) interactions to cover all possibilities. The absolute value of the antagonistic coefficient was set smaller than the synergistic coefficient, because we could find no evidence for mitigative antagonisms between nutrients and warming stress for seagrass. Thus, the effect size of the antagonism is set such that increasing a stressor could never have a positive effect (i.e. $a_3 \geq -a_2/C_{max}$). We present the relative change (scaled by its maximum value) in the interactive impact index when management is able to reduce nutrient inputs so that they no longer have a detrimental effect on seagrass ecosystems (i.e. $L_i = 0$). To account for variations in the size of the local stressor, we also present the change in the impact index per unit change in the local stressor. The management gain when there are antagonistic and synergistic interactions is plotted against the cumulative impacts index (i.e. assuming no interaction) and just the climate component of the impacts index. This was done to test the assumption that interactions can be disregarded and management will make greater gains at sites where the cumulative impacts are higher.

There are several important caveats to these analyses. First, by providing a regional view, we average over fine and meso-scale spatial patterns in global warming stress, nutrient stress and seagrass occurrence. Processes on a fine spatial scale can be important for seagrass growth (Burkholder *et al.*, 2007). There is probably a large amount of variation in effect sizes among seagrass species and regions (Burkholder *et al.*, 2007), but we used effect sizes from Halpern *et al.*(2008) for all seagrass locations, so that modelled spatial patterns in responses to management were not confounded by variation in effect sizes. Further, data necessary to estimate variation in effect sizes and fine-scale patterns of nutrient and climate impacts are available for very few regions. One of our intentions is to demonstrate that the management response varies for different interactions, in the hope that this will stimulate renewed field observation and experiments at finer scales that could be used to derive interaction directions and strengths.

(A) Results

(B) General result

First, we used a theoretical system to examine the improvement in the interactive impacts index when a local stressor that interacts with a global stressor is reduced. The reduction in the interactive impact index from reducing a local stressor was equal to $-L(a_2 + a_3C)$. For no interaction or a synergistic interaction, reducing the local stressor always improved the interactive impact index (Fig. 2a). Improvements were greater if the synergism is stronger (*a_3* is larger). For a weak antagonistic interaction or low climate stress, the interactive impact index was improved if management reduces the local stressor, but by a smaller amount than for synergistic interactions (Fig. 2a). For a strong antagonistic interaction or high climate stress, the interactive impact index was degraded when the local stressor was reduced (to the left of point x on Fig. 2a). This implies a mitigative antagonistic interaction.

Spatial variation in stressor magnitudes affected the magnitude of change in the interactive impact index when a local stressor was reduced. Where there were synergisms (a_3 positive), reducing the local stressor gave relatively greater gains in regions with high climate stress (Fig. 2b). Conversely, where there were antagonisms (a_3 negative), the greatest gains were achieved in regions with low climate stress. Where there were antagonisms and high climate stress, reducing the local stressor had little benefit or even contributed to declines (Fig. 2b). Where there was no interaction, then reducing the local stressor had the same benefit for all levels of the climate stressor.

(B) Seagrass case-study

Nutrient stress on seagrass was generally weak across the Australasian region, whereas warming stress was strong (Figs 3a & b). Reducing nutrient stress to zero improved the interactive stress index when there were synergistic interactions (Fig. 3c). Regions with relatively high nutrient and climate stress (e.g. coast near Bangkok, the Malay Peninsula, Western Java and Southern Australia) showed the greatest improvements. For the synergistic model, regions with existing low nutrient stress showed little improvements (e.g. Northern Australia). For an antagonistic interaction, reducing nutrient stress generated relatively small improvements in the interactive impact index across Australasia (Fig. 3d).

The per unit benefit of reducing the nutrient stressor increased for a higher cumulative impact index (i.e. only additive effects considered) for synergisms, but decreased for a higher cumulative impacts index for antagonisms (Fig. 4a, points). The same was true when the per unit change was plotted against the climate impacts alone (Fig. 4a, lines). There was scatter about the relationship between per unit change and the cumulative impacts index. This scatter is a consequence of disregarding the interactive effect in the cumulative impacts index, the magnitude of which depends on both the level of the nutrient and climate stressors. The climate index had a linear relationship with the per unit benefit (see also Fig. 2b).

The benefits from totally removing the nutrient stressor were greater if there was a synergism and the cumulative impact score was higher (Fig. 4b); whereas, benefits were lower if there was an antagonism, but still increased for higher cumulative impact scores. This estimate of improvement in the interactive impact index assumes that management reduces the nutrient stress to zero at each site. The positive relationship between the interactive impact index and the reduction in the index was confounded by sites with greater nutrient stress receiving greater direct benefits when the nutrient stressor was removed.

(A) Discussion

Previous approaches have implied that regions with the highest cumulative impact should be priority areas for management action (e.g. Grech *et al.*, 2011; Allan *et al.*, 2013). There are three main reasons this may not be the case: (1) Costs of management may be higher in high impact locations; (2) management success may be lower in high impact regions (Joseph *et al.*, 2009); and (3) stressors may interact. Here we demonstrated that interaction type and strength will influence the benefits of management and hence the decision to be made.

Our research suggests that interactions should be considered if cumulative impact maps are used to inform the identification of sites for management action. If system specific studies suggest there are no interactions between local and global stressors, then reducing the local stressor by a fixed amount will result in equal reductions in impacts in all locations. If an antagonism is likely, then managing at sites where global stressors are low (e.g. climate change refuges) will reduce the impact by the greatest amount. Whereas, if synergisms are likely, managing sites where global stressors are high will reduce the impact by the greatest amount. Commonly, the type of interaction between stressors is unknown. In this case, the most conservative strategy is to reduce the local stressor in sites with low climate impacts. This ensures some reduction in the impacts, regardless of the interaction type (Table 1). Schemes for the management of multiple stressors (e.g. Halpern *et al.*, 2010; Klein *et al.*, 2010;

Grech *et al.*, 2011; Allan *et al.*, 2013) should therefore consider the possibility of both antagonistic and synergistic interactions.

There are several caveats to our results. We have included interactions, but they are one aspect of a broader range of ecological responses not captured in cumulative impacts models. Thresholds in stressor tolerance could amplify responses to stressors (Scheffer *et al.*, 2001; Carr *et al.*, 2012). Further, caution should be used when applying linear models to restoration, because of non-reversibility of impacts or alternate stable states (Duarte *et al.*, 2009). For instance, if seagrass beds reach critically low biomass due to low light levels, sediment instability can inhibit re-colonisation, even if nutrient load is reduced (Carr *et al.*, 2012). Despite limitations of the additive interactions model used here, the results provide a useful generalisation of previous system specific studies. For instance, reducing nutrient inputs to a temperate reef ecosystem breaks down a synergistic interaction between nutrients and high carbon dioxide that drives establishment of algal turfs (Falkenberg *et al.*, 2013). Thus, local management can be effective at reversing the synergistic effect of eutrophication and increasing carbon dioxide.

A further caveat to our results is that we considered only pairs of stressors. An advantage of the stress mapping approach is that it allows consideration of numerous stressors, even when data are limited (Halpern *et al.*, 2008; Selkoe *et al.*, 2008). While antagonisms are just as common as synergisms for two-way interactions (Crain *et al.*, 2008; Darling & Cote, 2008), combinations of three or more stressors may be more likely to be synergistic (Crain *et al.*, 2008). Seagrasses are threatened by multiple local stressors (Grech *et al.*, 2011), and climate change is predicted to impact seagrasses in multiple ways, including heat stress (Jorda *et al.*, 2012) and sea-level rise (Saunders *et al.*, 2013). If there are more than two stressors, our results imply that management to address stressors that interact synergistically with multiple other stressors will return the greatest benefits. Our model does not consider management actions that simultaneously address two or more stressors, for instance revegetation of coastal habitats could reduce multiple kinds of water quality stress to seagrasses, including terrestrial nutrient inputs and pesticide pollution (Haynes *et al.*, 2007). Such management actions can be more effective if conducted in locations with greater levels of cumulative impact.

To address these caveats for identifying management priorities in our model and to stress mapping more generally, we advocate developing models of the processes that link threats with their impacts on ecosystem state (Blackwood *et al.*, 2011; Griffith *et al.*, 2012; Klein *et al.*, 2012; Brown *et al.*, 2013). These process models need not have a high level of complexity and can be used in data limited settings, much as cumulative impact indices are currently used (Blackwood *et al.*, 2011; Klein *et al.*, 2012). Further, if information on likely interaction types cannot be obtained, simple process models can help identify which management strategies are most robust to alternative assumptions about interactions (Brown *et al.*, 2013). Cumulative impact maps will form a base input to such process models, as they provide invaluable information on spatial variability in the impacts of multiple stressors.

There are several reasons for developing process models. First, they allow explicit specification of goals for the state of an ecosystem, for instance, area of seagrass habitat, fishery harvest or long-term persistence of threatened species. Defining state-based goals ensures that management actions are linked to desired outcomes, rather than threat abatement, which is not an outcome in its own right, but a path to an outcome. Second, process models can incorporate non-linear effects such as thresholds in response and non-reversibility of stressor impacts on ecosystems (e.g. Blackwood *et al.*, 2011; Carr *et al.*, 2012). Third, process models require explicit definitions of management actions. The most effective management actions can vary considerably with different goal definitions. For instance, the optimal marine reserve design when faced with cyclone disturbances depends on whether management seeks to maximize the health of a single coral reef or maximize the expected number of healthy reefs (Game *et al.*, 2008). Finally, the cost of the management action can be incorporated into process models, so that the most cost-effective management action can be identified (Wilson *et al.*, 2006; Klein *et al.*, 2012).

There are many global stressors of ecosystems that are difficult or impossible for regional management to address directly, including climate change, ocean-acidification and disease. It is difficult to predict whether ecosystems and species will respond antagonistically or synergistically to multiple stressors. Interactions for an ecosystem may also vary regionally, for instance, the interactive effects of stressors on seagrass responses can be species specific (Burkholder *et al.*, 2007; Collier *et al.*, 2011; García *et al.*, 2013). Identifying regional variations in interaction types and strengths will be important for ensuring the most effective management approach is used in a region. To-date, studies on stressor interactions have focussed on synergisms, however, more effort should be placed on documenting antagonisms and their mechanisms. Cumulative impact maps can be used to identify control and impact sites, which are necessary to separate the effects of multiple stressors in field studies of ecosystems. Building detailed understanding of interactions for management will require integrated empirical and modelling studies, which can detect interactions of different types and discover mechanisms for interactions (Brown *et al.*, 2011; Wernberg *et al.*, 2012). This information can then be combined with information on cost of actions, their chance of success and maps of impacts, to develop spatial models that can inform on priority actions for ecosystem conservation.

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Biosketch

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Author Contributions

All authors contributed substantially to devising the research idea, refining concepts and editing drafts. C.J.B. wrote the first draft and performed the analyses. C.J.B. and M.I.S. designed the figures.

Table

Table 1 Relative gain or loss in ecosystem state for reducing a local stressor in the presence of interactions with a global stressor.

Global stressor strength	Interaction type		
	Synergistic	Additive	Antagonistic
Low	Medium gain	Medium gain	Medium gain
High	High gain	Medium gain	Low gain/relative loss

Figure legends

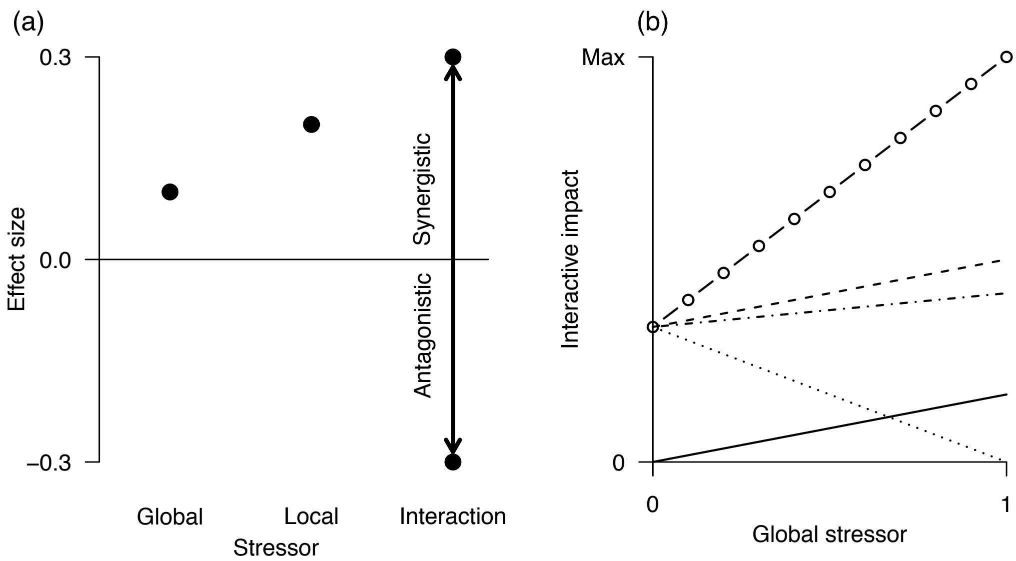

Figure 1 Conceptual illustration of interaction types, and their effect on the interactive impact index. (a) Effect size strengths for a local and global stressor on the interactive impact. If the interaction is antagonistic, the interaction will reduce the interactive impact index, whereas if the interaction is synergistic the interaction will increase the interactive impact index. (b) Predicted effects of locations with increasing global stress on the interactive impact. When there is no local stressor, interactive impacts are low, but increase in locations where the global stressor is high (solid line). When there is a local stressor, interactive impacts are higher, and increase evenly when there is no interaction (dashed line) and at a greater rate when there is a synergistic interaction (line with circles) or a weak antagonistic interaction (dot-dash line). Interactive impacts decrease in locations where the global stressor is higher, when there is a mitigative antagonistic interaction (dotted line).

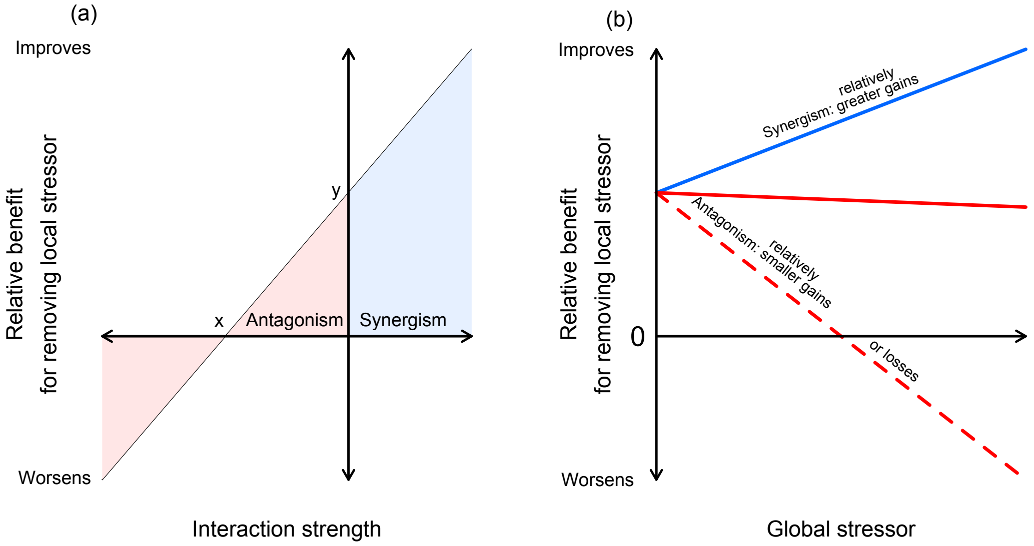

Figure 2 Conceptual illustration of change in the interactive impacts index when a local stressor is removed. (a) Synergistic interactions result in an improvement of interactive impacts if the local stressor is removed (dark grey in print, blue area online). Removing the local stressor for an antagonistic interaction can cause the interactive impacts to decrease slightly for a dominance antagonism or a weak mitigative effect, $a_3 > x$, or increase if the antagonism is strongly mitigative $a_3 < x$, where $x = -a_2/C$ (light grey in print, red area online). The y-intercept (y) = a_2L (b) There are greater improvements from reducing the local stressor in locations where the global stressor is greater for a synergistic interaction (solid line). For relatively weak antagonisms, there are modest improvements in the interactive impacts index, which decline in locations where the global stressor is greater (dashed line). For a relatively strong mitigative antagonism, interactive impacts can increase if the local stressor is removed and global stress is high (dotted line).

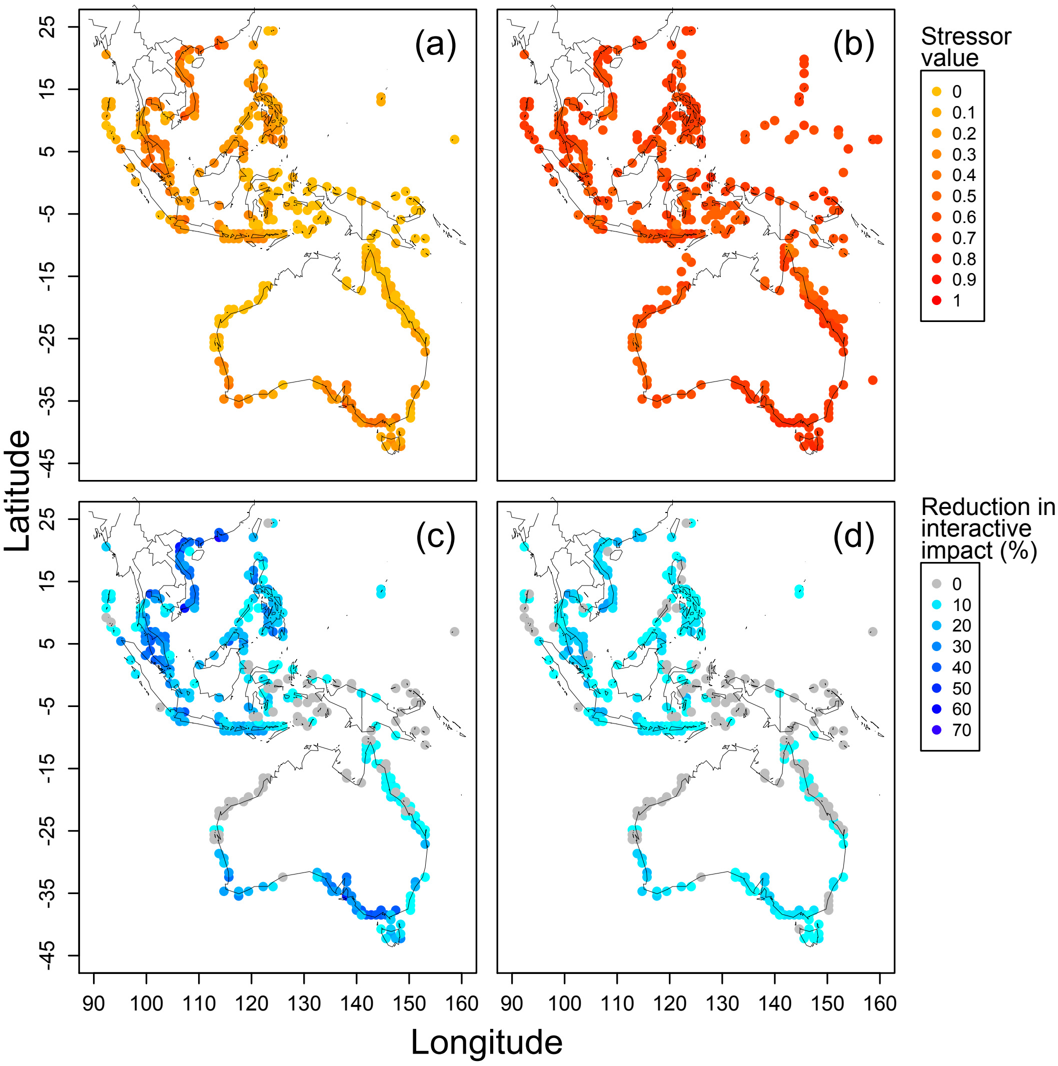

Figure 3 Maps of seagrass stressors and change in interactive impacts with management. (a) Nutrient (Halpern *et al.*, 2008) and (b) temperature (Halpern *et al.*, 2008) stressors in seagrass ecosystems (points) in the Australasian region. If management removes nutrient stress to accommodate temperature impacts, the interactive impacts index will (c) improve in many regions if there is a synergistic interaction, but (d) show little change if the interaction is antagonistic. Values in (c) and (d) are change relative to the maximum interactive impact value for each interaction.

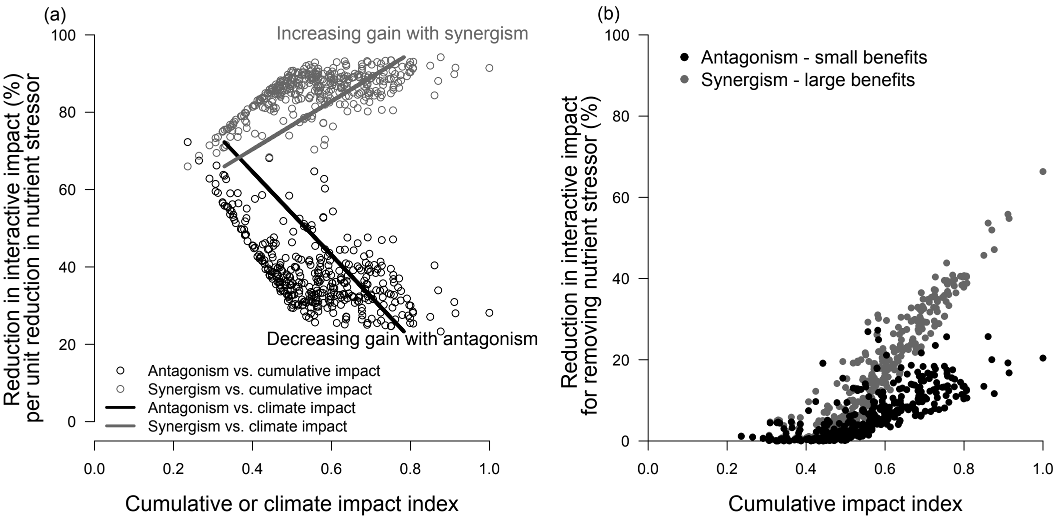

Figure 4 Relative improvement in the interactive impact index for reducing the nutrient stressor across seagrass sites for Australasia depends on interaction and the effect of management. In (a) nutrient stress is reduced by a fixed amount at each site. Improvements in the impact index are shown against the cumulative impact index (i.e. only additive effects considered, points) and by the climate impact index alone (lines). There are greater reductions in the interactive impact at sites with higher cumulative impact scores and, at sites with higher climate impact scores, if there is a synergism. The reverse is true if there is an antagonism. If the nutrient stressor is removed entirely (b) then there are greater benefits in regions with higher cumulative impacts. Benefits are greater if there is a synergism and smaller if there is an antagonism.