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REPORT

Building resilience into practical conservation: identifying local management responses to global climate change in the southern Great Barrier Reef

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Abstract Climate change is now considered the greatest long-term threat to coral reefs, with some future change inevitable despite mitigation efforts. Managers must therefore focus on supporting the natural resilience of reefs, requiring that resilient reefs and reef regions be identified. We develop a framework for assessing resilience and trial it by applying the framework to target management responses to climate change on the southern Great Barrier Reef. The framework generates a resilience score for a site based on the evaluation of 19 differentially weighted indicators known or thought to confer resilience to coral reefs. Scores are summed, and sites within a region are ranked in terms of (1) their resilience relative to the other sites being assessed, and (2) the extent to which managers can influence their resilience. The framework was applied to 31 sites in Keppel Bay of the southern Great Barrier Reef, which has a long history of disturbance and recovery. Resilience and 'management influence potential' were both found to vary widely in Keppel Bay, informing site selection for the staged implementation of resilience-based management strategies. The assessment framework represents a step towards making the concept of resilience operational to reef managers and conservationists. Also, it is customisable, easy to teach and implement and effective in building support among local communities and stakeholders for management responses to climate change.

Keywords Climate change · Coral reefs · Environmental management · Great Barrier Reef · Resilience

Introduction

Recent observations and projections of future change have given rise to grave concerns about the future of the world's coral reefs (Hoegh-Guldberg et al. 2007) but the extent to which a coral reef crisis unfolds will depend on the rate of climate change and the resilience of coral reefs to these changes (Hughes et al. 2003; Bellwood et al. 2004; Johnson and Marshall 2007). The concept of resilience has great intrinsic appeal and has received exponential coverage in the literature since 1990 but there remains an urgent need to incorporate resilience concepts into practical conservation solutions for coral reefs (review in Nystrom et al. 2008). Resilience is the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by a different set of processes (Pimm 1984; Walker 1995; Carpenter et al. 2001). For coral reefs, the 'qualitatively different state' that can follow disturbances is a shift from a coral-dominated state to an algae- or even rubble-dominated state (Done 1992). Avoidance of such a phase shift is a function of effective recruitment (e.g., connectivity and suitable substrate availability) (Hughes et al. 2007), growth and survivorship of corals. All can be strongly affected by anthropogenic stressors like poor water quality, unsustainable fishing pressure and physical impacts like anchor damage (Wooldridge et al. 2005). There have been a few examples of frameworks that incorporate or 'operationalise' resilience in reef-dependent social systems

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(see Folke 2006; Marshall and Marshall 2007), but efforts to formally apply resilience frameworks in the management of coral reef ecosystems are only just emerging despite being critically needed (Nystrom et al. 2008).

Our knowledge of measurable indicators of resilience for coral reefs is still developing (McClanahan et al. 2002), which creates challenges for the identification of resilient reefs and regions. Conservation organisations including The Nature Conservancy and the IUCN Working Group on Climate Change and Coral Reefs have been making important steps towards developing a protocol for assessing the resilience of coral reefs (Obura 2005; Grimsditch and Salm 2006). Using the resilience indicators they have identified as a foundation, this study developed a framework to assess resilience and rank coral reef sites based on their relative resilience, effectively identifying resilient reefs and/or regions. The framework described can be used to inform planning and decision-making and, in turn, target the implementation of management strategies aimed at building ecosystem resilience to climate change. While such strategies cannot hope to counteract climate change impacts, they can minimise the damage and, hopefully, avert ecosystem collapse. The framework was developed to be easy to teach and implement. The framework was also developed to be a process lead by local managers and used as a mechanism for engaging community members in the management of local reefs. The approach is modelled after Walker et al. (2002), who propose that the process of resilience analysis to inform management must involve stakeholders closely.

We trial and employ the resilience assessment framework at sites within Keppel Bay in the southern Great Barrier Reef, which has 16 continental islands located 15 km off the coastal town of Yeppoon. The Keppel Bay fringing reefs have a long history of disturbance from cyclones and flood events, and experienced a severe coral bleaching event in 2006 that killed 40% of corals at many sites (GBRMPA 2008). Reefs in the bay are subject to a range of different use restrictions as part of the Great Barrier Reef Marine Park zoning, ranging from Conservation zones (no-take marine reserves) to General Use zones that allow for commercial harvesting of some species (GBRMPA 2008). The planning mosaic in the Keppel Bay region, as elsewhere in the GBR Marine Park, is designed to provide a resilient network of reefs while also supporting sustainable uses of the Marine Park, including fishing and tourism.

Intense storms, floods and coral bleaching are projected to become more frequent and severe under future climate scenarios (IPCC 2007), raising concern about the ability of the benthic communities in Keppel Bay to continue to support recreational (snorkelling, diving, fishing) and commercial (fishing) activities for the rapidly growing local communities. Recent impacts from bleaching and floods and strong community interest in the management of local environmental issues make the reefs within Keppel Bay ideal as a case study for the application of the resilience assessment framework.

The resilience indicators, indicator weightings and the development of the resilience assessment framework are all described in the methods. The resilience and ‘management influence potential’ rankings from the Keppel Bay case study are presented in the results and applied to a range of candidate sites for targeted resilience-based management strategies in the Bay. The concluding section of the paper discusses the broad applicability of our approach to other reef regions. We share how the framework can and should evolve in the future as research in this area advances, and further trials are conducted and also include some key experiences from our application of this framework. Our accounts of these experiences can help managers overcome some of the challenges associated with using the framework to inform the implementation of resilience-based management strategies.

Methods

Resilience indicators

A suite of 19 resilience indicators were selected from lists of potential indicators identified in the literature. The final indicators were selected on the basis of their relevance to the specific social and environmental setting of Keppel Bay (i.e., indicators like ‘shading from shoreline cliffs’ and ‘presence of destructive fishing practices’ are not relevant to the Keppel Bay area). The 19 indicators can be broadly classified as those that influence ecological processes (e.g., substrate availability and herbivore abundance), anthropogenic impacts (e.g., fishing pressure and water pollution), biological variables (e.g., coral community type and absence of coral disease) and physical variables (e.g., exposure and mixing). The full list of resilience indicators and how they have been demonstrated to, or are hypothesised to, confer resilience to a reef site is presented in Table 1.

Resilience indicator weighting

Although there has been minimal testing of the relative importance of different resilience indicators, well-established ecological principles suggest that indicators will differ in the nature and magnitude of their contribution to ecosystem resilience. For example, water turbidity may increase the ability of corals to resist bleaching, but the relative proportion of taxa known to be intrinsically resistant to bleaching will have a much stronger influence over the amount of bleaching that occurs at a particular reef site (Marshall and Baird 2000; McClanahan 2004). To continue

Table 1 Weighting of resilience indicators, indicator description, justification for the indicators (the relationship between the indicators and reef resilience) and the direction in which the indicator confers resilience. For each indicator justification, references are given that either cover that topic specifically, or cover the topic within a review (i.e., the reference list provided for each justification is not meant to be exhaustive)

Indicator weighting	Resilience indicator	Indicator justification	Conferring resilience
Critically important	Connectivity	Reef recovery following severe disturbances depends on there being nearby and upstream reefs to provide coral and invertebrate recruits (Roberts 1997; Mumby and Hastings 2008)	More resilience is conferred upon sites that are connected to other sites, preferably of high resilience
	Free from water pollution	Pesticides, nutrients and pathogens have been shown to increase the susceptibility of corals to disease and to bleaching, and nutrient-rich waters increase the growth rates of algae that compete with corals and other invertebrates (Hughes et al. 2003; Adger et al. 2005)	More resilience is conferred upon sites where the concentration of pesticides, pathogens, and nutrients is low
	Previous exposure to thermal stress events	Previous exposure to, tolerance of, and/or quick recovery from a thermal stress event suggests the same could occur in the future (West and Salm 2003; Obura 2005)	More resilience is conferred upon sites that have tolerated, and or recovered quickly, from thermal stress events
	Coral cover	Many coral reefs are self-recruiting so high coral cover can ensure that if some die, there will still be corals to provide the next generation of recruits. Also, most corals grow slowly so high coral cover indicates that the site has either tolerated and/or recovered from past disturbances, or conditions at the site are rarely stressful enough to cause mortality. Also, high coral cover intensifies grazing in areas available for algal colonisation reducing the likelihood of a macroalgal bloom (Williams and Polunin 2001; Mumby et al. 2007a)	More resilience is conferred upon sites that have high coral cover
	Abundance of resistant/tolerant species	Massive slow-growing corals are, generally, more tolerant of thermal and physical stress than fast-growing branching and digitate types (Grimsditch and Salm 2006)	More resilience is conferred upon sites that have a high abundance of resistant/tolerant coral species
Very important	Water mixing	Mixing keeps water temperatures relatively constant and reduces the extent to which corals in shallow water are exposed to the rapid warming of surface waters that can coincide with long hot still conditions conducive to bleaching (McClanahan et al. 2002; Grimsditch and Salm 2006)	More resilience is conferred upon sites that are well mixed
	Free from physical impacts	Wave action produced by storms can cause breakage of coral colonies, resulting in lesions that take physiological resources to repair and increase susceptibility to disease and bleaching. As a result, there are fewer colonies that can act as a source of recruits (McClanahan et al. 2002)	More resilience is conferred upon sites that are free from physical impacts
	Abundance of mature coral colonies	Coral colonies grow slowly so most mature (large) healthy colonies have survived longer than a decade (in some cases, many decades) and during that time are likely to have withstood a range of stressors. Larger colonies are also likely to produce more recruits (Soong 1993; Mumby 2006)	More resilience is conferred upon sites where mature coral colonies are abundant
	Substrate availability	Successful coral recruitment following disturbances requires that suitable substrate is available for recruits to settle on and, subsequently grow (Hughes et al. 2007; Ledlie et al. 2007)	More resilience is conferred upon sites that have a high availability of suitable substrate
	Free from anthropogenic physical impacts	Carelessly placed anchors, as well as the fins of snorkelers and divers, damage coral, and can result in lesions that require physiological resources to repair increasing susceptibility to disease and bleaching (Rinkevich 1995; McManus et al. 1997)	More resilience is conferred upon sites that are not frequently damaged by anchors and divers/snorkelers
	Herbivore abundance	Herbivorous fish and invertebrates reduce the cover of algae that compete with corals for space and are particularly important post-disturbance as they help to ensure bare space is available for coral recruits. Their abundance is not always linked to fishing pressure (Hughes et al. 2007; Ledlie et al. 2007)	More resilience is conferred upon sites that have a high abundance of herbivores

Table 1 continued

Indicator weighting	Resilience indicator	Indicator justification	Conferring resilience
Important	Exposure to upwelling	The intrusion of cool nutrient-rich water reduces temperature stress, which could otherwise cause spatially extensive (‘mass’) bleaching events, usually during the summer season (Grimsditch and Salm 2006)	More resilience could be conferred upon sites that are exposed to some upwelling
	Light reduction	Factors that cool, screen or shade a site from high light, particularly during the brightest parts of the day, work to reduce stress to coral communities (Fabricius et al. 2004)	More resilience could be conferred upon sites where factors are present that reduce light intensity
	Free from fishing pressure	*Note: Fishing pressure will be ‘critically important’ as a resilience factor on reefs and in reef regions where herbivores (fish as well as other types like urchins) are targeted by fishers, which is not the case at the study site in Keppel Bay.* Large (> 20 cm) herbivorous fish are more efficient as grazers than small herbivores are. Grazing by herbivorous fish and other herbivore types like urchins reduces the cover of algae that compete with corals for space making their presence particularly important post-disturbance as they help to ensure bare space is available for coral recruits (Mumby 2006; Mumby et al. 2007b)	More resilience is conferred upon sites where fishing does not target herbivores of any type or where fishing pressure in general is low
	Topographic complexity	Small-scale topographic complexity on a reef results in self-shading that can reduce light stress during the long still hot periods that often precede the high temperatures that can cause bleaching (Fabricius et al. 2004)	More resilience is conferred upon sites that are topographically complex
	Coral submersion	Stress to corals exposed to the air for long periods can be severe enough to cause mortality (Anthony and Kerswell 2007)	More resilience is conferred upon sites where the coral communities always stay submerged
	Free from sedimentation	Tolerating sediment requires physiological resources increasing the susceptibility of affected colonies to other stressors (Rogers 1990; Anthony 2006)	More resilience is conferred upon sites where sediment delivery, resuspension and settlement is low
	Absence of bioeroders	Bioeroders prepare the reef for recovery but at high abundances can reduce the integrity of the reef framework which, in turn, results in a higher degree of susceptibility to physical stresses such as the intense wave action caused by tropical storms (Glynn 1997)	More resilience is conferred upon sites that have a low abundance of bioeroding organisms
	Absence of coral disease	Some types of coral diseases can advance quickly and kill colonies, while all increase the susceptibility of corals to other stressors (Harvell et al. 1999)	More resilience is conferred upon sites where coral disease is largely absent

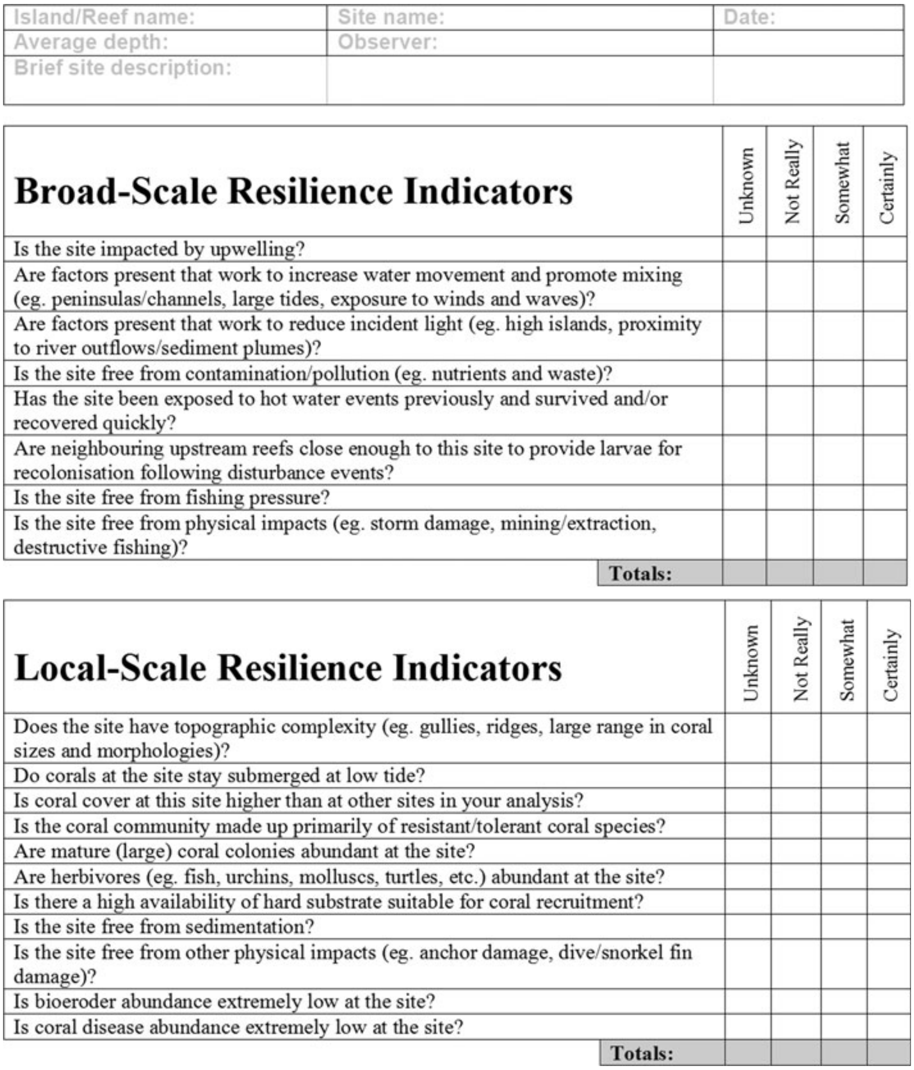
with this example, while turbidity and bleaching resistant taxa play roles in determining how a coral community initially responds to thermal stress, other indicators are critical in determining how a site recovers should stress lead to coral mortality. For the case study presented here, resilience indicators have been weighted based on the following: (1) the strength of the relationship between the indicator and reef resilience as evidenced in published literature (see Table 1 for references) and, for indicators that relate to anthropogenic impacts, (2) applicability to the case study region. Indicators with strong links to resilience have been classified as ‘critically important’. The links between ‘very important’ indicators and the resilience of reefs are not as strong as with the indicators classified as ‘critically important’, either because there is a weaker causal relationship or because there is higher uncertainty. In the case of indicators classified as ‘important’, the available literature suggests that the relationship between the indicator and reef resilience is weak relative to indicators in the other classes. Within the results section, the impact of weighting is made clear by comparing the resilience rankings of the highest and lowest-scoring sites with rankings produced when all indicators are unweighted. The extent to which any resilience indicator confers resilience to a reef site will vary spatially, particularly those related to anthropogenic impacts, and therefore indicator weightings may need to be re-evaluated for studies in other reef regions that use or emulate this framework.

Assessment framework

In the proforma used to assess resilience, the indicators have been divided into broad- and local-scale indicators and all are posed as questions (Fig. 1). Broad-scale indicators are applicable to the entire region and can be effectively assessed as a desktop exercise, while local-scale indicators must be assessed in the field. The resilience assessment takes between 30 and 45 min to complete for each site. Importantly, the assessment can be completed by an independent assessor highly familiar with the area of interest or, ideally, can be completed in collaboration with a small focus group that could include senior decision-makers, local managers, stakeholders and members of the public. Indicators have been posed as questions to ensure that there is no ambiguity when undertaking the assessment collaboratively with local community members and managers. The resilience assessment framework was undertaken collaboratively in the case study presented here using a focus group in a workshop setting that included a day of background presentations and classroom exercises and a day in the field. Through this process the resilience of 31 sites in Keppel Bay was assessed building on data collected during baseline biophysical assessments that identified habitat types in the area in May 2007 and September 2008 (GBRMPA 2008). Focus group participants included members of the Capricorn Coast Local Marine Advisory Committee, recreational fishers, aquarium fish collectors (commercial users), scientists, local government, members of the regional natural resource management group, local rangers, and staff from the climate change group, planning and information unit, and day to day management group of the Great Barrier Reef Marine Park Authority and the Queensland Parks and Wildlife Service (Queensland Department of Environment and Resource Management).

Resilience scores and resilience ranking

Each response to the indicator questions in the proforma—'not really', 'somewhat' and 'certainly' (see Fig. 1)—receives a value of 1, 2 and 3, respectively. Weightings are



Island/Reef name:	Site name:	Date:
Average depth:	Observer:	
Brief site description:		

Broad-Scale Resilience Indicators	Unknown	Not Really	Somewhat	Certainly
Is the site impacted by upwelling?				
Are factors present that work to increase water movement and promote mixing (eg. peninsulas/channels, large tides, exposure to winds and waves)?				
Are factors present that work to reduce incident light (eg. high islands, proximity to river outflows/sediment plumes)?				
Is the site free from contamination/pollution (eg. nutrients and waste)?				
Has the site been exposed to hot water events previously and survived and/or recovered quickly?				
Are neighbouring upstream reefs close enough to this site to provide larvae for recolonisation following disturbance events?				
Is the site free from fishing pressure?				
Is the site free from physical impacts (eg. storm damage, mining/extraction, destructive fishing)?				
Totals:				

Local-Scale Resilience Indicators	Unknown	Not Really	Somewhat	Certainly
Does the site have topographic complexity (eg. gullies, ridges, large range in coral sizes and morphologies)?				
Do corals at the site stay submerged at low tide?				
Is coral cover at this site higher than at other sites in your analysis?				
Is the coral community made up primarily of resistant/tolerant coral species?				
Are mature (large) coral colonies abundant at the site?				
Are herbivores (eg. fish, urchins, molluscs, turtles, etc.) abundant at the site?				
Is there a high availability of hard substrate suitable for coral recruitment?				
Is the site free from sedimentation?				
Is the site free from other physical impacts (eg. anchor damage, dive/snorkel fin damage)?				
Is bioeroder abundance extremely low at the site?				
Is coral disease abundance extremely low at the site?				
Totals:				

Fig. 1 Resilience assessment framework proforma. Broad-scale indicators can generally be assessed using a desktop study while local-scale indicators require fieldwork. All indicators have been posed as questions to reduce ambiguity and facilitate community engagement

then assigned, with scores of ‘critically important’ indicators multiplied by 3, ‘very important’ indicators multiplied by 2, and ‘important’ factors being unweighted (i.e., they are multiplied by 1; see Table 1). The higher the score, the more resilience is conferred upon the site as a result of that indicator. The final resilience score for each site is the sum of the scores for all of the indicator questions following weighting. Sites are then ranked from most resilient (highest resilience score) to least resilient (lowest resilience score).

Importantly, resilience has to be assessed as ‘relative’ when producing rankings meant to inform decisions regarding the targeting of management strategies. Therefore, for each indicator, the assessor(s) must frame their response in the light of a comparison between (1) the extent to which resilience is being conferred upon a site as a result of that indicator, and (2) the maximum extent to which resilience could be conferred on sites in the analysis pool (region) as a result of that indicator. Any number of sites could be included in a resilience assessment using the framework described here as long as the degree to which each indicator varies is known or can be estimated. The difference between the highest resilience score and the lowest score was divided by three, resulting in a score range used to classify sites as being of low, moderate or high resilience, relative to the other sites contained within the analysis.

Management influence potential

Only four of the 19 resilience indicators used in this framework can be influenced directly by management intervention in our case study area. The four are (1) free from fishing pressure, (2) free from water pollution, (3) free from sedimentation and (4) free from anthropogenic physical impacts. All are based on human activities and are somewhat interrelated; meaning that management responses to address each may be complementary. For example, the ecological consequences of water pollution and sedimentation may be different but the delivery mechanisms into the marine environment are linked and therefore action to address one stressor is likely to also address the other. In some regions, ‘abundance of herbivores’ may be closely linked to fishing pressure and would therefore be another resilience indicator that managers can influence. As herbivorous fish are not targeted in Keppel Bay (there is no commercial harvest of herbivorous fishes in the Great Barrier Reef Marine Park and no recreational netting or trapping of herbivores), their abundance is not linked to fishing pressure and therefore this resilience indicator has not been included in the list of indicators that managers can influence. Rankings of ‘management influence potential’ were produced following summing the scores for indicators that managers can influence for each of the study sites. The sites with the lowest scores would benefit the most, in terms of per cent increase in resilience score, from resilience-based management strategies, and the sites with the highest scores would benefit the least.

Results

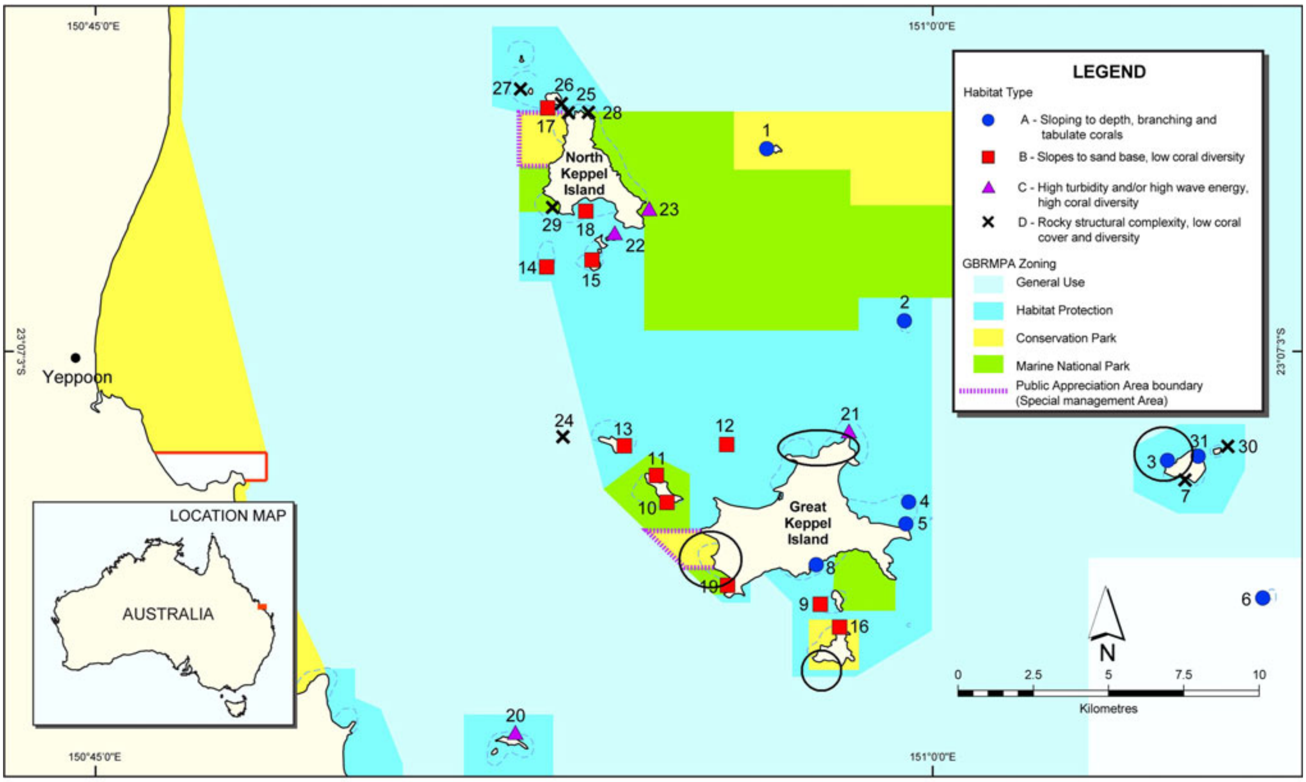
Resilience

Resilience scores ranged from 54 for the lowest-scoring sites (North Humpy Island and Monkey Beach Reef—Great Keppel Island) to 103 for the highest-scoring site (SE North Keppel Island, see Fig. 3). The top four ranked sites in order were SE North Keppel Island, West Outer Rock, West Halfway Island and Pumpkin Passage (see Fig. 2 for locations). The lowest-scoring sites were Pelican Island, Half-Tide Rocks, Monkey Beach Reef—Great Keppel Island, North Humpy Island (see Fig. 3). Four sites were classified as having high resilience (resilience scores between 89 and 103), 18 as having moderate resilience (72–86) and nine sites as having low resilience (54–69; Fig. 3). The weighting of resilience indicators helped to differentiate sites as being of low, moderate or high resilience by increasing the score spread, but indicator weighting did not change the order of the most and least resilient sites.

There was no clear relationship between habitat type and resilience score. The four highest-scoring sites represent three habitat types (B, A, and C—see Fig. 2), the only habitat excluded—D—is characterised by low coral cover, which is an indicator weighted here as being ‘critically important’. Four of the 10 sites classified as having low resilience are classified as habitat type D (see Fig. 2) but these are not the four lowest-ranked sites. The four lowest-ranked sites are habitat types B and C but, importantly, include the following: the site closest to land and the local river outlet, Pelican Island, the most frequently visited site in the area, Monkey Beach Reef, a site adjacent to a favoured island campground, Humpy Island, and a site known to be popular with recreational fishers, Half-Tide Rocks.

Management influence potential

The sites that would benefit most (in terms of percentage increase in resilience score) from the implementation of resilience-based management are Pelican Island, NW Barren Island, 40 Acre Paddock, North Humpy Island and Monkey Beach Reef. These all received the lowest possible score for at least two of the four resilience indicators that mangers can influence (see Fig. 4). The sites that would benefit least from additional resilience-based management (aside from measures already in place, like marine park zoning, see Fig. 1) are SE North Keppel and West Outer Rock, which received the highest possible score for all of



Habitat type A
1 - West Outer Rock
2 - Man & Wife Rocks
3 - North-west Barren Island
4 - Bald Rock
5 - 23-032
6 - Egg Rock
7 - Coral Garden-Barren Island
8 - Clam Bay-Great Keppel Island

Habitat type B
9 - West Halfway Island
10 - Observatory-Middle Island
11 - Olive Bay-Middle Island
12 - Half-tide Rocks
13 - Miall Island
14 - Square Rocks
15 - North Sloping Island
16 - North Humpy Island
17 - Corroboree Island south
18 - Mazie Bay-North Keppel Island
19 - Monkey Beach Reef-Great Keppel Island

Habitat type C
20 - Pelican Island
21 - Big Peninsula-Great Keppel Island
22 - Pumpkin Passage
23 - South-east North Keppel Island

Habitat type D
24 - 40 Acre Paddock
25 - Corroboree Passage south
26 - Corroboree Island south-east
27 - West Conical Island
28 - North-east North Keppel Island
29 - Eagle Rock-North Keppel Island
30 - The Child
31 - Hole in Wall-Barren Island

Fig. 2 Surveyed sites, by habitat type, within the Keppel Bay. Circled sites denote locations where reef protection markers were installed in November of 2008

the resilience indicators that managers can influence, a total score of 21 (Fig. 4). Overall, scores were low for the indicators ‘free from fishing pressure’ and ‘free from anthropogenic physical impacts’ indicating that these two factors are compromised in much of the study area.

Discussion

Anthropogenic physical impacts emerged as a major threat working to lower resilience throughout much of Keppel Bay and are the type of impact that can be easily mitigated through management action. For that reason, measures to reduce the risk of damage from vessel anchors were identified by local managers and community members as a suitable priority for a first-stage management response aimed at maximising the resilience of reefs in the area. In some high-use regions of the Great Barrier Reef Marine Park, anchor damage has been effectively reduced through installation of reef protection markers (RPMs) that delineate reef areas where anchoring is prohibited through regulation or best practice codes of behaviour (Day 2002). The resilience and management influence potential rankings produced using the resilience assessment framework described here informed site selection for RPM installation in Keppel Bay. In November 2008, following community consultation, RPMs were installed at four sites of either low or moderate resilience where anchor damage is severe and visitation is high. This strategy received strong community support as a measure to increase resilience by eliminating anchor damage while also engendering stewardship through education and awareness raising—2 of the four sites selected are amongst the most frequently visited in the area. RPMs were installed at Monkey Beach Reef located on the SW corner of Great Keppel Island, Big Peninsula on north Great Keppel Island, the western edge of Barren Island called Hole in Wall, and offshore of a campground on Humpy Island (see Fig. 2). Installation of the RPMs was accompanied by an educational programme that highlighted the role reef users can play in building the

Resilience Conferred:
🟥 = Least
🟨 = Some
🟩 = Most

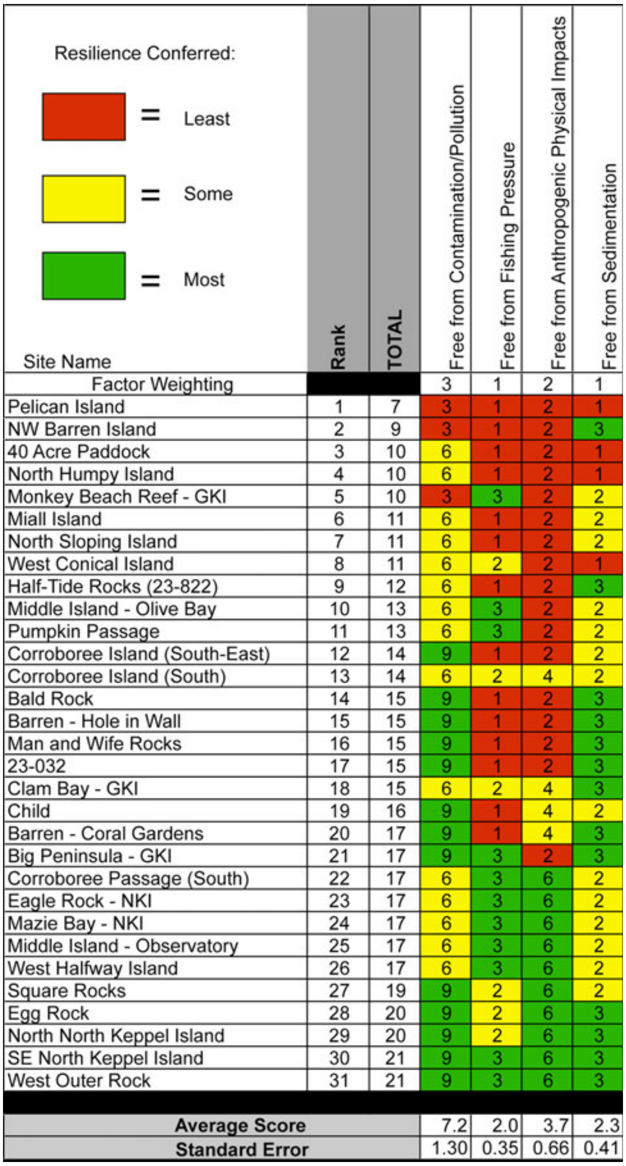
Site	RANK	TOTAL	**Broad-scale Factor Total**	**Connectivity**	**Hot Water Events**	**Free from Contamination/Pollution**	*Water mixing*	*Free from Physical Impacts*	Exposure to Upwelling	Free from Fishing Pressure	Reduction in Light Stress	**Local-scale Factor Total**	**Coral Cover**	**Resistant/Tolerant Corals**	*Abundance of Herbivores*	*Abundance of Mature Corals*	*Substrate Availability*	*Free from Anthropogenic Physical Impacts*	Coral submersion	Absence of Bioeroders	Topographic Complexity	Free from Sedimentation	Absence of Coral Disease
				3	3	3	2	2	1	1	1		3	3	2	2	2	2	1	1	1	1	1
SE North Keppel Island	1	103	48	9	9	9	6	6	3	3	3	55	9	9	6	6	6	6	3	3	2	3	2
West Outer Rock	2	94	44	6	9	9	6	6	3	3	2	50	9	6	6	6	4	6	2	3	2	3	3
West Halfway Island	3	89	41	9	9	6	4	6	2	3	2	48	9	6	6	6	4	6	1	3	2	2	3
Pumpkin Passage	4	89	44	9	9	6	6	6	3	3	2	45	9	9	4	6	4	2	1	3	2	2	3
Big Peninsula - GKI	5	86	40	9	6	9	6	2	3	3	2	46	9	6	6	4	6	2	2	3	2	3	3
Square Rocks	6	86	41	6	9	9	6	6	1	2	2	45	9	3	6	4	6	6	2	2	2	2	3
Mazie Bay - NKI	7	83	41	9	9	6	6	4	3	3	1	42	6	6	4	2	6	6	2	3	2	2	3
Barren - Coral Gardens	8	82	42	9	6	9	6	6	3	1	2	40	9	3	2	6	2	4	3	3	2	3	3
Egg Rock	9	81	40	6	6	9	6	6	3	2	2	41	6	3	4	4	4	6	3	3	2	3	3
Middle Island - Observatory	10	81	38	9	9	6	2	6	1	3	2	43	9	3	6	4	2	6	2	3	3	2	3
Corroboree Passage (South)	11	79	40	6	9	6	6	6	2	3	2	39	3	3	6	2	6	6	3	2	3	2	3
Clam Bay - GKI	12	78	35	9	6	6	4	4	2	2	2	43	9	3	4	6	4	4	2	3	2	3	3
Child	13	77	39	9	6	9	6	4	2	1	2	38	6	3	4	4	4	4	3	3	2	2	3
Barren - Hole in Wall	14	77	39	9	6	9	6	2	3	1	3	38	6	3	6	4	4	2	3	3	2	3	2
North North Keppel Island	15	77	39	9	6	9	6	2	3	2	2	38	3	3	4	2	6	6	3	3	2	3	3
North Sloping Island	16	76	33	9	9	6	4	2	1	1	1	43	9	3	6	6	6	2	2	2	2	2	3
Corroboree Island (South)	17	76	33	6	9	6	4	2	2	2	2	43	9	3	6	4	6	4	1	3	2	2	3
Man and Wife Rocks	18	76	35	3	9	9	6	2	3	1	2	41	6	3	6	4	6	2	2	3	3	3	3
Miall Island	19	75	37	9	9	6	6	2	2	1	2	38	9	3	4	6	2	2	2	3	2	2	3
Bald Rock	20	75	32	6	3	9	6	2	3	1	2	43	9	3	6	4	6	2	2	3	2	3	3
Middle Island - Olive Bay	21	74	34	9	9	6	2	2	1	3	2	40	9	3	6	2	6	2	2	3	2	2	3
Corroboree Island (South-East)	22	72	32	6	6	9	4	2	2	1	2	40	6	3	6	6	4	2	3	3	2	2	3
Eagle Rock - NKI	23	69	35	9	6	6	4	4	1	3	2	34	3	3	4	2	4	6	2	3	2	2	3
23-032	24	69	32	6	3	9	6	2	3	1	2	37	9	3	4	4	2	2	2	3	2	3	3
NW Barren Island	25	67	32	3	6	9	6	2	3	1	2	35	6	3	2	4	4	2	3	3	2	3	3
West Conical Island	26	66	34	3	9	6	6	4	2	2	2	32	3	3	6	4	2	2	3	3	2	1	3
40 Acre Paddock	27	65	34	9	9	6	4	2	1	1	2	31	3	6	4	4	2	2	3	2	1	1	3
Pelican Island	28	60	26	3	6	3	6	2	2	1	3	34	6	3	2	4	4	2	3	3	3	1	3
Half-Tide Rocks (23-822)	29	58	23	3	3	6	4	2	2	1	2	35	6	3	2	4	4	2	3	3	2	3	3
Monkey Beach Reef - GKI	30	54	25	9	3	3	2	2	1	3	2	29	3	3	4	2	4	2	1	3	2	2	3
North Humpy Island	31	54	27	9	3	6	2	2	2	1	2	27	6	3	2	2	2	2	1	3	2	1	3
	Average Score			7.3	7	7.2	5	3.5	2.2	1.9	2		6.9	3.9	4.6	4.1	4.3	3.5	2.3	2.9	2.1	2.3	2.9
	Standard Error			1.3	1.3	1.3	0.9	0.6	0.4	0.3	0.4		1.2	0.7	0.8	0.7	0.8	0.6	0.4	0.5	0.4	0.4	0.5

Fig. 3 Summary of resilience rankings and scores for all indicators for all sites. Bold, italicised and normal font used for the indicators corresponds to the indicator weightings: critical, very important and important, respectively. Indicators highlighted in grey can be influenced in Keppel Bay by managers

resilience of local reefs to climate change. Importantly, installation of RPMs at these Keppel Bay reef sites is not expected to single-handedly ensure that the reefs in the area are resilient to climate change. However, with relatively low cost to local managers and minimal impact on users of the area, they provide a chance to test the efficacy of local management actions in building the resilience of impacted sites, and, in turn, to the larger Keppel Bay reef system.

In the spirit of active adaptive management (Walters 1986), this resilience assessment framework enables transparent decisions about the most effective resilience-based management by using current knowledge, while also testing and refining hypotheses about the relative importance of different putative resilience indicators. The now-widespread definition of resilience used in this paper, and popularised by the Resilience Alliance, includes tolerating and absorbing shocks as well as recovering from them. Therefore, active adaptive resilience-based management to give reefs the best chance of avoiding and/or recovering from phase shifts requires a two-pronged approach of: (1) being active by planning for an uncertain future, and (2) being adaptive by responsively implementing strategies post-disturbance that reduce anthropogenic stressors that could increase recovery times (Day 2002; Folke et al. 2004). Management resources are limited and need to be invested in both general resilience-building strategies and in responding to specific disturbance responses. The resilience assessment framework presented here can inform the allocation of resources to both strategic and responsive management initiatives.

Climate change requires that managers plan for an uncertain future in which pressures on reef ecosystems will



Resilience Conferred:

🟥 = Least

🟨 = Some

🟩 = Most

Site Name	Rank	TOTAL	Free from Contamination/Pollution	Free from Fishing Pressure	Free from Anthropogenic Physical Impacts	Free from Sedimentation
Factor Weighting			3	1	2	1
Pelican Island	1	7	3	1	2	1
NW Barren Island	2	9	3	1	2	3
40 Acre Paddock	3	10	6	1	2	1
North Humpy Island	4	10	6	1	2	1
Monkey Beach Reef - GKI	5	10	3	3	2	2
Miall Island	6	11	6	1	2	2
North Sloping Island	7	11	6	1	2	2
West Conical Island	8	11	6	2	2	1
Half-Tide Rocks (23-822)	9	12	6	1	2	3
Middle Island - Olive Bay	10	13	6	3	2	2
Pumpkin Passage	11	13	6	3	2	2
Corroboree Island (South-East)	12	14	9	1	2	2
Corroboree Island (South)	13	14	6	2	4	2
Bald Rock	14	15	9	1	2	3
Barren - Hole in Wall	15	15	9	1	2	3
Man and Wife Rocks	16	15	9	1	2	3
23-032	17	15	9	1	2	3
Clam Bay - GKI	18	15	6	2	4	3
Child	19	16	9	1	4	2
Barren - Coral Gardens	20	17	9	1	4	3
Big Peninsula - GKI	21	17	9	3	2	3
Corroboree Passage (South)	22	17	6	3	6	2
Eagle Rock - NKI	23	17	6	3	6	2
Mazie Bay - NKI	24	17	6	3	6	2
Middle Island - Observatory	25	17	6	3	6	2
West Halfway Island	26	17	6	3	6	2
Square Rocks	27	19	9	2	6	2
Egg Rock	28	20	9	2	6	3
North North Keppel Island	29	20	9	2	6	3
SE North Keppel Island	30	21	9	3	6	3
West Outer Rock	31	21	9	3	6	3
Average Score			7.2	2.0	3.7	2.3
Standard Error			1.30	0.35	0.66	0.41

Fig. 4 Management influence potential rankings calculated as the sum score at each site for the resilience indicators that managers can influence. In this case, low scores receive the highest rankings

rapidly escalate (IPCC 2007). A broad range of resilience-building strategies will need to be implemented if reef ecosystems are to have the best chance of coping with these threats. For two of the four indicators managers can influence in Keppel Bay, water quality and fishing pressure, management strategies that have already been implemented at the ecosystem scale (whole of GBR) to support resilience. Rezoning of the GBRMP in 2003 increased conservation (no-take) areas from 5 to 33% (Hughes et al. 2003; Russ et al. 2008), and the reef water quality protection and reef rescue plans (2003 and 2007, respectively) are addressing diffuse sources of terrestrial run-off to improve water quality of the inshore marine environment (State of Queensland and Commonwealth of Australia 2003). Both of these strategies are improving a number of 'critically important' and 'very important' resilience indicators at a reef-wide scale. Given the 'critically important' weighting of the resilience indicator 'free from water pollution' in this framework, the continued improvement of water quality over large spatial scales will provide one of the greatest improvements to the resilience of all reefs in Keppel Bay. This adds further justification to the need to focus on local-scale measures to build resilience (such as reducing anchor damage at heavily used sites) as such measures will be crucial complements to larger-scale initiatives, such as those that address fishing pressure and water quality (Marshall and Schuttenberg 2006).

Informed and effective planning requires supportive social and political frameworks to ensure managers can rapidly implement strategies following disturbances that reduce compounding stressors and allow for recovery (Folke et al. 2004). The most feasible and cost-effective strategies to increase recovery potential involve reducing anthropogenic stressors. Many of these measures, such as reducing anchor damage, require changes to patterns of use, either through regulation and compliance, or through voluntary arrangements. The success of these approaches will be maximised if users understand and support the measures, and if genuine efforts to reduce the social, economic and cultural impacts have been made (Berkes et al. 2006). Key ingredients in the success of resilience-based management strategies, therefore, are effective communication between managers, scientists and reef users, and meaningful engagement of reef users in decision-making processes. For this case study, the application of the resilience framework was used as a tool and opportunity to engage with stakeholders. Participation in the assessment of reef resilience and the targeting of sites for management strategies increased understanding and stewardship within the Keppel Bay community and raised the support required for the installation of reef protection markers. It is likely that this engagement has also laid the foundations for future resilience-building strategies, including responsive actions to future disturbances like coral bleaching events.

Participants making up the focus group that completed the resilience assessment framework presented here were all highly educated on issues relating to the marine environment and coral reef management, highly familiar with the reef environments and conditions within Keppel Bay, or both. Though plans are underway, the framework has yet to be trialled in other locations. For those hoping to trial the framework, the experiences gained through the case study presented here suggest that those leading or at least people closely involved need to be very familiar with the subject reef area, and the background presentations and classroom exercises, which serve to educate, need to be tailored to the knowledge level of the participants. As an example, in a setting where local participants do not have a high level of knowledge of ecosystem processes and management, as in many developing nations with significant reef resources, more time might be spent on education prior to having everyone actively participate in the field assessment.

Importantly, the framework presented here cannot be used in isolation. At a minimum, it needs to be complemented with assessments of habitat types in the wider region of interest to evaluate the uniqueness, or conservation significance, of reef types included in the resilience assessment. This works to ensure managers have the opportunity to include a representative sample of habitat types when implementing management strategies, a key criterion for building resilience in reef ecosystems, and for raising political and community support. The benefit of the framework presented here is that it can be used to assess and rank the resilience and management influence potential of any number of sites. The assessment, however, must be specific about its spatial extent as the resilience score is a relative measure based on the extent to which each indicator varies within the focal region. The range of values for any indicator within the focal region can be determined through a combination of reviewing existing datasets, expert surveys and local knowledge. Therefore, the framework can be calibrated using information of varying levels of precision and reliability—the final assessment and hence the magnitude of management decisions can simply be scaled to match the information base and the uncertainty. Here, again, involving stakeholders in the assessment and decision-making process can reduce the burden for justification of decisions and facilitate more decisive and inclusive management actions. Lastly, the weighting of resilience indicators, within the framework presented here, reflects current state-of-science as well as knowledge of resilience within the subject area. In this study, weighting the resilience indicators helped to differentiate sites but did not change the ranking order of the sites deemed to be of lowest and highest resilience. Other studies that use a framework similar to that presented here may not have the same result. The relative importance of indicators will vary spatially and potentially temporally highlighting that anyone implementing this or a similar resilience assessment framework will need to consider changing indicator weightings. With the above considerations, this framework has the potential to be applied at all scales, from local to global.

Some climate change is inevitable, even if global greenhouse gas emissions are significantly reduced in the coming decades (Donner et al. 2005). There is, therefore, an urgent need for managers to implement practical and immediate actions to address stressors that exacerbate those of climate change (Marshall and Johnson 2007). Though critical, resilience-building initiatives, like all management decisions, require trade-offs between social, ecological and economic interests and therefore must be supported by robust and defensible information. The framework presented here provides a transparent and inclusive approach for gathering such information by determining the relative resilience of coral reef sites and by identifying potential resilience-building strategies. As a major step towards making resilience operational for coral reef managers, we hope this framework will accelerate the implementation of informed local management actions that will help give some coral reefs the best chance of surviving climate change.

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References

Adger WN, Hughes TP, Folke C, Carpenter SR, Rockstrom J (2005) Social-ecological resilience to coastal disasters. Science 309:1036–1039

Anthony KRN (2006) Enhanced energy status of corals on coastal, high-turbidity reefs. Mar Ecol Prog Ser 319:111

Anthony KRN, Kerswell AP (2007) Coral mortality following extreme low tides and high solar radiation. Mar Biol 151: 1623–1631

Bellwood DR, Hughes TP, Folke C, Nystrom M (2004) Confronting the coral reef crisis. Nature 429:827–833

Berkes F, Hughes TP, Steneck RS, Wilson JA, Bellwood DR, Crona B, Folke C, Gunderson LH, Leslie HM, Norberg J, Nystrom M, Olsson P, Osterblom H, Scheffer M, Worm B (2006) Globalization, roving bandings and marine resources. Science 311: 1557–1558

Carpenter S, Walker B, Anderies JM, Abel N (2001) From metaphor to measurement: resilience of what to what? Ecosystems 4:765–781

Day JC (2002) Zoning: lessons from the Great Barrier Reef. Ocean Coast Manage 45:139–156

Done TJ (1992) Phase shifts in coral reef communities and their ecological significance. Hydrobiologia 247:121–132

Donner SD, Skirving WJ, Little CM, Oppenheimer M, Hoegh-Guldberg O (2005) Global assessment of coral bleaching and required rates of adaptation under climate change. Global Change Biol 11:2251–2265

Fabricius KE, Mieog JC, Colin PL, Idip D, van Oppen MJH (2004) Identity and diversity of coral endosymbionts (zooxanthellae) from three Palauan reefs with contrasting bleaching, temperature and shading histories. Mol Ecol 13:2445–2458

Folke C (2006) Resilience: the emergence of a perspective for social ecological systems analyses. Global Environ Change 16:253–267

Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist T, Gunderson L, Holling CS (2004) Regime shifts, resilience, and biodiversity in ecosystem management. Annu Rev Ecol Syst 35:557–581

GBRMPA (2008) Bio-physical assessment of the reefs of Keppel Bay: a baseline study September 2008. Great Barrier Reef Marine Park Authority, Townsville

Glynn PW (1997) Bioerosion and coral reef growth: a dynamic balance. In: Birkeland C (ed) Life, death of coral reefs. Chapman and Hall, New York, pp 68–95

Grimsditch GD, Salm RV (2006) Coral reef resilience and resistence to bleaching. IUCN, Gland

Harvell CD, Kim K, Burkholder JM, Colwell RR, Epstein PR, Grimes DJ, Hofmann EE, Lipp EK, Osterhaus ADME, Overstreet RM, Porter JW, Smith GW, Vasta GR (1999) Emerging marine diseases: climate links and anthropogenic factors. Science 285:1505–1510

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME (2007) Coral reefs under rapid climate change and ocean acidification. Science 318:1737–1742

Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nystrom M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J (2003) Climate change, human impacts, and the resilience of coral reefs. Science 301:929–933

Hughes TP, Rodrigues M, Bellwood D, Ceccarelli D, Hoegh-Guldberg O, McCook L, Molschaniwskyj N, Pratchett M, Steneck R, Willis BL (2007) Phase shifts, herbivory, and the resilience of coral reefs to climate change. Curr Biol 17:360–365

IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S (ed) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Johnson JE, Marshall PA (eds) (2007) Climate change and the Great Barrier Reef: a vulnerability assessment. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Townsville

Ledlie MH, Graham NAJ, Bythell JC, Wilson SK, Jennings S, Polunin NVC, Hardcastle J (2007) Phase shifts and the role of herbivory in the resilience of coral reefs. Coral Reefs 26:641–653

Marshall PA, Baird AH (2000) Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. Coral Reefs 19:155–163

Marshall PA, Johnson JE (2007) The Great Barrier Reef and climate change: vulnerability and management implications. In: Marshall PA, Johnson JE (eds) Climate change and the Great Barrier Reef: a vulnerability assessment. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Townsville

Marshall NA, Marshall PA (2007) Conceptualizing and operationalizing social resilience within commercial fisheries in northern Australia. Ecology and Society 12: [online] URL: http://www.ecologyandsociety.org/vol12/iss1/art1/

Marshall PA, Schuttenberg H (2006) A reef manager's guide to coral bleaching. Great Barrier Reef Marine Park Authority, Townsville

McClanahan T (2004) The relationship between bleaching and mortality of common corals. Mar Biol 144:1239–1245

McClanahan T, Polunin N, Done T (2002) Ecological states and the resilience of coral reefs. Conserv Ecol 6:Artn 18

McManus JW, Reyes RB, Nanola CL (1997) Effects of some destructive fishing methods on coral cover and potential rates of recovery. Environ Manag 21:69–78

Mumby PJ (2006) The impact of exploiting grazers (Scaridae) on the dynamics of Caribbean coral reefs. Ecol Appl 16:747–769

Mumby PJ, Hastings A (2008) The impact of ecosystem connectivity on coral reef resilience. J Appl Ecol 45:854–862

Mumby PJ, Hastings A, Edwards HJ (2007a) Thresholds and the resilience of Caribbean coral reefs. Nature 450:98–101

Mumby PJ, Harborne AR, Williams J, Kappel CV, Brumbaugh DR, Micheli F, Holmes KE, Dahlgren CP, Paris CB, Blackwell PG (2007b) Trophic cascade facilitates coral recruitment in a marine reserve. Proc Natl Acad Sci USA 104:8362–8367

Nystrom M, Graham NAJ, Lokrantz J, Norstrom AV (2008) Capturing the cornerstones of coral reef resilience: linking theory to practice. Coral Reefs 27:795–809

Obura DO (2005) Resilience and climate change: lessons from coral reefs and bleaching in the Western Indian Ocean. Estuar Coast Shelf Sci 63:353–372

Pimm SL (1984) The complexity and stability of ecosystems. Nature 307:321–327

Rinkevich B (1995) Restoration strategies for coral reefs damaged by recreational activities: the use of sexual and asexual recruits. Restor Ecol 3:241–251

Roberts CM (1997) Connectivity and management of Caribbean coral reefs. Science 278:1454–1457

Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Mar Ecol Prog Ser 62:185–202

Russ GR AJ, Cheal AM, Dolman MJ, Emslie EvansRD, Miller I, Sweatman H, Williamson DH (2008) Rapid increase in fish numbers follows creation of world's largest marine reserve network. Curr Biol 18:514–515

Soong K (1993) Colony size as a species character in massive reef corals. Coral Reefs 12:77–83

State of Queensland and Commonwealth of Australia (2003) Reef water quality protection plan; for catchments adjacent to the Great Barrier Reef world heritage area Queensland Department of Premier and Cabinet, Brisbane, Australia

Walker B (1995) Conserving biological diversity through ecosystem resilience. Conserv Biol 9:747–752

Walker B, Carpenter, S, Anderies JM, Abel N, Cumming GS, Janssen M, Lebel L, Norberg J, Peterson GD, Pritchard R (2002) Resilience management in social-ecological systems: a working hypothesis for a participatory approach. Conserv Ecol 6:14 [online] URL: http://www.consecol.org/vol6/iss1/art14/

Walters C (1986) Adaptive management of renewable resources. Macmillan, New York

West JM, Salm RV (2003) Resistance and resilience to coral bleaching: implications for coral reef conservation and management. Conserv Biol 17:956–967

Williams ID, Polunin NVC (2001) Large-scale associations between macroalgal cover and grazer biomass on mid-depth reefs in the Caribbean. Coral Reefs 19:358–366

Wooldridge S, Done T, Berkelmans R, Jones R, Marshall PA (2005) Precursors for resilience in coral communities in a warming climate: a belief network approach. Mar Ecol Prog Ser 295: 157–169