National Marine Science Plan, White paper submissions for Biodiversity Conservation and Ecosystem Health
- *Ecosystem Health*

Abstract

Healthy ecosystems are fundamental to ensuring a thriving marine environment and to sustaining human populations. Marine ecosystems are facing a suite of pressures driven by natural processes and human activities at global to local scales. Understanding the opportunities and limitations for management and strategic planning of Australia's marine environment will be critical to sustaining healthy and productive ecosystems now and in the future. This white paper provides the science needs, perspective and realisation on Australia continuing to be a world leader in marine ecosystem health.

Background

A healthy ecosystem can be described as a system that is resilient, maintains intact ecosystem functions (population survivorship, growth and replenishment), displays functional response diversity and is able to provide goods and services (Chapin et al. 2000; Nystrom et al. 2000; Limburg et al. 2002). Further, a healthy ecosystem has a suite of trophic levels and good spatial connectivity among subsystems (Tett et al. 2013).

Australia's marine ecosystems are facing stressors from a suite of natural and anthropogenic sources, collectively posing a threat to the health of benthic and pelagic ecosystems across its marine estate (Poloczanska et al. 2007; State of the Environment 2011; Howard et al. 2012; GBRMPA 2014). To keep Australia's marine ecosystems sustainable requires an effective environmental strategy building on ecosystem-based management (e.g. Samhouri et al. 2012). Our research needs to meet the critical information needs of marine ecosystem managers via an effective marine science plan and knowledge transfer between stakeholders (Cvitanovic et al. 2013). This strategy must build on a deeper systems understanding at multiple scales and across disciplines, be intimately linked to clear management and policy goals and objectives, identify pathways to impact, and demonstrated environmental, social and economic outcomes.

Research is currently undertaken by:

- Universities
- State and Federal Government departments [e.g., Qld Department of Science, Information Technology, Innovation and the Arts (DSITIA); SA Environment Protection Authority, NSW Department of Primary Industries – Marine Ecosystems Research, WA Department of Parks and Wildlife - Marine Science Division]
- Federal research agencies [Australian Institute of Marine Science (AIMS), Commonwealth Scientific and Industrial Research Organisation (CSIRO)]

The research is funded by:

- Federal Government [Department of the Environment (DoE); Australian Research Council (ARC)]
- State Governments [DSITIA; Qld Department of Environment and Heritage Protection (EHP), WA Marine Science Institute (WAMSI)]

- Industry – via offsets (Pluto Offset to WA DPaW), direct partnerships (e.g. Oil & Gas contracts with AIMS), and in some cases industry may directly contribute to funding projects related to ecosystem health (e.g. Spencer Gulf Ecosystem Development Initiative)
- National and international foundations (e.g. Ian Potter Foundation, Great Barrier Reef Foundation)

Australia is a world leader in marine ecosystem health research, along with the USA and Europe – this is based on the quality of science in the international literature and our world-class Excellence in Research Australia (ERA) rankings (rating of 4 or higher) for disciplines related to ecosystem science (e.g. environmental science & management, ecological applications, ecology, earth sciences, fisheries sciences). Terrestrial and freshwater ecology have traditionally been leading the innovation in ecosystem health research through advanced monitoring studies, analytical approaches, adaptive management strategies and in the decision science field. In recent years, advances in marine science in Australia are closing these gaps from monitoring (e.g. Integrated Marine Observing System) through modelling to management. Australia needs to maintain that edge, in part by investing and engaging more in international cross-disciplinary partnerships.

Relevance

Understanding the cumulative impacts of multiple activities and stressors on marine ecosystem health is of relevance to a wide range of Australian stakeholders and end-users. These include federal and state/territory government, local government, non-government organisations (NGO's), public interest groups and an array of industries. Specifically, these are:

- Federal and State departments – Departments incorporating environment, fisheries, aquaculture, biosecurity, transport (ports), marine parks, natural resources, mining and other resource development specifically DoE, Department of Agriculture, DSITIA, Biosecurity Queensland, State-based Primary Industries and Environment agencies
- Statutory management agencies (e.g. DoE, Great Barrier Reef Marine Park Authority)
- Regional Development Australia, which brings together all levels of government to enhance development of Australia's regions
- Local government (e.g. local councils or central local government groups such as Upper Spencer Gulf Common Purpose Group) and Natural Resource Management agencies
- Industry end-users include agriculture, fisheries, aquaculture, marine pests, tourism operators (e.g. Association of Marine Park Tourism Operators), ports and shipping, defence, mining, manufacturing, oil & gas, energy, tourism
- Indigenous groups
- Public interest groups & non-government organisations

Further, an understanding of the drivers of ecosystem health is relevant to strategic assessments being undertaken through the Sustainable Regional Development Program (see below) and for long-term sustainability plans (e.g. Reef 2050 Plan, http://www.environment.gov.au/marine/gbr/reef2050; Australian Ecosystem Science Long-Term Plan [ESLTP 2014], http://www.ecosystemscienceplan.org.au/).

Evidence of end-user engagement

Individual development proposals often investigate effects of specific drivers and activities on ecosystem health, but usually only at a local scale (e.g. individual environmental impact assessment). At a high level, the Department of the Environment produces the State of the Environment Report (http://www.environment.gov.au/science/soe/2011) through consultation with the science community and other data providers to give an overview of environmental status and trends. The Federal Government and State Governments also undertake strategic assessments that focus on larger spatial and temporal scales and consider a broader set of issues resulting from development and other activities, including natural impacts and global pressures from climate change and ocean acidification. These assessments investigate direct, indirect and cumulative impacts on the ecosystem from a multitude of sources. They work with all levels of government and the private sector with the aim being to have a more streamlined and collaborative approach to environmental protection. Two such assessments are the comprehensive strategic assessments of the Great Barrier Reef World Heritage Area and adjacent coastal zone, undertaken by GBRMPA and EHP (e.g. GBRMPA 2014). Several other high growth regions (e.g. Lower Hunter, NSW; Perth and Peel Regions, WA and Upper Spencer Gulf, SA) also have strategic assessments underway, although these may not be as comprehensive as that undertaken for the Great Barrier Reef World Heritage Area.

Science needs

Characterising marine ecosystem health requires a multi-pronged approach combining ecosystems understanding, integrated monitoring and modelling at multiple scales. A useful approach to combining environmental and social-economic aspects of ecosystem health within a management framework is the *Drivers, Pressures, Impacts (on values) and Responses (DPSIR)* hierarchy (Borja 2006; Jago-on et al. 2009; GBRMPA 2014). Integration, coordination and management of monitoring data and models lead to improved understanding of ecosystem status and trend, and attribution of drivers and pressures, in turn lead to more informed management decisions now and into the future. In particular, we need to address large disparities in research effort among different parts the Australian marine estate (Fisher et al. 2011).

While assessing marine ecosystem health can be more challenging than terrestrial systems due to restrictions on large-scale surveys and observation via remote-sensing techniques, science innovation and interdisciplinary approaches are closing this gap (e.g. AUV research, advancement in optical remote sensing of coastal marine ecosystems, IMOS and other ocean-scale oceanographic surveillance via Argo floats). The setting of targets for ecosystem health is a critical component of management plans (e.g. GBR 2050, ESLTP 2014) and form part of an adaptive management approach (McCook et al. 2010; GBRMPA 2014). To set and meet targets for various components of ecosystem health, however, requires understanding of the co-dependencies between these ecosystem components – in other words, how does the failure to meet one ecosystem health target influence the ability to meet another target? Practical approaches are required which consider different levels of data availability, and which can be used at different spatial scales. The DPSIR framework, integrated monitoring programs and linked social-ecosystem models can help illuminate paths to a management strategy that can deliver on multiple targets (e.g. Anthony et al. 2013; Anthony et al. 2014).

As the marine environment becomes subject to greater use including extractive (e.g. fisheries) and non-extractive uses (e.g. shipping), higher temperatures and higher CO_2 levels, it is increasingly important to understand the cumulative impacts of these multiple stressors and how they affect ecosystem health (Hoegh-Guldberg et al. 2007; Knowlton and Jackson 2008; Connell and Russell 2010; Anthony et al. 2014). Marine ecosystems are vulnerable to global, regional and local scale disturbances and, increasingly, approaches are required that take an integrated view to management and consider pressures facing the entire ecosystem and the linked social system (Chapin et al. 2010). The objective of such an approach would be to keep the system resilient – i.e. preserve its ability to absorb and recover from disturbances while maintaining function (e.g. Gunderson 2000). A resilient system is less likely to be vulnerable to disturbances (Fussel and Klein 2006; Mumby et al. 2014).

Ecosystem based management examines environmental drivers and activities and their impact on marine ecosystems using a range of indicators of resilience, vulnerability, diversity, integrity, stability and adaptability. Science needs can be focused around three broad areas: identifying indicators, linking habitats to biological attributes, and understanding cumulative stressors and dynamics of perturbed systems (see below). In addition, there are significant gaps around ensuring that the appropriate legislative and policy framework is in place to support implementation of integrated marine management, especially at the state level. There is a need to consider links between marine and terrestrial systems although this is improving (e.g. as currently occurs in the Queensland Paddock to Reef Program).

Identifying indicators that capture ecosystem processes

Descriptive indicators relating to ecosystem structure (e.g. diversity, species composition, abundance) and quantitative indicators that represent ecosystem processes (e.g. productivity, nutrient cycling, metabolism) can provide information on ecosystem health. The ability to capture resilience, vulnerability and adaptability to stressors requires combinations of monitoring techniques as well as modelling approaches. Here, high-quality empirical data are critical for model calibration and validation, and to verify that indicators have fidelity to the processes that they are expected to represent. Cost-effective ecosystem health assessments will involve multiple indicators that are sensitive to a suite of stressors, and which collectively provide a comprehensive health profile. Multi-scale and multi-disciplinary approaches will be critical to provide a whole-of-ecosystem health profile – from microbial process indicators (e.g. McDole et al. 2012) to remote sensing of large-scale climatic forcing agents and the response of ecosystem components (e.g. Leifer et al. 2012).

Integrative approach linking habitat to biological attributes

Australia currently has no national integrated mapping system for the management of marine resources. The Integrated Marine Observing System (IMOS) is a step towards such a system for open-water and coastal pelagic environments, but with a primary focus on physical and chemical oceanography. The eAtlas is a portal for marine spatial biological information and is a step towards an integrated system for spatial management. Further research should be carried out in the short term on a national integrated intertidal and subtidal habitat classification system for coastal marine and estuarine habitats. This could be integrated with existing systems (e.g. Interim Australian National Aquatic Ecosystem Classification Scheme, National intertidal/subtidal benthic habitat classification scheme and Marine Coastal Atlas).

Habitat structural complexity has been assumed to be positively related to species abundance, diversity, ecosystem function and maintenance of key ecological processes. Measuring structural complexity is challenging using quantitative and reproducible techniques (Kovalenko et al. 2012). Multidisciplinary research and technological advances have recently shown that computer vision can accurately, precisely and in a repeatable manner quantify subtidal habitat structural complexity using 3D models (e.g. Steffan Williams, U Syd). The relationship between habitat structural complexity and ecosystem health parameters (e.g. fish abundance) is often correlated (e.g. Jones et al. 2004) but can be non-linear and with multiple covariates. In the near future, research regarding the quantification of habitat complexity should focus on developing and streamlining the 3D model building process from underwater images. Images can be collected from different platforms (i.e. divers, autonomous underwater vehicles) but at present processing requires a high level of expertise and complicated computer algorithms. We now also have the ability to estimate 3D space use of fish and other organisms (e.g. Simpfendorfer et al. 2012) enabling greater integration of habitat and organisms.

Other habitat characteristics important for benthic ecosystem health assessments are:

1. Substrate quality (e.g. the presence of crustose coralline algae in hard-bottom habitats, e.g. Doropoulos et al. 2012)
2. Sediment quality and chemical micro-environment in soft-bottom environments (Borja and Tunberg 2011)
3. Microbial communities across all environments – specifically pathogens, commensal communities and symbionts (McDole et al. 2012, see also white paper on microbial processes).
4. Community composition and evidence of the outcome of competitive interactions (e.g. macroalgae and hard corals, kelp forests and urchin barrens)

All of the above characteristics are some of the good candidate indicators for monitoring and assessment of marine ecosystems.

Understanding cumulative stressors and dynamics of perturbed systems

Marine ecosystems are inherently complex and human activities are capable of transforming the habitats and the services they provide into less desirable states. The system may become vulnerable as resilience declines. A gradual change in the system can bring the system to a bifurcation point (a tipping point) where a small change can result in a shift to an alternate state. However, the drivers or values at which responses are triggered (critical threshold) are not generally known but can often be resolved from models (Mumby et al. 2007; Scheffer et al. 2009; Anthony et al. 2014). Empirical data is critical for such models.

Importantly, definitions of desirable and undesirable ecosystem states need to consider natural gradients in environmental variables and community baselines. For example, on coral reefs, high algal cover and high turbidity are a subset of indicators generally pointing to an unhealthy state. However, while this holds for offshore reefs, coral reefs in coastal water have always had more macroalgae and turbidity than offshore reefs. Also, inshore and offshore reef communities differ naturally in their composition on par with observed changes across terrestrial vegetation zones.

Marine-based sectors (e.g. fishing, aquaculture, shipping, recreation) may not only extract resources, but also affect other aspects of the marine environment. Such activities vary in intensity of impact and spatially across the marine environment. There is potential not only for conflict among different sectors but also for overlapping impacts across sectors resulting in cumulative impacts. Rather than focus on single sectors, there is increasing need to quantitatively consider multi-use, multi-sector needs and potential impacts on marine ecosystem health. Knowledge of the spatial distribution of stressors and how humans value different areas is lacking for many regions of Australia. This underscores the need for a linked social-ecological approach to ecosystem-based management.

For many species, there are cross jurisdictional boundary issues that may impact on health and status of populations. For example, many species are widely distributed around Australia but are managed on a State-by-State basis. Mobile species may be listed differently in Federal and State legislation – for example, the scalloped hammerhead is listed as Endangered in NSW but not listed in Qld yet the stock is likely shared across State borders.

In summary, a national science plan for sustaining the health of Australia's marine ecosystems needs to strive towards the following outcomes:

- An integrated systems approach to understanding causal links between natural and anthropogenic drivers, activities, pressures and impacts on ecosystem values (DPSIR framework) and their consequences for ecosystem values and social and economic implications
- More targeted environmental monitoring at multiple scales closely tied to management strategies and policy objectives on 5, 10 and 25 year time scales
- Better implementation of the principles of adaptive ecosystem-based management
- Application of transparent decision-making processes within adaptive environmental management plans and for development approvals
- Investment in deeper understanding of ecosystem thresholds and tipping points under cumulative stressors from global, regional and local pressures
- Adoption of science- and evidence-based precautionary management and policy instruments to minimise risk of ecosystem collapses (exceedance of thresholds)

Perspective & Realisation

The health of Australia's marine ecosystems over the next 5 to 20 years will be influenced by global, regional and local drivers and pressures. Some drivers and pressures will have national and regional management and policy levers and some (e.g. climate change, ocean acidification and extreme weather) will not (Anthony et al. 2014). An effective marine science plan for Australia will need to consider how research programs can best deliver outcomes that help reach ecosystem health targets in a changing global environment and in a regional setting where social benefits and economic growth are high priorities. There are also strong links to other components of the National Marine Science plan that need to be recognised – i.e. food security, dealing with climate change, optimal resource allocation, urban coastal environments and infrastructure.

To understand and set targets for the ecosystem health of Australia's marine estate **we require a comprehensive assessment of current system status and trends across ecosystem types and scales and develop a deeper understanding of natural cycles in ecosystem state upon which to build historical baselines**. Initiatives for an integrated monitoring, modelling and management program are planned for the Great Barrier Reef World Heritage Area (GBRMPA 2014) to help meet the challenge of a long-term sustainable plan for this large system. However, similar initiatives are lacking for other biodiverse regions of global significance (e.g. World Heritage Ningaloo Marine Park, Western Australia) and need to be developed across marine ecosystems Australia-wide using the GBR World Heritage Area framework.

Importantly, while marine ecosystem health assessments provide synoptic views of current states and trends, they do not directly provide information on expected impacts in ecosystem health under different global or regional change scenarios. **For Australia to develop an environmental insurance policy for marine ecosystems that ensures targets can be met in the short and long term we require a combination of targeted monitoring, ecosystem modelling and strategic process studies to continually improve our system's understanding and to guide adaptive management.**

Australia should assess health of its marine **ecosystems** at a range of spatial scales. While global studies may include Australia, there is considerable finer scale variation and vast differences between tropical, temperate and Antarctic systems in terms of stressors, environmental drivers and the characteristics of ecosystem processes.

The following are high level priorities:
Encourage greater collaboration and research partnerships across government (commonwealth and state agencies), industry and universities to maximise capability and expertise, address research priorities and allow sharing of data. Effective data sharing and use can be facilitated by creative-commons arrangements among research and management partners and end-users [e.g. eAtlas, Integrated Marine Observing System (IMOS), Australian Ocean Data Network (AODN)].

Improved open data protocols across industry (e.g. environmental impact assessments), government and universities are required to facilitate broader collaborations, provide baseline data on natural variability in marine ecosystems, and allow easy access to data for use in ecological and ecosystem modelling, as well as assessment of ecosystem health. Integrated monitoring programs and integrated data management systems (e.g. Gladstone Healthy Harbour) can help facilitate this.

Multidisciplinary collaborations are required to test the relationship between habitat characteristics and ecosystem health indicators as well as to develop innovative and cost effective approaches (e.g. eDNA, microbiomics, soundscapes) for monitoring ecosystem health into the future (including the human components, the influence of which can not be under-estimated as sustainability is a process not an end point). Interdisciplinary collaborations to understand how systems respond across the driver–state causal chain are important. We need to think cell to ecosystem scales here using approaches ranging from water samples to remote sensing. Process studies will be key to linking observations to models and to help inform health predictions and diagnostics in a changing environment.

Encourage **development of decision support tools** with user-friendly interfaces to allow for scenario testing by a wide range of stakeholders including community. Such tools would allow tests of how the ecosystem is likely to be affected by future activities and conditions. Importantly, structured decision-support frameworks provide transparent means to integrate management and policy objectives of a marine science plan with (1) the science evidence (e.g. monitoring and modelling), (2) risks to ecosystems and (3) their consequences for social and economic values.

Links to international efforts – The Ocean Health Index, which evaluates the condition of marine ecosystems based on 10 human goals representing ecological, social and economic benefits, calculates an overall score for each exclusive economic zone and provides a tool for ongoing assessment against which to compare future changes (Halpern et al. 2012). This index has been implemented globally at the level of country, but is now being implemented at regional scales in United States, Brazil and Fiji. A similar approach could be used at various scales within Australia. Regional ground truthing also benefits global assessments and assists with ensuring more reliable standardised approaches. Besides assisting with resource management and policy, such a tool provides a powerful way to raise public awareness and can also assist with prioritising scientific research.

The US National Ocean Policy and the European Union Maritime Strategy are initiatives that rely heavily on ecosystem health using an ecosystem based management framework. Australia is currently at the forefront of integrated ecosystem based management, however, risks being supplanted by other political regions that are placing increased emphasis on marine ecosystem health.

Australia should **consider being part of global initiatives** assessing ecosystem health. Australia is ideally placed as one of the only countries that spans coastlines from tropical to temperate to Antarctic waters. We can build on examples of other global initiatives, e.g. the framework for global ocean acidification networks (Feely et al. 2010), GOOS (http://www.ioc-goos.org/) and IndiSeas (http://www.indiseas.org/).

There is a requirement for **long-term monitoring** of ecological data and environmental parameters. Some of the environmental parameters are currently collected through the IMOS, but these are often located offshore of coastal regions. There is a need for observing systems in estuarine and nearshore State coastal waters and for ongoing maintenance of such equipment. There is also a need for funding cycles that recognise the importance of long-term datasets.

Research priorities of State/Territory and Federal agencies need to be clearly articulated to researchers and regularly updated. Greater emphasis should be placed on co-funded, co-investigated research partnerships involving government and Universities. Increasingly, industry is also likely to be an important funding source.

Postgraduate students and early career researchers are the **leaders of the future**. Research funding and coordination of large scale projects (e.g. NERP, CRC, CoE) should consider these groups. Greater diversity (cultural, gender) is also required within marine sciences especially at more senior levels. Targeted funding may be required around policies and programs to obtain a more diversified workforce in marine science.

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References

Anthony KRN, Dambacher JM, Walshe T, Beeden R (2013) A framework for understanding cumulative impacts, supporting environmental decisions and informing resilience-based management of the Great Barrier Reef World Heritage Area, Final Report to the Great Barrier Reef Marine Park Authority and the Department of the Environment, http://www.environment.gov.au/resource/framework-understanding-cumulative-impacts-supporting-environmental-decisions-and-informing

Anthony KRN, Marshall PA, Abdulla A, co-authors a (2014) Operationalizing resilience for adaptive coral reef management under global environmental change. Global Change Biol doi doi: 10.1111/gcb.12700

Borja A (2006) The new European Marine Strategy Directive: Difficulties, opportunities, and challenges. Mar Poll Bull 52: 239-242 doi 10.1016/j.marpolbul.2005.12.007

Borja A, Tunberg BG (2011) Assessing benthic health in stressed subtropical estuaries, eastern Florida, USA using AMBI and M-AMBI. Ecol Indic 11: 295-303 doi 10.1016/j.ecolind.2010.05.007

Chapin FS, III, Carpenter SR, Kofinas GP, Folke C, Abel N, Clark WC, Olsson P, Smith DMS, Walker B, Young OR, Berkes F, Biggs R, Grove JM, Naylor RL, Pinkerton E, Steffen W, Swanson FJ (2010) Ecosystem stewardship: sustainability strategies for a rapidly changing planet. Trends Ecol Evol 25: 241-249 doi 10.1016/j.tree.2009.10.008

Chapin FS, Zavaleta ES, Eviner VT, Naylor RL, Vitousek PM, Reynolds HL, Hooper DU, Lavorel S, Sala OE, Hobbie SE, Mack MC, Diaz S (2000) Consequences of changing biodiversity. Nature 405: 234-242 doi 10.1038/35012241

Connell SD, Russell BD (2010) The direct effects of increasing CO_2 and temperature on non-calcifying organisms: increasing the potential for phase shifts in kelp forests. Proceedings of the Royal Society B - Biological Sciences 277: 1409-1415 doi DOI 10.1098/rspb.2009.2069

Cvitanovic C, Wilson SK, Fulton CJ, Almany GR, Anderson P, Babcock RC, Ban NC, Beeden RJ, Beger M, Cinner J, Dobbs K, Evans LS, Farnham A, Friedman KJ, Gale K, Gladstone W, Grafton Q, Graham NAJ, Gudge S, Harrison PL, Holmes TH, Johnstone N, Jones GP, Jordan A, Kendrick AJ, Klein CJ, Little LR, Malcolm HA, Morris D, Possingham HP, Prescott J, Pressey RL, Skilleter GA, Simpson C, Waples K, Wilson D, Williamson DH (2013) Critical research needs for managing coral reef marine protected areas: Perspectives of academics and managers. J Environ Manage 114: 84-91 doi 10.1016/j.jenvman.2012.10.051

Doropoulos C, Ward S, Diaz-Pulido G, Hoegh-Guldberg O, Mumby PJ (2012) Ocean acidification reduces coral recruitment by disrupting intimate larval-algal settlement interactions. Ecol Lett 15: 338-346 doi 10.1111/j.1461-0248.2012.01743.x

Feely RA, Fabry VJ, Dickson AG, Gattuso J-P, Bijma J, Riebesell U, Doney S, Turley C, Saino T, Lee K, Anthony KRN, Kleypas J (2010) An international observational network for ocean acidification. In: J. H, Harrison DE, Stammer D (eds) Proceedings of OceanObs' 09: Sustained Ocean Observations and Information for Society (Vol 2), Venice, Italy, 21–25 September 2009. ESA Publication WPP-306

Fisher R, Radford BT, Knowlton N, Brainard RE, Michaelis FB, Caley MJ (2011) Global mismatch between research effort and conservation needs of tropical coral reefs. Conservation Letters 4: 64-72 doi 10.1111/j.1755-263X.2010.00146.x

Fussel HM, Klein RJT (2006) Climate change vulnerability assessments: An evolution of conceptual thinking. Climatic Change 75: 301-329 doi 10.1007/s10584-006-0329-3

GBRMPA (2014) Great Barrier Reef Region Strategic Assessment: Strategic assessment report - Final Report. Great Barrier Reef Marine Park Authority, Townsville

Gunderson LH (2000) Ecological resilience - in theory and application. Ann Rev Ecol Syst 31: 425-439 doi 10.1146/annurev.ecolsys.31.1.425

Halpern BS, Longo C, Hardy D, McLeod KL, Samhouri JF, Katona SK, Kleisner K, Lester SE, O'Leary J, Ranelletti M, Rosenberg AA, Scarborough C, Selig ER, Best BD, Brumbaugh DR, Chapin FS, Crowder LB, Daly KL, Doney SC, Elfes C, Fogarty MJ, Gaines SD, Jacobsen KI, Karrer LB, Leslie HM, Neeley E, Pauly D, Polasky S, Ris B, St Martin K, Stone GS, Sumaila UR, Zeller D (2012) An index to assess the health and benefits of the global ocean. Nature 488: 615-+ doi 10.1038/nature11397

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 doi 10.1126/science.1152509
Howard WR, Nash M, Anthony KRN, co-authors a (2012) Ocean acidification. In: Poloczanska ES, Hobday AJ, Richardson AJ (eds) Marine Climate Change in Australia - Impacts and Adaptation Responses 2012 report card. <http://www.oceanclimatechange.org.au>
Jago-on KAB, Kaneko S, Fujikura R, Fujiwara A, Imai T, Matsumoto T, Zhang J, Tanikawa H, Tanaka K, Lee B, Taniguchi M (2009) Urbanization and subsurface environmental issues: An attempt at DPSIR model application in Asian cities. Science of the Total Environment 407: 3089-3104 doi 10.1016/j.scitotenv.2008.08.004
Jones GP, McCormick MI, Srinivasan M, Eagle JV (2004) Coral decline threatens fish biodiversity in marine reserves. Proceedings of the National Academy of Sciences of the United States of America 101: 8251-8253 doi 10.1073/pnas.0401277101
Knowlton N, Jackson JBC (2008) Shifting baselines, local impacts, and global change on coral reefs. Plos Biol 6: 215-220 doi 10.1371/journal.pbio.0060054
Kovalenko KE, Thomaz SM, Warfe DM (2012) Habitat complexity: approaches and future directions. Hydrobiologia 685: 1-17 doi 10.1007/s10750-011-0974-z
Leifer I, Lehr WJ, Simecek-Beatty D, Bradley E, Clark R, Dennison P, Hu Y, Matheson S, Jones CE, Holt B, Reif M, Roberts DA, Svejkovsky J, Swayze G, Wozencraft J (2012) State of the art satellite and airborne marine oil spill remote sensing: Application to the BP Deepwater Horizon oil spill. Remote Sensing of Environment 124: 185-209 doi 10.1016/j.rse.2012.03.024
Limburg KE, O'Neill RV, Costanza R, Farber S (2002) Complex systems and valuation. Ecol Econ 41: 409-420 doi 10.1016/s0921-8009(02)00090-3
McCook LJ, Ayling T, Cappo M, Choat JH, Evans RD, De Freitas DM, Heupel M, Hughes TP, Jones GP, Mapstone B, Marsh H, Mills M, Molloy FJ, Pitcher CR, Pressey RL, Russ GR, Sutton S, Sweatman H, Tobin R, Wachenfeld DR, Williamson DH (2010) Adaptive management of the Great Barrier Reef: A globally significant demonstration of the benefits of networks of marine reserves. Proceedings of the National Academy of Sciences of the United States of America 107: 18278-18285 doi 10.1073/pnas.0909335107
McDole T, Nulton J, Barott KL, Felts B, Hand C, Hatay M, Lee H, Nadon MO, Nosrat B, Salamon P, Bailey B, Sandin SA, Vargas-Angel B, Youle M, Zgliczynski BJ, Brainard RE, Rohwer F (2012) Assessing coral reefs on a Pacific-wide scale using the microbialization score. Plos One 7 doi 10.1371/journal.pone.0043233
Mumby PJ, Chollett I, Bozec Y-M, Wolff NH (2014) Ecological resilience, robustness and vulnerability: how do these concepts benefit ecosystem management? Current Opinion in Environmental Sustainability 7: 22-27 doi 10.1016/j.cosust.2013.11.021
Mumby PJ, Hastings A, Edwards HJ (2007) Thresholds and the resilience of Caribbean coral reefs. Nature 450: 98-101 doi 10.1038/nature06252
Nystrom M, Folke C, Moberg F (2000) Coral reef disturbance and resilience in a human-dominated environment. Trends Ecol Evol 15: 413-417 doi 10.1016/s0169-5347(00)01948-0
Poloczanska ES, Babcock RC, Butler A, Hobday A, Hoegh-Guldberg O, Kunz TJ, Matear R, Milton DA, Okey TA, Richardson AJ (2007) Climate change and Australian marine life. In: Gibson RN, Atkinson RJA, Gordon JDM (eds) Oceanography and Marine Biology, Vol 45, pp 407-478
Samhouri JF, Lester SE, Selig ER, Halpern BS, Fogarty MJ, Longo C, McLeod KL (2012) Sea sick? Setting targets to assess ocean health and ecosystem services. Ecosphere 3 doi 10.1890/es11-00366.1
Scheffer M, Bascompte J, Brock WA, Brovkin V, Carpenter SR, Dakos V, Held H, van Nes EH, Rietkerk M, Sugihara G (2009) Early-warning signals for critical transitions. Nature 461: 53-59 doi 10.1038/nature08227
Simpfendorfer CA, Olsen EM, Heupel MR, Moland E (2012) Three dimensional kernel utilization improve estimates of space use in aquatic animals. Can J Fish Aquat Sci 69: 565-572
State of the Environment (2011) Australia state of the environment 2011. Independent report to the Australian Government Minister for Sustainability, Environment, Water, Population and Communities. DSEWPaC, Canberra
Tett P, Gowen RJ, Painting SJ, Elliott M, Forster R, Mills DK, Bresnan E, Capuzzo E, Fernandes TF, Foden J, Geider RJ, Gilpin LC, Huxham M, McQuatters-Gollop AL, Malcolm SJ, Saux-Picart S, Platt T, Racault MF, Sathyendranath S, van der Molen J, Wilkinson M (2013) Framework for understanding marine ecosystem health. Mar Ecol Prog Ser 494: 1-27 doi 10.3354/meps10539