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Increasing accessibility of coral reefs from the latter third of the 20th century led quickly to recognition of the vulnerability of coral reef communities to a combination of direct and indirect human impacts. Coral reefs are confronted by the stark threats of climate and ocean changes from the increasing number, intensity and forms of human use impacting global and marine systems. Management, particularly of accessible coral reefs, occurs in the context of multiple scale transboundary water column linkages of lifecycle processes and increasing human use of coastal and marine space. Four decades of experience have demonstrated the combined importance of biophysical and socio-economic sciences and sharing knowledge with communities for developing implementing effective management. In the face of environmental and socio-economic change the challenge for science and management is to develop knowledge and management responses that can better understand and increase resilience to improve he outlook for coral reef communities.

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Highlights

Coral reef experience illustrates broader challenge of managing marine biodiversity.

Adaptive management cycle for maximising resilience of coral reef communities

Trans-boundary challenges of managing within protected area boundaries

International multi-disciplinary network support for research and management

Reconciling social, economic and environmental objectives for coral reefs areas

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Increasing accessibility of coral reefs from the latter third of the 20th century led quickly to recognition of the vulnerability of coral reef communities to a combination of direct and indirect human impacts. Coral reefs are confronted by the stark threats of climate and ocean changes from the increasing number, intensity and forms of human use impacting global and marine systems. Management, particularly of accessible coral reefs, occurs in the context of multiple scale transboundary water column linkages of lifecycle processes and increasing human use of coastal and marine space. Four decades of experience have demonstrated the combined importance of biophysical and socio-economic sciences and sharing knowledge with communities for developing implementing effective management. In the face of environmental and socio-economic change the challenge for science and management is to develop knowledge and management responses that can better understand and increase resilience to improve he outlook for coral reef communities.

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Introduction

Coral reefs have been charismatic since 16th century mariners brought tales to Europe of travels through perilous waters to colourful coral gardens, plentiful fish and strange sea creatures. In the 18th and 19th century community and scientific interest in coral reefs grew with exotic specimen collections, illustrations and reports from voyages of trade, exploration and hydrographic survey. The logistic challenges for sustained research in remote tropical areas were substantial but the prospect of studies of marine environments very different from those of high latitude Atlantic coastal waters was enticing. Bowen (2015) identifies the Carnegie Institution of Washington 1913 Murray (Mer) Island studies in Torres Strait and the year-long Royal Society, Great Barrier Reef Committee Expedition of 1928-29 as the first sustained field laboratory and in situ studies of coral reefs .

Before external contact, local customary practice based on traditional knowledge provided for conservation of coral reefs and associated ecosystems. This was part of a management system with a common stake in sustaining marine food resources and related cultural values. Many of these practices were constrained or lost where colonisation brought a cultural clash between customary tenure and the western legal concept of freedom of the seas (Johannes, 1978). Increased accessibility and economic engagement brought the need to manage activities and impacts in areas with limited baseline data, limited surviving knowledge of customary management and no tradition of, or prior exposure to, biophysical research.

After World War 2 the newly available technologies of SCUBA diving and underwater photography enabled direct survey, observation and experimental studies of coral reefs. Images and reports of field studies in the 1950's television series of Hans Hass and Jacques Cousteau brought the beauty of coral reefs to a wide audience and stimulated a growth of ecological research. The first permanent reef research stations were established at Coconut Island Hawaii in 1947, Heron Island in

the southern Great Barrier Reef (GBR) in 1958, Discovery Bay Jamaica in 1965 and Panama in 1966 enabling sustained field and laboratory studies of local reefs accessible by small boats Bowen (2015).

The growth of coral reef science in the second half of the 20th century, brought studies of changes ranging from direct impacts of destructive human uses and severe natural events. The need for conservation of the biodiversity and natural resource sustainability of coral reef ecosystems was increasingly apparent. This occurred against the broader background consultative processes started in 1958 to develop and implement the Law of the Sea Convention (UN, 1982), the Convention on Biological Diversity (1992) and regional agreements for management of seas and fisheries.

The issues for coral reef science and management span jurisdictions and scales from locally accessible reefs with high human use to rarely visited remote island and archipelagic regions.

The Great Barrier Reef (GBR) has played a substantial role in knowledge sharing and development of international programs of coral reef research and management. This paper draws on that experience to provide a brief overview of the application of coral reef science in development of management for conservation and resource sustainability.

The growth of scientific studies and coral reef management

From the 1960s coral reef research expanded rapidly thanks to the growing ease of travel from high latitude research centres to tropical coasts. The accessibility of complex biological communities in clear, warm shallow waters provided opportunities for substantial curiosity driven research. The first International Coral Reef Symposium (ICRS 1962) was held in India in 1969 where 36 scientific papers were presented to a total of 72 participants mostly from the Indo-Pacific Region. Most of the papers reported descriptive surveys and studies of species distributions, diversity and taxonomy. Issues of management were not directly addressed but the symposium recommended taxonomic studies, not only of coral but of other members of reef biota as fundamentally necessary for understanding the ecology and physiology of coral reefs. A subsequent outcome was the establishment of an international working group outcome to:

1. Identify the major scientific problems in the quantitative ecology of coral reefs;
2. Evaluate and test existing methods for the quantitative description of abundance, composition and distribution of benthic invertebrate communities on reefs;
3. Recommend standard field techniques suitable for the problems identified under 1 above; and
4. Consider the need for a future symposium on the quantitative ecology and productivity of coral reefs.

This resulted in agreement on the need to support future ICRS as a regular forum for discussion and coordination of coral reef science. in 1974, a workshop at the Heron Island research station following ICRS 2 that led to the publication in 1978 of "Coral reefs: research methods" (UNESCO 1978) . In 1975, an IUCN conference on Marine Protected Areas recognised the importance of coral reefs in calling for the establishment of a well-monitored system of Marine Protected Areas (MPAs) representative of the world's marine ecosystems identifying coral reefs as ecosystems of particular vulnerability (IUCN, 1976).

In Australia in the 1960s two controversial issues raised concerns for the future management of issues affecting the GBR. Both illustrated a substantial need for science to understand the issues for an unprecedented scale of management for conservation and sustainable use of coral reef areas within a large marine ecoregion.

Observations of large populations of Crown-of-Thorns starfish causing locally severe coral mortality on reefs in the central Great Barrier Reef raised many questions (Barnes and Endean 1964). These related to the normality and possible causes of population outbreaks; the consequences of death of coral cover; potential time for recovery; and the need for and feasibility of management response. An ad hoc Committee of the Australian Academy of Science considered the available, but limited, evidence concluding that while local mortality was severe it did not did not appear to represent a threat to the geological structure of the Great Barrier Reef (Walsh et al, 1970). This did not assuage public concerns and the Australian Commonwealth and Queensland governments established an Advisory Committee to oversight Research into the Crown-of thorns starfish (Australian Government, 1975 Kenchington, 1978).

A proposal to mine coral reefs for limestone and anticipation of expansion of fisheries and tourism were issues of growing contention but the issue of permits for oil drilling raised particular concern and led to the appointment in 1970 of a Royal Commission into petroleum drilling in the area of the Great Barrier Reef (Australian Government and Government of the State of Queensland, 1974). The Commission heard evidence from many of the leading global researchers on the extent, relevant gaps in, and management implications of, contemporary scientific knowledge of coral reefs. It found that limitations of research knowledge were such that its members were unable to agree on a recommendation on the question of whether there were any " localities wherein the effects of an oil or gas leak would cause so little detriment that drilling there for petroleum might be permitted".

The Commission recommended that "a special statutory authority should be established responsible to the appropriate Parliament for ecological protection and the control of research and development within the Great Barrier Reef Province". This was addressed in the passage of the Great Barrier Reef Marine Park Act (1975) to provide for conservation and reasonable use of the Great Barrier Reef Region. In 1976 the Great Barrier Reef Marine Park Authority (GBRMPA) was established with an expectation that the GBRMP would be established in about a decade.

Substantial investment in Great Barrier Reef research capacity included the establishment of the marine biology department at James Cook University in1968; the Australian Institute of Marine Science in 1972; research stations at Lizard Island by the Australian Museum in 1978, at Orpheus Island by James Cook University in 1979; and expansion by the University of Queensland of facilities at the Heron Island Research Station.

At the same time in the Philippine archipelago, protection of coral reefs had become the subject of research because of falling fish stocks. A vicious cycle had emerged with growing human population, increasing fishing pressure, longer workdays for fishers that encouraged explosive, cyanide and other destructive fishing techniques that damaged coral reef habitats. The damage to coral reef habitats caused stocks to fall faster. A long term research and management program reviewed by (Alcala et al, 2005) was established in 1982 through close engagement and knowledge sharing with the local communities of the studied islands by researchers working at Siliman University. Management was through creation of, and sustained compliance with, marine reserves protecting coral reef habitat were initiated and demonstrated to increase fish stocks within and beyond reserve boundaries over two decades.

Similar local scale research and management initiatives for biodiversity conservation and food security in coastal and island coral reefs emerged in Indonesia, Pacific Islands, the Indian Ocean and East Africa are summarised in IUCN (2000).

The international context of coral reef management

At ICRS4 in Manila in 1981, UNESCO supported presentation of 50 papers to addressing resource management and environmental impact; a workshop on research and training priorities for coral

reef management; and the subsequent publication of a coral reef management handbook (UNESCO 1984).

A workshop on managing coastal and marine protected areas was held during the World Congress on National Parks in Bali Indonesia in 1982. This shared knowledge of widespread activity in coral reef conservation and resulted in the publication in 1984 of the first edition of the IUCN guide for planners and managers of marine and coastal protected areas. This was subsequently updated to a third edition (IUCN 2000).

The UNEP Regional Seas program developed between 1976 and 1985 to support coordination and development of environmental management in the coral reef regions of the Caribbean, West Africa, the Red Sea and Gulf of Aden, Arabian Gulf, Gulf of Oman and South Asia, East Asian Seas and the

Pacific Ocean. In 1987 an edited volume synthesized and updated knowledge of human impacts on coral reefs (Salvat, 1987) and the UN "Brundtland Commission" Report on Sustainable Development (UN 1987) identified coral reefs as vulnerable marine ecosystems with high levels of human dependency.

The 1992 UN Rio Summit on Sustainable Development adopted Agenda 21 (UN 1992)in which Chapter 17 addressed: "Protection of the Oceans, All Kinds of Seas, including Enclosed and Semienclosed Seas, and Coastal Areas and the Protection, Rational Use and Development of their Living Resources." In the follow-up to the Rio Summit, small island developing nations raised management of their coral reefs as a matter of crucial economic and cultural importance.

As a result in 1994 the governments of 8 nations[1] established the International Coral Reef Initiative (ICRI) enabling an international meeting at Dumaguete City, Philippines at which policy specialists, managers and scientists from 40 nations adopted a Call for Action and a Framework for Action to address the conservation and sustainability of the resources of coral reefs (ICRI 1995). The call for action identified 4 primary areas of activity:

- Integrated Management
- Capacity Building
- Research and monitoring; and
- Reviews or evaluation of management.

ICRI currently has 37 members from govts or govt agencies, 23 non-government organisations and tropical Regional Seas. It holds annual meetings of all members, and additional ad hoc regional meetings or workshops to share knowledge on the status and management of coral reefs and associated ecosystems. In addition, International Tropical Marine Ecosystem Managers Symposia (ITMEMS) are held at approximately quadrennial intervals with a format that enables managers to share knowledge of coastal and marine issues and experience of management implementation; and provides peer networking and facilitation of ongoing communication of priority information for management.

The challenges of science and management engagement

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[1] Australia, France, Japan, Jamaica, the Philippines, Sweden, the United Kingdom and the United States of America

Addressing the management challenge of coral reefs is a jurisdictionally and socioeconomically 'wicked' policy problem – difficult to solve because it arises from a set of highly complex interdependent environmental, cultural and socio-economic factors (Rittel and Weber 1973, Brown et al, 2010).

For coral reefs the "wickedness" arises because of the need to address the impacts and sustainability local within-boundary activities against the background of impacts arising as the downstream consequences of activities beyond the boundaries of the managed area. Action to remove or reduce the downstream impacts involves complex trans-sectoral coordination at multiple scales between marine and terrestrial jurisdictions within nations, regionally and internationally. The challenges of starting management under pressure with limited baseline data and limited local availability of scientific expertise are common. An outcome of the 1995 ICRI meeting in Dumaguete Philippines was the development of international and regional government and non-government cooperative networks to enable sharing of knowledge and experience. (ICRI 1995) . At any scale, the management of coral reefs involves responding to knowledge from best available local knowledge of the biophysical and socio-economic context, ongoing review, and adaptation to changing circumstance. The evolution of the Great Barrier Park addresses a particular context but can illustrate elements common to adaptive management from local to bio-regional scales.

The first section of the GBR Marine Park (GBRMP) covered the area of the Capricorn and Bunker Groups of islands and reefs, which was chosen for the initial section because it was accessible and separated from the outer GBR. Its current and historical use patterns were reasonably well known and there was a substantial body of research by Australian and international scientists at the research stations at Heron and One Tree Islands. The design of a management regime involved a strategic study to explore the opportunities and constraints for adapting terrestrial spatial management practice of zoning to the marine context (GBRMPA, 1979). Implementing overarching multiple use environmental legislation for conservation and reasonable use involved engagement to enable integration with pre-existing sectoral contexts of fisheries, recreational and tourism activity management with coastal sectoral legislation and management.

The strategic study developed three options for zoning. Each was based on the best contemporary scientific and socio-economic knowledge and was consistent with the provisions of the Act but framed to prioritise the likely preferred solution for the major interest groups: the fishing industry; tourism and recreation; and biodiversity conservation. The study was a key resource for declaration in 1979 of the Capricornia Section as the first area of the Marine Park. It provided substantial information for discussion of contemporary and likely futures of intended purposes of use and entry for zoning options. This was crucial during the consultative processes to develop understanding of the concept of reasonable use consistent with conservation and consequent constraints and opportunities for possible solutions. The Capricornia Section zoning Plan came into effect in July 1981.

Preparations for declaration and planning of subsequent sections had to contend with information gaps. Much of the GBR Region was unsurveyed and there was limited knowledge of ecoregionalisation, usage or potential uses of areas. There were few long-term users and little recorded knowledge of use or observations of change over previous decades. Development and application of appropriate scientific methodologies to inform planning and management presented significant resource implications. The challenge of understanding scales from local to bioregional was substantial but relieved by the emerging opportunity to develop and apply rectification and false colour indicative bathymetry from LANDSAT imagery.(Claasen and Pirazozoli, 1985, Jupp et al 1985) .

The arrangements for management of the GBR Marine Park were recognised as good practice in 1982 through inclusion of the GBR on the World Heritage List and in subsequent professional literature(e g Ruckelshaus et al. (2008) Agardy (2010). The 37 page nomination document addressed the four criteria in Article 2 of the World Heritage Convention through a brief summary statement of the outstanding universal values and management arrangements of the Great Barrier Reef (Commonwealth of Australia 1981). More substantial description of values was required by 1995 to meet growing reporting requirements of the World Heritage Committee and to incorporate new knowledge from research and experience of management. The Great Barrier Reef Marine Park Authority commissioned a report on the outstanding universal value of the GBR World Heritage Area (Lucas et al, 1997). This report and a 25 year strategic plan for the Great Barrier Reef World Heritage Area (GBRMPA 1994) provided crucial guidance for a program to revise and unify sectional zoning into a single zoning plan that came into effect in 2004.

A variety of surveys of coral reefs was undertaken following the initial report of crown of thorns starfish on the GBR (eg Pearson and Garrett, 1976; Done et al 1981). These showed that coral reefs can recover substantially in 10-15 years after episodes of significant coral damage from outbreaks of crown of thorns starfish predation, storm damage and coastal runoff. Since 1983 the Australian Institute of Marine Science and the Great Barrier Reef Marine Park Authority have conducted a long term monitoring program to report consistently on the contemporary impacts and state in relation to prior reports.

Mass coral bleaching impacts have been reported in large areas of the GBR in 1998, 2002, 2006,2014, 2016 and 2017 caused by unusually warm summer sea surface temperatures and in some cases exacerbated by the impact of severe cyclones. The reductions of coral cover from the accumulation and increasing frequency of impacts raises urgency of the need to protect the recovery capacity or resilience of reef species and communities and to reduce the level of risk to the World Heritage Values of the GBR.

Legislative amendment in 2007 introduced the statutory requirement for an adaptive cycle of review and management through a five yearly Outlook Reports (GBRMPA, 2009, 2014). Where earlier State of the Reef reports had addressed the pressures and responses relating to the contemporary state, the Outlook reports are also required to address drivers of impacts and pressures influencing the current and projected future environmental, economic and social values.

Stakes and issues in coral reef management

Adaptive management for sustainability of coral reefs involves interaction of quantitative and qualitative knowledge of environmental, social and economic issues. Leith et al (2014) discuss the roles of biophysical and socio-economic science in addressing the range of issues and stakes in the "wicked" problems of coastal management in terms of understanding problem structures. (fig. 1). In unstructured problems the role of science is to signal issues from available or partial data and analysis. With increasing trans-disciplinary and inter-disciplinary research there can be progress through poorly and moderately structured to well-structured problems solved by spanning the boundaries between stakeholders with robust data and shared understandings from disciplinary studies. The experience of implementing a solution changes the dynamics and raises the need for an adaptive cycle of monitoring, review and response to implementing the of the solution and other emerging issues.

The initial stage of developing coral reef management usually starts with an unstructured or poorly structured complex of sectoral issues and stakes. These may individually be moderately or wellstructured with respect to their sector or stakeholder group but collectively unstructured or poorly structured with respect to other stakeholders, common threats and mutual interests.

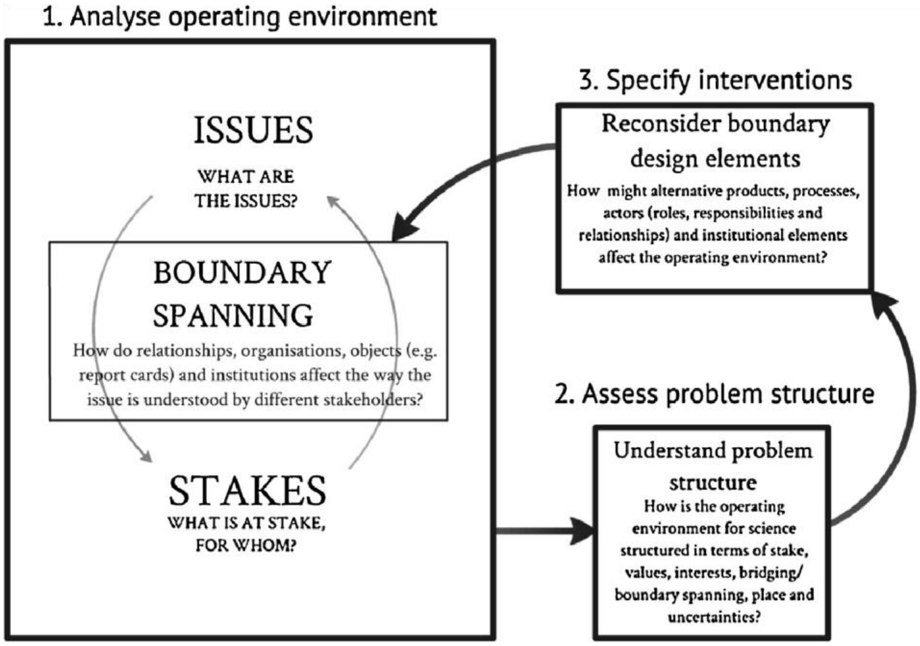


Fig. 1 – Schematic process for diagnosing and intervening in the operating environment for sciences.(from Leith et al (2014)

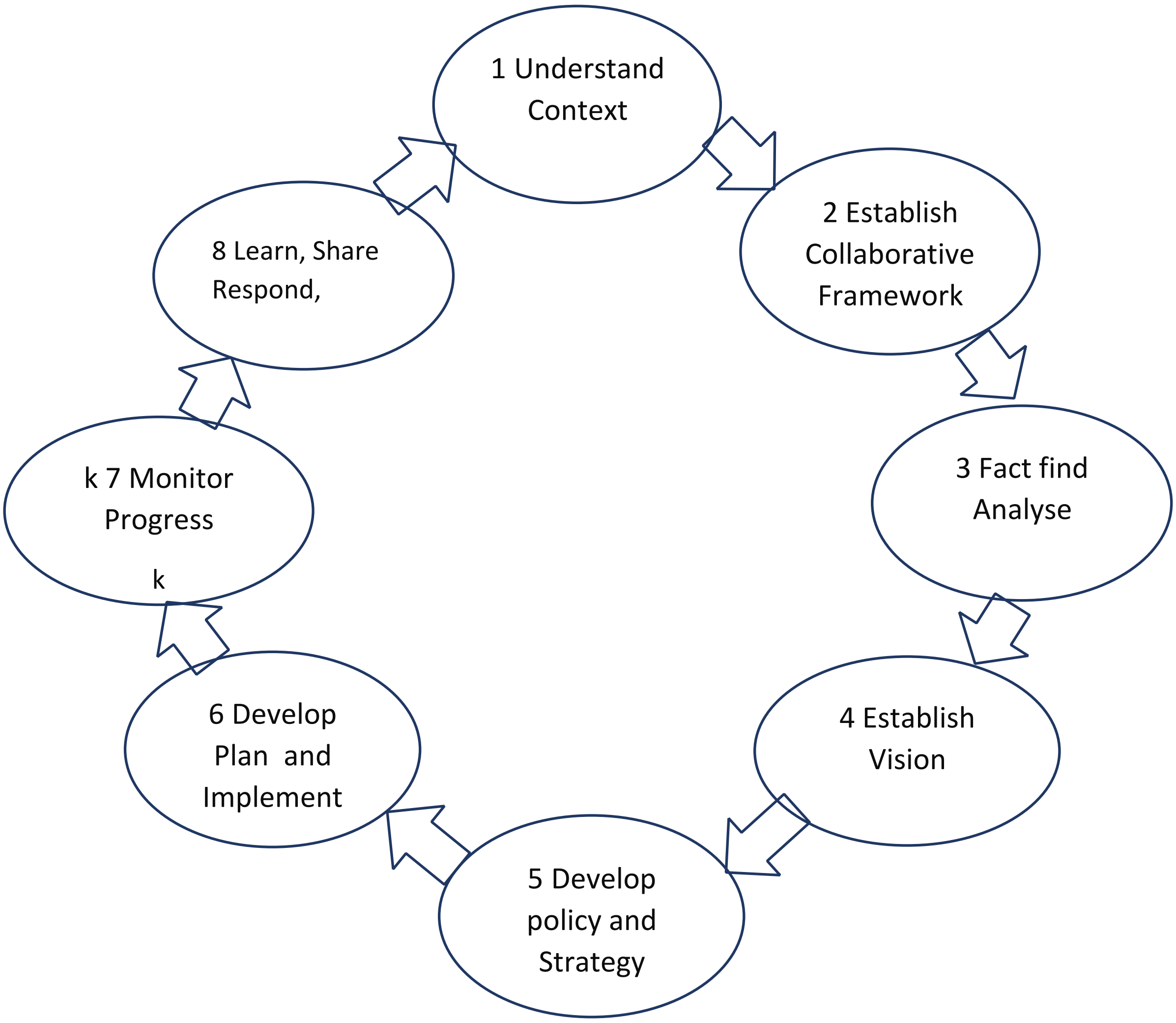
Economic activities such as market and recreational fishing, nature-based recreation, tourism, education and scientific research depend substantially or partially on, and thus have a stake in, the understanding and protecting the health of coral reefs. For activities that impact but do not depend on the health of coral reefs, the cost of effort to protect them may be seen as an issue of economic externality whereby the cost of management increases the cost of doing business with no corresponding benefit to the proponent of the activity. Local residents who are stakeholders in nondependent activities may have social or cultural stakes in maintaining reef health.

The roles of science in an adaptive management cycle

The interactive roles of biophysical and socio-economic science are central to exploring stakes and issues at the start of a process to create or review a management plan for the best solution possible for the complex of problems. Scientists can be information providers and explainers of information; decision support analysts and advisors to proponents or stakeholders of research opportunities in the planning and management processes.

Under initial planning and ongoing implementation of a management plan, understanding and the context of solutions will change over time with experience of management . This should be addressed by some form of an adaptive management cycle such as Fig 2 from Kenchington at al (2012).

Figure 2. Adaptive management cycle for establishing and managing coastal issues from Kenchington et al 2012.



1. Establishing a collaborative framework

- Understanding stakeholders and social networks
- Trustworthy party within boundary spanning organisation

The objective of this phase is to establish a group of respected and effective individuals from stakeholder groups who can span the boundaries between their interest groups through mutual understanding of issues and knowledge. This enables preparation for broader community discussion of the opportunities and constraints for development of management.

In a planning team social scientists with disciplinary research knowledge of local social networks are likely to have significant roles in establishment and operation of such a group.

Biophysical and socio-economic scientists have roles as trustworthy synthesisers, presenters and explainers of their field of disciplinary research, literature and gaps in knowledge. Some may also have a sectoral advocacy role with respect to issues relating to their facilities and programs of research.

2. Fact finding and analysis

- Biophysical constraints, opportunities and possibilities for response
- Ecological risk assessment and vulnerability
- Social network and economic analysis

This is a substantial phase for scientists. It involves synthesis and updating the baseline with new information from local studies and literature and particularly community or stakeholder information enabled by the collaborative framework.

The product should be a substantial accessible document or database of issues and background information explaining the issues to be addressed in introducing management. This is likely to be the critical source of information for achieving formal agreement by government or relevant agencies to proceed with planning.

3. Establishing or reviewing vision

- Engagement in the knowledge sharing process

The role of scientists in this process is sharing and explaining research and knowledge from the baseline statement and participating as stakeholders.

Developing a collective vision is a socio-cultural process of collective engagement with stakeholder representatives to consider the current condition and likely trajectories under current trends. The objective is to develop a collective decadal or longer view of how the condition should be at a horizon beyond the immediate issues of operational environment. This requires discussion of current values and desired values and condition for future generations.

Depending on local context and scale this may be effectively addressed by the boundary spanning collaborative framework or it may require broader engagement and discussion through further outreach to stakeholders and the broader community.

The statement of vision may seem obvious after the discussion but the process of developing, discussing and agreeing a vision from different perspectives establishes an important reference point for setting shorter term targets for monitoring and evaluating progress when management is implemented.

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4. Developing policy and strategic options

- Decision support analysis of biophysical and socio-economic implications
- Sharing knowledge in an consultative process

The roles of scientists are to provide decision support analysis of biophysical and socio-economic options and implications with respect to the vision, operational principles established for the planning process and identification of measurable performance outcomes.

5. Implementing the plan

- Determining operational standards with operational agencies
- Engaging with community for data collection and availability

- Establishing monitoring regime, data collection and reporting protocols

At this stage the plan has been accepted and management is being implemented. Science has a major role in design and oversight of operational arrangements for monitoring outcomes. This involves close engagement of scientists with the management team and, with or through the team, with the community for stakeholder and community engagement in data collection, sharing and reporting.

6. Monitoring and reporting progress and outcomes

- Data management, analysis and reporting
- Ongoing engagement with community data collection
- Report cards and other means for sharing information with stakeholders

This is a substantial and ongoing role of scientific engagement with management and the community throughout the management cycle. Implementation is evaluated in terms of achievement of biodiversity and socio-economic objectives, operational performance of management and compliance with plans. Analysis and regular reporting of routine monitoring of the condition of biodiversity, and the performance of management is the core requirement. This may involve summary report cards with opportunities for stakeholders to access substantial reports if required. Communication with involved community stakeholders should maintain engagement through an ongoing collaborative framework and should enable early awareness of emerging issues through representative meetings or

7. Learning, sharing and responding

- Analysis and reporting of performance against objectives
- Reporting on outlook and vulnerabilities with no change to current management

This is the process of review of lessons of experience, outcomes and performance of management against the plan objectives and of changes in biophysical or socio-economic context since the plans was introduced. This review becomes the starting document for considering needs for adaptation in the next iteration of the management cycle.

Discussion

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The future extent, form and diversity of coral reefs depends on acceptance and implementation by human communities of actions that can help to reduce and reverse human impacts on tropical marine ecosystems. Warming, severe weather events and associated terrestrial runoff will continue for decades even if targets for limiting global warming are achieved. Hughes at al (2003) observed that some species showing far greater tolerance to climate change and coral bleaching than others and that reefs are likely to change rather than disappear entirely. Nevertheless,the increasing frequency of impacts and phase shifts in coral reef communities (eg Hughes et al 2007) increases

uncertainties as to the ways in which current coral-dominated communities may rebuild and change between repeated disturbances.

Marine biodiversity management involves addressing issues of marine commons and the right to fish; traditional, cultural or long-standing usage patterns; rights of navigation; and the challenge of understanding and addressing the drivers and effects of human activities. This can present wicked socio-cultural problems of design for planning and enforcement within managed areas and addressing cross boundary impacts from the multi-directional flows and mixing of coastal and ocean waters. These typically require trans-sectoral and trans-jurisdictional protocols.

The most recent statements of international objectives for marine policy and management are provided in the targets of UN Sustainable Development Goal 14" to conserve and sustainably use the oceans" (UN 2015). The implications for coral reef management of the overlaps in SDG 14 targets are unclear.

SDG 14.2 addresses sustainable management, protection of ecosystems, strengthening resilience and restoration to achieve healthy and productive ecosystems.

SDG 14.4 addresses restoration of fish stocks to maximum sustainable yield in the shortest time feasible while

SDG 14.5 addresses conservation of at least 10% of coastal and marine areas, consistent with international law and based on the best available scientific information (SDG 14.5).

There is a lack of clarity concerning the extent to which "protection of ecosystems" in SDG 14.2 may be presumed to be addressed by SDG 14.5 conservation of 10% of coastal and marine areas and whether that 10% is to be addressed by strictest "no take" protection in the sense of IUCN Category I or II Marine Protected Areas. There is also lack of clarity on sectoral responsibilities for achieving healthy and productive ecosystems in the remaining 90% (Neumann et al 2017).

The bio-physical processes and linkages of marine systems limit the extent to which biodiversity conservation can be addressed by within-boundary protective management of areas of habitat significance. Hutchings and Kenchington (2015) discuss the differences between marine and terrestrial protected areas highlighting the need for measures beyond the boundaries of protected areas to address the multiple scale linkages of life cycles, food chains, water quality and movement of species that are integral to within-boundary conservation.

Terrestrial biodiversity conservation can be addressed as a matter of land use management with areas allocated for the purpose of maintaining the ecosystem of a habitat area, adequately protected from human impact so that it can oscillate around the apparent equilibrium state for which it was recognised for conservation significance. This may involve substantial defined or fenced boundaries; protection and control of within-boundary human uses and impacts; and supportive protocols to address upstream impacts reaching the area through unidirectional drainage flows down and within catchments.

Coral reef ecosystems of continental and archipelagic shelf waters are increasingly accessible from populated coasts and islands and likely to be, or to become, affected by a combination of issues of frequent fishing, recreation, tourism, coastal development, land sourced pollution and aquaculture facilities. Within boundary conservation is constrained in the absence of management of the water column impacts from external polluting activities (eg Brodie and Pearson 2016). Remote reefs may be subject to infrequent human visitation and less directly impacted by land sourced pollution.

Edgar et al (2014) concluded from a worldwide study of 87 Marine Protected Areas that conservation benefits increase exponentially with the accumulation of five features: no take, well enforced, old (>10 years), large (>100km2), and isolated by deep water or sand. They comment that MPAs often fail to reach their full potential as a consequence of factors such as illegal harvesting, regulations that legally allow detrimental harvesting, or emigration of animals outside boundaries because of continuous habitat or inadequate size of reserve.

On this basis conservation of coral reefs implies significant long term commitment to management, surveillance and effective enforcement capacity to a spectrum of regimes for biodiversity protection of coral reefs. One extreme is very remote large areas isolated by water or sand with very limited human access. The other, given the accessibility of reefs in coastal and islands, implies systems of highly protected areas buffered by areas with well understood, generally accepted and well enforced conditions of use and access. Achievement of these conditions requires addressing substantial cultural, historic, social, and economic concepts of freedom of access, rights to fish, food security and increasing opportunities for uses of marine space and resources that do or may affect or protect coral reefs.

Research to integrate understanding of biophysical and socio-economic opportunities and constraints for adaptive management is crucial. The challenge for trans-disciplinary research and management is to develop methods and technologies that inform and enable adaptive management to respond effectively to changing environmental, social and economic conditions. There is an increasing body of information but the challenge for many managers and policy makers is that workloads leave little time for reading, writing or keeping abreast of published research, grey literature and current awareness of work in progress. Further, managers and decision-makers may come to coral reef management with qualifications and experience in a range of relevant disciplines but limited prior exposure to biophysical science.

Over the years, and in differing contexts, the challenge of science/management communication has been addressed workshops at international meetings such as the International Coral Reef Symposia, International Tropical Marine Ecosystems Management Symposia, regional workshops supported by ICRI partners, UNESCO and UNEP Regional Seas partners. These workshops enable sharing of current experience, updating knowledge of relevant research findings and identifying management information needs. Appendix 1. Provides a collation of needs identified at several such workshops and grouped under the headings of resource analysis, analysis of use, information management and management effectiveness. This provides a checklist of issues that may be relevant for identifying available or needed information for adaptive management of coral reefs at operational scales from remote local areas to ecoregional and global programs.

An immediate scientific priority is to better understand how to sustain and increase resilience to accelerate re-establishment in corals and other reef species. An ongoing need is to monitor, inform and share knowledge with affected human communities on the condition and trends of marine ecosystems, and the effectiveness of management in the face of global and local change.

Conclusion

The experience of 40 years of management of the Great Barrier Reef has been increasing chronic stress associated with a complex of external human impacts including water quality, and ocean warming causing repeated severe events of crown of thorns starfish predation and coral bleaching.

The effects on coral reefs include recurrent substantial losses of coral cover and reduced resilience for recovery of reef communities (Hughes et al 2017, Brodie and Pearson, 2016).

Coral reef science is developing a substantial and growing biophysical understanding of the distribution, variability and ecology of coral reefs. The challenge for sustainable coral reef management is to reconcile the constraints and opportunities apparent from biophysical science with the dynamics of social and economic values and opportunities. This has added broader significance for addressing the impacts of marine global change because the threats of human impacts to the colour and garden-like properties of coral reefs are more readily recognised than is the case for less charismatic coastal and marine ecosystems.

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Appendix 1

Information needs identified in coral reef management workshops

Resource analysis

- Biophysical science ○ Baseline survey, monitoring, reporting,
  - At scales of space and time to identify and address extent and probable significance of changes
  - what is "normal" condition - what marks a significant change?
    - Variability in recruitment, growth, behaviour, species distributions
    - Environment or resource use sustainability of uses/impacts
    - Symptoms of departure from normal
    - Criteria for recovery
    - Individual, species and community resilience ○ Community and indigenous knowledge ○ What are sustainable levels of human uses/impacts?
    - Indicators or thresholds
    - How can impacts be removed or reduced? ○ what areas should be/could be protected?
    - communities, habitats, distributions
    - Linkages
    - Vulnerabilities
    - Threats ○ Diseases, departures from normal
    - Symptoms
    - Aetiology
    - Prognosis
    - Possible treatments

Analysis of use

- Socio-economic science ○ Uses and values of resources and areas
  - Community historical knowledge
  - Economic, social and cultural dependencies and conflicts
  - Governance
  - Social networks
- Survey and surveillance of uses of area and resources ○ To understand usage and apparent compliance levels ○ Changes in use patterns
  - New uses
  - New technologies
- What measures could be applied to achieve effective management? ○ within the managed area

- o outside the managed area but within national jurisdiction ○ outside the managed area and beyond national jurisdiction ○ technologies for surveillance and enforcement

Information management

- Information content and technologies for plan development
  - o Materials and strategies for stakeholder groups ○ Interactive methods and technologies for information sharing with stakeholders ○ Scenario modelling of management options
- Information content and technologies for ongoing management ○ Accessible materials on plan
  - ▪ Identifying areas and conditions for uses
  - ▪ Management notices on seasonal or other changes
  - ▪ Opportunities for users to report observations, experience ○ Ongoing current awareness for broader community
- Reporting and monitoring performance of management ○ Biophysical outcomes
  - ▪ Regular report cards
  - ▪ Periodic reviews ○ Socio-economic outcomes
  - ▪ Community support
  - ▪ Community engagement reports
  - ▪ Level of compliance with management regulations ○ Targetted reports
  - ▪ Government
  - ▪ Community
  - ▪ Sectoral
  - ▪ Professional literature

Review or evaluation of management

- o Surveillance of compliance with management regulations
  - ▪ Accumulated data for awareness and pattern analysis
  - ▪ To provide evidence for prosecution
- o Performance review ○ Emerging management issues
  - ▪ Trend and scenario projections
- From area monitoring data and current science
- From international literature and current awareness
  - o New technologies
    - ▪ Opportunities and threats for management