



Suggestions for marine protected area management in Australia: a review of temperature trends and management plans

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Abstract

Climate change and related ocean warming have affected marine ecological and socioeconomic systems worldwide. Therefore, it is critically important to assess the performance of conservation mechanisms, particularly marine protected areas (MPAs) to moderate the risks of climate-related impacts. In this study, sea surface temperature trends of Australian Commonwealth MPAs are assessed against climate change management criteria, as defined in *Adapting to Climate Change: Guidance for Protected Area Managers and Planners*. Monthly sea surface temperature trends between 1993 and 2017 were statistically assessed using the Mann–Kendall trend test and management plans were subject to a thematic analysis. Temperature trends showed variable SST changes among the regions, with the northern reserves all showing statistically significant increases in temperature, and the Southwest Network having the least number of reserves with statistically significant increases in temperature. The thematic analysis shows that management plans address approximately half of the climate change adaptation criteria. Several management strategies, such as dynamic MPAs, replication, and translocations, are currently absent and have been suggested as necessary tools in supporting the climate readiness of Australian MPAs. This study is significant because it helps to identify and synthesize regions most vulnerable to the impacts of ocean warming and provides management suggestions make MPAs “climate ready.”

Keywords Ocean warming · MPAs · Temperature trends · Management plans · Thematic analysis

Introduction

A consequence of climate change is an increase of ocean temperatures, known as climate-induced ocean warming (Koenigstein et al. 2016; Yu and Chen 2018; Voss et al. 2019). Elevated temperatures affect marine ecosystems and species by increasing metabolic oxygen demand (Pörtner and Knust 2007; Cahill et al. 2013) and altering species composition (Benning et al. 2002; Pounds et al. 2006; Ytrehus et al. 2008; Cahill et al. 2013; Hastings et al. 2020), such

as changes in the migratory patterns of southern bluefin tuna and sardine within the Australia Marine Parks (Beeton et al. 2015; Buxton and Cochrane 2015). Increased temperatures can lead to the poleward shifts of species, up to 37 miles per decade (Lenoir et al. 2020), resulting in biogeographic changes (Cheung et al. 2009; Hoegh-Guldberg and Bruno 2010; Frainer et al. 2017; Stige and Kvile 2017), reductions in sea ice coverage (Vinnikov et al. 1999; Comiso 2011; Frainer et al. 2017), increased light availability favoring predators (Varpe et al. 2015; Frainer et al. 2017), and an increase in primary production (Arrigo et al. 2008; Kahru et al. 2016; Frainer et al. 2017). These changes or “climate velocities” are faster in the deep ocean than at the surface (Brito-Morales et al. 2020) and projected climate velocities (2050–2100) will be faster in layers at depth, as opposed to the surface. This change indicates that the Southeast and Southwest marine parks in Australia will experience climate impacts to deep-sea habitats and species (Director of National Parks 2013a; Director of National Parks 2018a). Ocean warming also leads to coral bleaching (Raj et al. 2018; Monroe et al. 2018; Sully et al. 2019), which occurs

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when the temperature increases above the threshold of the corals, causing them to expel the symbiotic zooxanthellae, leading to bleaching and death. This is evident in the Coral Sea marine park, where coral bleaching events have occurred multiple times since 2016 (Hoey 2020, 2021). The effects of ocean warming could also be detrimental to the marine parks located in the North of Australia, which harbor tropical habitats such as coral reefs (Director of National Parks 2018b; Director of National Parks 2018c). Other climate-related impacts to the marine environment, aside from ocean warming, include shifts in currents (Yang et al. 2020), rising sea level, ocean acidification (Klein et al. 2021), and changes in the variability of winds and storm frequency and intensity (Irrgang et al. 2022).

Due to these impacts, there is heightened awareness that marine habitats require modified approaches to protection and conservation. Marine protected areas (MPAs) have been shown as a possible solution to aid habitat conservation and allow marine environments to adapt to impacts from climate-induced ocean warming (McLeod et al. 2009; Green et al. 2014; United Nations 2015; Roberts et al. 2017; Dudley et al. 2017). Evidence suggests that the corals within the MPAs are more resilient than the corals situated outside of MPAs due to protective measures against fishing and other synergistic pressures (Mumby et al. 2007; Wooldridge 2009; Mumby and Harborne 2010; Olds et al. 2014; Roberts et al. 2017), increasing the resilience of coral reef habitats (Mellin et al. 2016), and allowing faster recovery following climate change-related disturbances (Bates et al. 2019).

While MPAs that are well-managed can help to mitigate non-climate-related threats, such as fishing, habitat loss, and pollution (Jackson et al. 2001; Lester et al. 2009; Edgar et al. 2014; Bruno et al. 2018), impacts from climate-induced ocean warming are likely to continue to disrupt ecosystems within MPAs (Bruno et al. 2018). Historically, MPAs have been developed on an individual basis to address local impacts and stressors with more recent implementation of MPA networks to achieve larger scale conservation objectives and protecting broader scale ecological communities and habitats. However, there has been concern that these MPA networks have not been designed with ocean warming in mind (Gaines et al. 2010), and that the low predictability and variability of ecosystems to climate-related impacts may undermine the effectiveness of conservation measures. Furthermore, O'Regan et al. (2021) found that most MPAs did not consider climate change in their management plans, emphasizing the need to review the management plans performance against climate change impacts.

The focus of this study, Australia Marine Parks, was formerly referred to as the Commonwealth marine reserves. Some of the earlier reserves established include the Lihou Reef and Coringa-Herald National Nature Reserves, established in 1982. The subsequent expansion of the

Commonwealth marine reserves now covers 36% of waters within the Australian Government's marine jurisdiction area (Beeton et al. 2015; Buxton and Cochrane 2015). This includes the marine reserves located in Southwest, Northwest, North, Temperate East, and the Coral Sea regions of the country. These reserves were reviewed in 2016 by an expert scientific panel (Beeton et al. 2015) and bioregional advisory panel (Buxton and Cochrane 2015) regarding their zoning, policies, and impacts. The reserves were then modified based on the two reports and subsequently renamed into marine park networks in 2016. The Australia Marine Parks were set up to protect and conserve biodiversity and to provide for the sustainable use of natural resources in accordance with the objectives of the management plans of the respective networks (Director of National Parks 2013b; Director of National Parks 2018c; Director of National Parks 2018d; Director of National Parks 2018e; Director of National Parks 2018b; Director of National Parks 2018a). With climate change affecting various habitats and species within the marine parks, there is a need to review the management plans to assess their performance in reducing climate change impacts, especially climate-induced ocean warming.

Using a mixed methods approach, the aim of this study is to conduct a national-scale analysis of temperature trends within MPAs over the past 25 years, a period during which ocean warming and its impacts have been most severe. This study further assesses the scope of MPA management/implementation plans in relation to these warming trends and provides recommendations on strategies that can be implemented to increase the climate adaptive capabilities of reserves within each network/region. This research contributes to the existing body of literature that assesses the effectiveness of MPAs, in particular the role of MPAs with respect to climate change impacts and to provide management suggestions for MPA managers. We hypothesize that most MPAs, being spatially static boundaries, are not explicitly prepared to address climate-induced ocean warming. Though the presence of MPAs can help to reduce synergistic impacts and increase the resilience, several management changes are still needed to increase the effectiveness of their management scope.

Methods

This research employs a mixed-methods approach involving temperature trend analysis and management plan content analysis. The approach is applied to 58 MPAs and 6 networks managed by the Australian Commonwealth government as distributed across the various IUCN categories (Table S1). Australia's marine jurisdiction stretches from tropical waters to sub-Antarctic waters and encompasses a

variety of seabeds, open ocean and shoreline ecosystems, and near-shore marine and estuarine waters. These environments are rich in biodiversity, including a large number of endemics. The MPAs range from small, highly protected marine reserves to large, multiple-use marine parks (e.g., Great Barrier Reef Marine Park) and are based on the CAR (comprehensive, adequate, and representative) principles (ANZECC Task Force on Marine Protected Areas 1999). Therefore, this study represents a unique national-scale analysis throughout Australia's marine jurisdictions useful to assess the long-term ecological viability of the marine environment, to maintain ecological processes, and to protect Australia's biological diversity at all levels under the threats of climate-induced ocean warming.

Sea surface temperature trend analysis

Monthly averaged sea surface temperature (SST) data was acquired from the Australian Ocean Data Network. The data is a single-sensor multi-satellite product using observations from Advanced Very High-Resolution (AVHRR) instruments on NOAA polar-orbiting satellites (IMOS 2019). The $0.02^\circ \times 0.02^\circ$ ($2.2 \text{ km} \times 2.2 \text{ km}$) cylindrical equidistant projected data covers the region 70°E to 170°W , 20°N to 70°S . This high-resolution SST product provides superior resolution over coarser, long-term datasets (e.g., HadISST ($1^\circ \times 1^\circ$), typically used in assessing climate-related trends. This will permit the examination of trends within specific regions and parks, as opposed to only those areas within the limited pixel resolution. Monthly data between 1993 and 2017 were downloaded as NetCDF files and imported into the R software using the *raster* package v3.0–12 (Hijmans 2020). Marine protected area boundaries were obtained from the World Database on Protected Areas (WDPA) (<https://www.protectedplanet.net/country/AUS>).

An iterative script was developed to select the individual boundaries of the 58 marine parks and to extract the monthly average temperature for each park. The Mann–Kendall trend test was applied to determine the significance of temperature trends. To alleviate the false detection of significant trends in a time series (Helsel and Hirsch 2002), a test for serial autocorrelation was conducted. After determining the presence of serial autocorrelation, different Mann–Kendall trend tests were applied to those data showing serial autocorrelation and to those data that did not have serial autocorrelation. For data with serial autocorrelation, a variance correction approach was applied following the methods described in Yue and Wang (2004). Data are initially detrended and the effective sample size was calculated using significant serial autocorrelation coefficients. A $p < 0.05$ indicated statistically significant temperature trends while the τ value (positive or negative) determined the direction (increasing or decreasing) of the trend.

Management plan thematic analysis

An inductive approach of thematic analysis (Guest et al. 2012), primarily with descriptive and exploratory orientation, was used to assess the MPA management plan scope. MPA management plans were assessed against criteria and sub criteria (Table S2) described in *Adapting to climate change: guidance for protected area managers and planners* (Gross et al. 2017).

First, an initial read through of the framework was conducted to become familiar with its contents and the ideas surrounding the best practices of climate change adaptation for protected area managers. In a second reading, important phrases and passages were coded, and relevant criteria and sub criteria were identified. NVIVO 12 software was used to create a list of the identified sub criteria for each of the six regional management plans. MPA management plans were also subjected to an initial read through for familiarity. In the second reading, the important texts in the management plans were coded against the sub criteria identified from the framework. Implementation plans of each marine park networks (except Temperate East Marine Park) (Parks Australia 2014; Parks Australia 2022a; Parks Australia 2022b; Parks Australia 2022c; Parks Australia 2022d) and additional coral sea survey reports (Beeton et al. 2015; Beeton et al. 2015) were read through and important texts were extracted and coded against the sub criteria. Results were then recorded into a table, describing three different degrees of management plan performance, *yes*, *partially*, and *no*. *Partially* means management plans have mentioned or emphasized the importance of achieving the sub criteria, but lack detailed explanations and strategies.

Results

Sea surface temperature trends

The outcome of the Mann–Kendall trend test for individual reserves is available as supplementary material (Table S1) and is summarized in Figs. 1 and 2. Temperature trends within almost all reserves showed an upward trend (except Macquarie Island Marine Park Region B and Lord Howe Marine Park A). Increasing trends in temperature over the sampling period (1993–2017) were particularly obvious for the North Network (Figs. 1 and 2) where all 11 reserves showed statistically significant increasing trends in SST. Within the Northwest and Southeast Networks, 17 of 20 and 15 of 21 reserves showed statistically significant increases in SST, respectively. The Southwest Network had the least amount (4 of 28) of reserves showing statistically significant increasing trends, and the Temperate East Network also had few (5 of 14) reserves with statistically

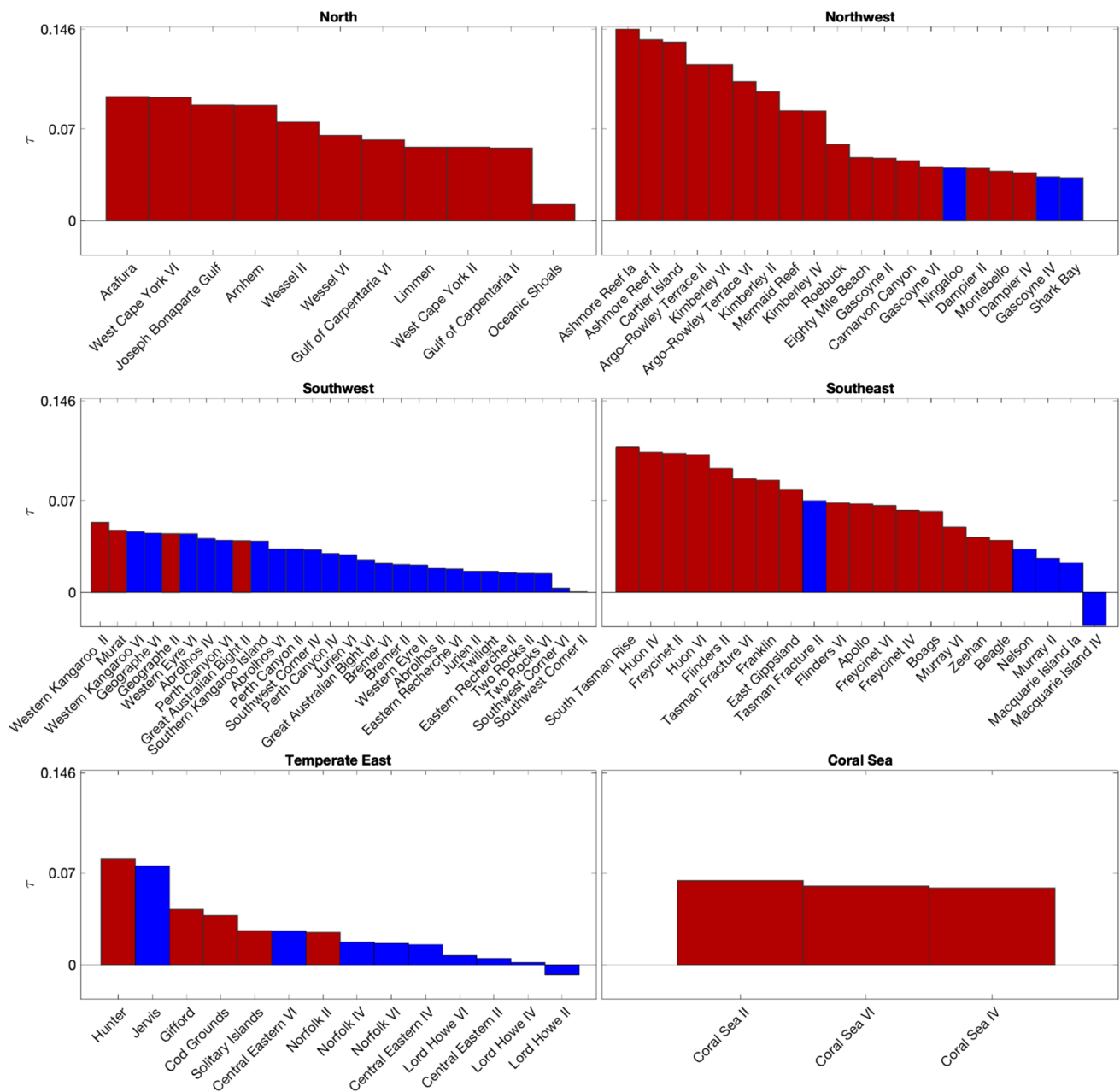
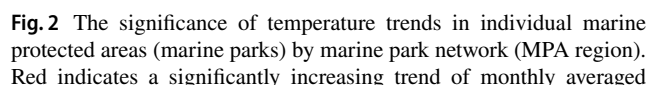


Fig. 1 The tau values of temperature trends in individual marine protected areas (marine parks) by marine park network (MPA region). Red and blue indicate that the trend of monthly averaged temperatures between 1993 and 2017 was significant and non-significant, respectively

significant increasing trends. All the reserves within the Coral Sea Marine Park were statistically significant. On average, the temperature change (1993–2017) of all significant regions increased by 0.642 °C and 0.238 °C non-significant reserves. Tau values for reserves in networks that showed statistically significant increasing trends (Fig. 1, e.g., Northwest and North) were greater than those not showing statistically significantly increasing trends (Fig. 1, e.g., Southwest).

Management plan thematic analysis

Overall, the 28 sub criteria are divided into five different steps of climate change responses with an extra step for building an international network of MPAs (Table S3). In general, the thematic analysis indicates that Commonwealth Marine Parks management plans have met or partially met roughly half (Fig. 3) or between 13 and 16 climate adaptation sub-criteria (Table S3). All networks only fully

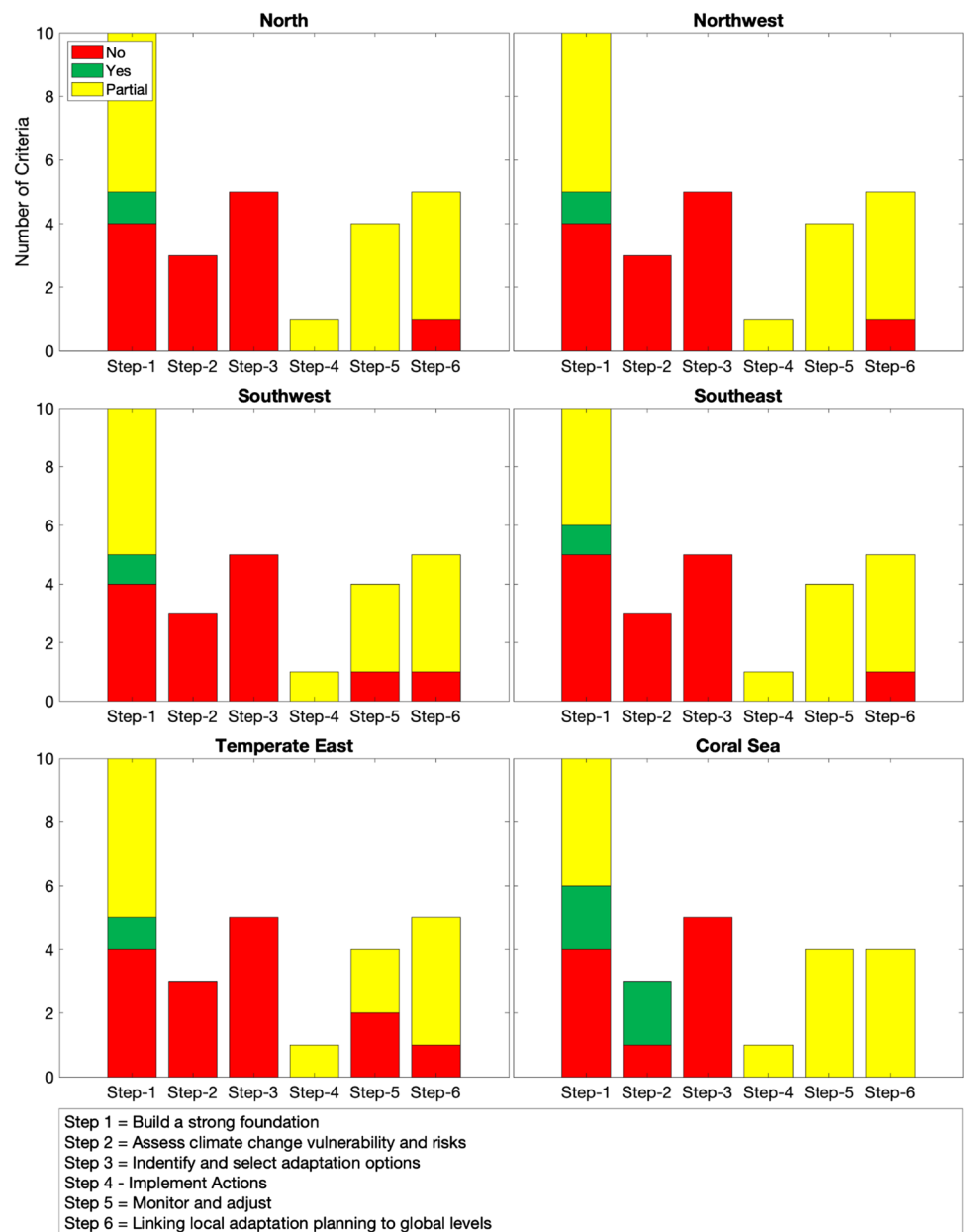


When sub-criteria were addressed, but details regarding to specific management strategies were lacking, or when the management plan contained the basis to address sub criteria, but lacked climate focus, a “partially addressed” score was given. Partially addressed sub-criteria fell largely in climate change step response one, “Building a Strong Foundation” (Fig. 3, Step 1), and step five, “Monitor and Adjust” (Fig. 3, Step 5), as well as the step “Implement Action” and “Linking Local Adaptation Planning to a Global Level” (Fig. 3, Step 6). The sub-criteria under step two, “Assess Climate Change Vulnerability and Risk” (Fig. 3, Step 2), and step three, “Identify and Select Adaptation Options” (Fig. 3, Step 3), were not addressed.

- 1) “Adopt new goals that consider climate change”
- 2) “Link adaptation actions to climate change impacts to ensure relevance”
- 3) “Integrate climate change into existing plans”
- 4) “Communicate nature-based solutions to climate change”

The Southwest and Temperate East management plans were those that addressed the least number of sub-criteria, with scores of 15 sub-criteria not met (Fig. 3, and Table S3). The standout sub-criteria not met for these management plans were under step five, “Monitor and adjust,” and include “identify how monitoring and evaluation will

Fig. 3 The proportion of criteria addressed (green), not addressed (red), and partially addressed (yellow) for each step described in *Adapting to climate change: guidance for protected area managers and planners* (Gross et al. 2017)



contribute to climate change adaptation” and “anticipate and design monitoring for change” (Table S3). The Southwest and Southeast management plans further failed to address the sub-criteria, “increase climate literacy within the professional workforce,” under step one (Table S3).

Discussion

Marine protected areas are important tools needed to help mitigate and reduce impacts to marine species (Péron et al. 2013), habitats within and beyond boundaries (Gell and Roberts 2003), and ecosystems (Grober-Dunsmore et al. 2007). MPAs that are well-managed protect fisheries

(Guidetti 2002; Roberts et al. 2005) and mitigate against habitat loss, boosting the overall health of an ecosystems and building its resilience against stochastic and unpredictable climate-related impacts such as ocean warming (McLeod et al. 2009; Green et al. 2014; Roberts et al. 2017; Dudley et al. 2017).

Despite the role of MPAs in moderating the impacts of climate-induced ocean warming, ocean warming stressors interact with local habitats, ecosystems, and ecosystem processes in a variety of ways. A more thorough understanding of regional and localized temperature trends coupled with an analysis of the management scope is needed to better prepare MPAs to confront climate-induced ocean warming impacts.

Regional temperature trends

As expected, temperature trends varied across the networks with variability largely justified by large scale current systems. In the Southwest Network (Fig. 1), the lack of significantly increasing trends is largely driven by variation and changes to the strength of the Leeuwin Current (Caputi et al. 2009). Lima and Wethey (2012) found that temperature off the west coast of Australia is dropping slowly, at a rate of approximately -1°C per decade, particularly near Shark Bay. There have also been an increase in extreme cold days, and areas off the continental shelf have experienced slower warming (Lima and Wethey 2012; Pearce and Feng 2007).

In contrast, increasing trends across the Southeast network are consistent with Lough and Hobday (2011), who found rates of warming along Southeast Australia higher than the global average, due to the increasing southern extent of the East Australian Current. Increasing temperature trends in reserves in the North and the majority in the Northwest network are consistent with the results of Yuan et al. (2018), Lough and Hobday (2011), and Lough (2008), who have shown that the SST increase of the Northwest Network has been attributed to the strengthening of the Indonesian Throughflow. Studies from the Coral Sea also show long-term increasing trends (Calvo et al. 2007).

Regional management approach

Currently, Parks Australia utilizes regional-scale management plans. There are six management plans, one for each of the five networks (the North, Northwest, Southwest, Southeast, and Temperate East networks) and one for the Coral Sea Marine Park. These management plans largely focus habitats, important species, and marine communities. Acknowledgement of climate-related impacts appears in some but not all of the management plans, for example:

Pressures related to the effects of climate change and associated large-scale effects on the marine environment are unpredictable and may include shifts in major currents, rising sea levels, ocean acidification, and changes in the variability and extremes of climatic features (e.g., sea temperature, winds, and storm frequency and intensity). (Director of National Parks 2013a)

Areas with the greatest proportion of statistically increasing temperature trends should further develop management plans to specifically address climate-related impacts. These include the North, Northwest, Southeast, and Coral Sea management plans, each addressing at least one criterion under Step 1, “Build a Strong Foundation.” The North, Northwest, and Southeast networks also had a high proportion of partially met criteria, an important consideration for

implementing climate change adaptations in these significantly warming regions. In order to improve the management of climate-induced stressors within MPAs, details regarding specific climate pressures (ocean warming) and alleviation strategies should be incorporated in more detail. These are discussed below.

Strategies for climate-induced ocean warming

First, as other studies point out, there is a need to focus on change with regards to sustaining target ecological features and to realign existing conservation goals to address a warming ocean (Gross et al. 2017; Mawdsley 2011; Margoluis and Salafsky 1998; The Nature Conservancy 2006). Combining habitat conservation goals and incorporating alleviation strategies can be achieved by incorporating the concept of ecosystem services. For example, mangrove forests not only act as important nursery areas for marine organisms, but also provide important ecosystem services, such as dissipating energy of storm surges along exposed coastlines (Alongi 2008; Das and Vincent 2009; Shepard et al. 2011; Jones et al. 2012), thereby protecting coastal communities from more frequent storms under recent climate change scenarios (Emanuel 2005; Jones et al. 2012).

After re-evaluation of current goals, strategies relevant to ocean warming scenarios need to be adopted. The best approach is to incorporate the context of SST trends into current conservation goals by deconstructing and recrafting them (Gross et al. 2017). None of the existing plans have goals and actions that are structured within this “ocean warming context.” We suggest management plans adopt clearer, more explicit conservation efforts and actions to address ocean warming impacts most relevant to the individual reserves, and not generally described conservation actions to cover all the reserves in a region. These actions should consider the technical capabilities, conservation needs, and the available resources of individual reserves (Gross et al. 2017). More specifically, the management plan of the Coral Sea marine park, in which all reserves experienced statistically significant increases of SST, could implement dynamic boundaries on an annual basis. These dynamic boundaries could moderate the impacts of bleaching and be based on the frequency and severity of bleaching events. Alternatively, management actions could focus on protecting emerging benthic configurations (e.g., macroalgae) that could still provide important biodiversity and fishery benefits (Graham et al. 2020).

Sub-criterion, “Assemble baseline information from local, national and international sources,” from all management plans, except the Southeast management plan, mentions marine science programs aimed at obtaining baseline data and establishment of ecological, social, and economic baselines to support adaptive management. To address this

need, information collection around ocean warming impacts and potential responses to these impacts need to be prioritized (Gross et al. 2017). This should be prioritized in the Northwest which showed the highest, significantly increasing temperature trend in reserves such as Ashmore Reef, Cartier Islands, and the Argo Rowley Terrace (Fig. 1). Furthermore, this should also be carried out in the apparent climate refugia of the Southwest and Temperate East regions to determine resilience characteristics of marine habitats. Reserves in this region (e.g., Two Rock, Southwest Corner and Eastern Recherche in the Southwest and Norfolk, Central Eastern and Lord Howe in the Temperate East) have low tau values and statistically insignificant trends in SST.

Furthermore, the management plans emphasize the importance of knowledge exchange by establishing education and awareness programs. However, there is no mention of climate literacy in the current knowledge exchange program and the public is not as well-educated regarding climate change (ocean warming) impacts on the marine environment, compared to pollution, fishing, and habitat alteration (Lotze et al. 2018). Therefore, climate change knowledge should be incorporated into training regimes, such as site-based and online training courses (Lundquist and Granek 2005; Gleason et al. 2010; Gross et al. 2017) (Table 2) as well as public communication to improve awareness regarding climate change impacts. For example, the Coral Sea marine park is the only region that fully addressed the sub criteria “communicate climate literacy within the professional workforce.” This was addressed by incorporating use of annual reports to communicate new information regarding climate impacts and management suggestions (Hoey 2020, 2021). Coral Sea management plan also partially addressed the sub criteria “Manage networks to ensure improvements in their ecological resilience to climate change impacts” by carrying out regular surveys of the reef areas and providing suggestions to improve management (Hoey 2020, 2021). We suggest the director to adopt this practice in other marine parks to increase knowledge transfer on climate literacy within the professional workforce that manages reserves in other networks.

All management plans briefly discuss adaptive management and flexible management practices but, again, lack detail on strategies under the step “Monitor and Adjust” (Fig. 3, Step 5). As quoted in the North management plan, “Regular monitoring, evaluation, reporting and review of the implementation of this management plan will be essential to achieve the vision for Australian Marine Parks and the objectives for this plan.” This describes the importance of adaptive management, but it is still important to improve the management scope of this criteria by developing the capacity to adapt to climate-induced ocean warming. There are two key components of adaptive management recommended by Gross et al. (2017), (1) a framework encouraging

responsiveness to changing conditions, and (2) instilling stakeholders with the mindset of embracing that framework. We suggest the formation of climate adaptive workforce to ensure responsiveness in dealing with climate change impacts and ensure up to date information is disseminated to stakeholders.

For “Assess Vulnerability and Risk” under step 2, management plans lacked clear descriptions of vulnerability assessments (VA) that were clearly aligned with specific goals and conservation needs of individual MPAs. Gross et al. (2017) suggested undertaking VAs for multiple periods to allow a broad range of decision-making. Scenario planning is one useful tool to identify future conditions to be considered in VAs and at the same time identify potential adaptation methods (Gross et al. 2017; Mawdsley 2011; Peterson et al. 2003). As suggested above, a climate adaptive workforce could undertake the VAs within each individual marine parks to identify their vulnerability to climate change and ocean warming, as well as identify and select the optimum strategies to reduce their impacts.

Another strategy is to select representative or “backup” habitats and areas to help increase resilience (Watson et al. 2011; Gross et al. 2017), while another method is to review boundaries regularly and modify when necessary. McNeely and Schutysse (2003) and Mitchell et al. (2007) suggested to increase the amount of MPAs in areas that experience low impacts from warming SST, creating climate refugia. Dynamic MPAs are also another consideration (Game et al. 2009). Hannah et al. (2007) reported that the protected areas situated in Mexico, South Africa, and western Europe are likely to fail in the face of climate change due to the alteration in the distribution of species, which causes species to move out of “static” protected area boundaries. We suggest managers to carry out surveys to identify similar habitats with similar species compositions and evaluate their degree of sensitivity to climate change impacts and ocean warming. This would enable managers to set up climate refugia (e.g., in Southwest and Temperate East regions). The survey should also include species movement to identify the effects of climate change on species distribution to aid the establishment of dynamic MPAs. After identifying the changes in distribution, management actions can then be determined to allow for adaptive management of the marine parks.

Recommended strategies

Based on SST trends and thematic analysis, it is clear that adaptive management strategies should be implemented to increase the preparedness of Australian MPAs against climate-induced ocean warming. Table 1 presents recommended strategies, some of which are discussed below that should be considered within current management plans, depending on the needs of each individual marine parks.

Table 1 Management adaptation strategies that can be implemented to increase the climate adaptive capabilities of reserves within each network/region (Green et al., 2014; Gross et al., 2017; Mawdsley et al., 2009; Villamizar et al., 2017)

Strategies	Description
Design management plan specific to each MPA	Specific management plan should be tailored for MPAs located in the north and northwest networks due to most of them being statistically significant and should be prioritized
Reconsider conservation goals	Re-evaluate conservation goals and objectives and if they are not viable, then there is a need to adopt climate-informed goals and objectives. This can be done by incorporating climatic context into current goals and objectives by deconstructing current goals and then recrafting into goals that considered climatic context
Climate refugia	Increase the number of climate-refugia, which are areas that experienced low impacts from climate change. Efforts could also be focused on areas deemed essential for climate-induced wildlife movements
Non-climatic stressors removal	Helps to increase the chance of climate adaptation for each species, more suitable for marine system large-scale climate adaptation
Modifications of laws and regulations	To achieve effective climate adaptations, managers need to have full flexibility in MPA management, and not only focusing on protecting “static” biodiversity
Dynamic MPAs	MPAs set up not with static boundaries, but with boundaries that are dynamic, depending on the climate change impacts and the movement of marine organisms
Prioritize information collection and potential responses	Establish education and awareness programs that focus on collecting information around climate change impacts and potential responses available to adapt to these impacts
Community-based adaptation and climate training	Incorporate climate change knowledge into training regimes for community and workers to gather information and transmit scientific rigor, as well as develop skills to manage MPAs under climate change
Communicate MPAs as solutions to climate change	Effective outreach needed to influence the public to support climate adaptation management actions. Insights from other disciplines should be considered to improve communication with public
Design VA that incorporates climatic context	VA will need to be designed by considering the goals, objectives, the conservation needs of individual MPAs, and the technical capabilities of the assessment team
Adopt flexible monitoring protocols	Accommodate shifting priorities and indicators. SMART framework should be adopted to adapt to changing targets and identify suitable climate-adaptive indicators
Fisheries co-management	To balance between conservation of marine biodiversity, improvements of livelihoods, and cultural survival of traditional populations
Increase replication within MPA networks	Conserve multiple examples of each ecosystem type
Translocate species at risk of extinction	Moving marine organisms from sites that are gradually becoming unsuitable for the species due to climate change to other sites with more favorable conditions
Adopt clearer, more explicit conservation efforts and actions	These actions need to be clear and concise and prioritize addressing climate impacts most relevant to individual MPAs, while considering their technical capabilities, conservation needs, and available resources

Strategies implemented within plans should not only be regionally specific but should also be adjusted to reflect reserve specific conditions. “Climate refugia” should be a key element of the strategies (West and Salm 2003; Salm et al. 2006; McLeod et al. 2009, 2012; Green et al. 2014). To achieve this, management/implementation plans need to determine areas where habitats and species are known to have withstood environmental changes in the past (Green et al. 2014). Areas with historically variable SST are good candidates for climate refugia, as habitats and species there are more likely to withstand future changes in SST (Sully et al. 2019). Another definition of climate refugia refers to areas with a lower chance of being impacted by

future climate change (e.g., extreme or anomalous conditions) (Ban et al. 2016). Climate refugia refer to areas in the ocean with relatively stable conditions, while the surrounding areas may be changing more rapidly (Ban et al. 2016). Ban et al. (2016) have conducted a study to identify climate refugia in Canadian waters. The usage of empirical data and expert input allowed the comparison of contemporary changes with anticipated future changes through the use of climate models allowed them to identify areas that can act as potential climate refugia. Therefore, we suggest assessments to be carried out within each network to identify potential climate refugia areas, with the priority being networks with the greatest number of marine parks

affected by climate-induced ocean warming, such as the North and Northwest networks.

Refugia, combined with non-climate stressor removal, could further increase the climate readiness of Australian marine parks. Fischlin et al. (2007) and Robinson et al. (2005) indicate the possibility of this being the only practical large-scale adaptation policy for marine systems. This strategy would be more successful in areas where (1) threats such as overfishing and destructive fishing are managed effectively and are (2) adjacent to other effectively managed marine or terrestrial areas (Green et al. 2014). Ban et al. (2016) have stated that although climate refugia could be a good strategy to reduce climate change impacts, it is unlikely to be effective without other conservation and adaptation strategies that reduce the negative effects of non-climate-related stressors, such as pollution and habitat degradation. This requires innovative re-evaluation of current impacts within the marine parks to remove non-climate stressors affecting the marine habitats and species within.

Dynamic MPAs are another strategy. With dynamic MPAs, managers can learn and adapt from their actions, revise management goals and objectives, and adjust boundaries (Grafton and Kompas 2005; Hughes et al. 2007; Game et al. 2009). Dynamic MPAs can help with the management of mobile resources (McClanahan et al. 2006; Game et al. 2009), a strategy that will be useful for addressing species range shifts (Hastings et al. 2020; Lenoir et al. 2020). Tittensor et al. (2019) described dynamic MPAs as “climate-responsive biodiversity closures.” Given that climate change (climate-induced ocean warming) is affecting the distributions of marine species, MPAs, especially those with static boundaries, may lose their protection functions to achieve ecological objectives (Cashion et al. 2020). Cashion et al. (2020) found that while dynamic MPAs may provide ecological benefits, it is harder to apply this strategy in coastal areas due to the heightened conflict between marine protection and livelihood. However, it is possible that dynamic MPAs could provide benefits in protecting many threatened species when applied to MPAs further offshore. Even though the application of dynamic MPAs can shift the balance of an ecosystem by favoring some species over others and potentially lower the revenue of fisheries, the overall biomass of the ecosystem could still be improved (Cashion et al. 2020). Furthermore, the application of dynamic MPAs could help protect habitat of species with crucial life history stages (Gilman et al. 2019) by shifting protected area boundaries temporally and spatially. Consequently, the effectiveness of dynamic MPAs depends on the goals and objectives of the respective MPAs. Managers should first consider the goals and objectives of each individual marine parks, conduct assessments to identify changes in species distribution in each individual marine parks, and modify MPA boundaries based on the assessment results. Annual reports, like those

from the Coral Sea marine park scientific team (Report 2021), could be helpful in determining the changes in species distribution and habitat cover.

Dated laws, regulations, and policies regarding MPAs should be reviewed to ensure their provisions are consistent with the needs of managers to deal with the ocean warming impacts (Mawdsley, O'malley, and Ojima 2009). For example, the Environment Protection and Biodiversity Conservation Act, created in 1999, was largely designed to conserve biodiversity that is “static” (Lemieux and Scott 2005; Lovejoy 2006; Mawdsley et al. 2009). International fishing agreements face similar challenges. Oremus et al. (2020) reviewed 127 such agreements and found that not one had language explicitly addressing climate change-driven losses of fishing stocks. Species mobility and range shifts should be more clearly addressed in MPA management (Oremus et al. 2020).

Translocation of organisms is another adaptation strategy that can be applied (Hoegh-Guldberg et al. 2008; Mawdsley et al. 2009; McLachlan et al. 2007; Mitchell et al. 2007). However, there is a risk of failure and even extinction (Groombridge et al. 2004; Mawdsley, O'malley, and Ojima 2009). One of the risks being the difficulty in predicting the optimal locations for assisted dispersal due to lack of knowledge on the biology of rare species and challenges in forecasting optimal future habitats (Caroll 2005; Mawdsley et al. 2009; Suárez-Seoane et al. 2004; Tolimieri and Levin 2004). As above, an assessment is needed to identify threatened species for translocation and should only be used when other methods have failed to conserve such species.

These suggestions were provided to strengthen the weakness of the management plans of these networks. The IUCN guidelines (Gross et al. 2017) applied in this study aim to provide guidance for managers to incorporate climate change considerations into management and implementation plans. As of now, the management plans of the networks are unclear in terms of the strategies and actions taken to mitigate or reduce climate change impacts. For example, the establishment of marine science program to increase understanding of marine parks is a good start, but lacks clear outline on strategies to increase knowledge of marine parks (e.g., survey techniques, survey frequency, monitoring, etc.). Therefore, we strongly suggest the director to outline the strategies and actions for managing each of the individual marine parks clearly within the management plans.

Conclusion

This national-scale analysis illustrates the variability of SST trends across a variety of static MPA networks and reserves across Australia and identifies regions most susceptible to climate-induced ocean warming impacts. It also acted as a

guide by providing management recommendation for these MPAs. In order to combat the impacts of climate-induced ocean warming, new innovative management approaches are needed. In the North Network and the Coral Sea Marine Park, all the reserves showed significant increasing trends of SST. These areas should be identified as an “MPA climate hotspot” and managed accordingly. The Northwest, Southeast, Temperate East, and Southwest Networks had MPAs with varying trends of temperature increase. In their current state, all management plans for the networks have at least 13 of 28 climate-induced ocean warming sub criteria addressed or partially addressed. Several management strategies, such as dynamic MPAs, replication, and translocations, have been suggested and can be potentially incorporated into management plans, depending on the conditions of each network.

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