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Technical paper

Evaluation of the performance of NSW Marine Protected Areas; biological and ecological parameters

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Contents

1. Background and context of this paper

The paper reviews the biological and ecological science relevant to assessing the performance of New South Wales Marine Protected Areas. While there are multiple approaches to the management of marine and estuarine environments, Marine Protected Areas (MPAs) are a spatial management tool that are a highly regarded and common approach globally to marine conservation (Spalding and Hale, 2016). This is reflected by the United Nations Convention on Biological Diversity (CBD, 1992) to which Australia is a signatory. The importance of MPAs in marine management is reflected by the Convention's 2011-2020 strategic plan which urges party states to conserve, by 2020, 10 per cent of their coastal and marine areas (CBD, 2011) *via* MPAs, and there is now discussion of increasing this to 30% by 2030 ("30 by 30"; IUCN, 2016). MPAs currently occupy approximately 5.8% of the area of the world's oceans, with 2 - 2.5% categorised as "highly protected" (Marine Conservation Institute, 2020; Sala et al., 2018).

MPAs are an integral component of Australia's Strategy for Nature 2019-2030 (Interjurisdictional Biodiversity Working Group, 2019). Since the 1990s the Australian Government, and all State and Territory Governments, have been working to develop a National Representative System of Marine Protected Areas (NRSMPA) which is Comprehensive, Adequate and Representative (CAR; Marine Protected Areas Working Group, 2007).

MPAs are similarly an integral part of the management of the NSW Marine Estate. In NSW MPAs cover approximately 35% of state coastal and estuarine waters including: 20,000 hectares comprising aquatic components of terrestrial national parks and nature reserves; 12 aquatic reserves covering around 2,000 hectares; and six multiple use marine parks covering approximately 345,000 hectares. Approximately 6% (CAPAD, 2018) of the NSW Marine Estate is zoned as highly protected or no-take, equivalent to IUCN protected area category II National Park, with the remainder allowing varying levels of extractive resource use and other activities, equivalent to Category IV Habitat/ Species Management Area (Day et al., 2012).

The primary legislation relating to MPAs in NSW is the Marine Estate Management Act 2014 ("the Act"; Marine Estate Management Act 2014). Under the Act, the primary purpose of the Marine Parks is: "to conserve biodiversity, and maintain ecosystem integrity and ecosystem function, of bioregions in the Marine Estate". Aquatic Reserves (some of which were established before the Act) conserve smaller areas than Marine Parks and are intended to be a flexible and responsive spatial management tool focused on a specific component of an ecological community important in a particular local area. Where consistent with the primary purposes of biodiversity conservation, the secondary purposes under the Act allow for other uses in Marine Parks and Aquatic Reserves. These include, for example, use of resources consistent with the principles of ecologically sustainable development, research, education, appreciation, enjoyment and Aboriginal cultural uses.

In 2017, the NSW Government released the Marine Protected Areas Policy Statement which clarified the future role and purpose of MPAs in the management of the NSW marine estate. The Policy Statement aims to maintain the existing comprehensive network of marine protected areas in NSW, while improving their management within the holistic management arrangements for the entire NSW marine estate as under the Marine Estate Management Act and via the application of the Marine Estate Management Authority's five-step decision-making process. It notes that MPAs are an important management tool to address priority threats, as identified by an evidence-based threat and risk assessment, to marine and estuarine habitats and biodiversity and to the social and economic benefits derived from the NSW marine estate. The Policy Statement builds on the NSW Government Response to the Independent Scientific Audit of Marine Parks in NSW (March 2013) and the Authority's document Managing the NSW Marine Estate: Purpose, Underpinning Principles and Priority Settings (November 2013).

This review arose initially from discussions within the Marine Estate Expert Knowledge Panel (MEEKP), within the context of their advisory role to the Marine Estate Management Authority MEMA (i.e., Sect 9 in the Act) and the Authority's Steering Committee (MASC). MEEKP recommended that an update of the earlier audit of NSW Marine Parks (Beeton et al., 2012) was timely, given 1) the substantial increase in the literature on Marine Parks globally and in NSW since 2012 and 2) the increasing inclusion in MEEKP's work program of matters relating to Marine Parks, including the need to provide up-to-date advice on the current revision of NSW Marine Park Management Plans. This review thus forms part of that advice. MEEKP and MASC acknowledged that a broad package of works was desirable for such a review, for example covering socio-economic studies as well as biophysical science. However, given that the primary purpose of marine parks is conserving biodiversity and maintaining ecosystem integrity and function, MEEKP have first reviewed the biological and ecological science relevant to assessing the performance of NSW MPAs towards achieving their primary purposes under the Act.

The focus of the review is on peer reviewed literature from relevant biological and ecological studies in NSW in the last ~10 years (i.e., from 2010 to early 2020), noting that earlier literature was reviewed by Beeton et al. (2012). However, earlier sources or additional literature are on occasion included where useful, and to provide background on particular points. There is furthermore an extensive global literature on MPAs which provides useful context and insights for the more specific evidence from NSW, and so we first include an overview of the global literature, with some focus on issues which are most relevant for NSW. Moreover, while there are a variety of policy, planning, regulatory, educational and other management actions (e.g., site protection facilities) applied to MPAs, scientific studies and reviews in NSW and globally have primarily focused on the biological and ecological effects of spatial management regulations, i.e., zoning, in MPAs. This thus necessarily adds an additional focus for this review.

Finally, we also consider the capacity of NSW MPAs to mitigate environmental threats and risks in the context of the NSW Marine Estate Management Authority's Threat and Risk Assessment (BMT WBM 2017). Recommendations are then outlined to inform future priority areas of research on MPAs so as to inform an assessment of their effectiveness in achieving the requirements of the Act and Policy Statement.

2. Performance of MPAs globally (outside of NSW)

2.1 General overview

MPAs are now a widespread conservation and management tool, and there are hundreds of papers in the global peer reviewed literature on MPAs. It is very much beyond the scope of this paper to comprehensively review that literature, in part because there are already numerous reviews and compilations of global or regional (including Australian) data in the literature which summarise these effects. Selected recent examples of reviews of the biological/ecological impact of MPAs include Edgar et al. (2014), Baskett and Barnett (2015), the volume edited by Wescott and Fitzsimons (2016), a collection of papers in Vol 75[3] of the *ICES Journal of Marine Science* (see introduction by Pendleton et al., 2018), Carr et al. (2019) and Edgar et al. (2018). We also note the recent position paper on Australian MPAs by the Australian Marine Science Association (AMSA, 2019).

The reviews summarise the extensive evidence from across the globe for the effects of MPAs, particularly no-take MPAs (= Sanctuary Zones in NSW), in modifying properties of individual taxa or of ecosystems, especially when MPAs are appropriately located and effectively managed. These effects include increases in the abundance (biomass or density), size or biodiversity of various organisms (e.g., Edgar et al., 2014, Soler et al., 2015, Starr et al., 2015, and many others), enhancement or restoration of ecosystem function (Ling and Johnson, 2012, Leleu, 2012) or resilience (Mellin et al., 2016, Roberts et al., 2017) and enhancement of ecosystem services such as fishery yield (Kerwath et al., 2013, Freeman, 2012) and recreational values (Vianna et al., 2012). In general, there is more information on the effects of MPAs on the abundance, size distribution or diversity of individual taxa. However, there are increasingly studies of more emergent ecosystem properties or functions such as habitat structure, climate resilience, trophic web structure and trophic transfers, carbon sequestration and others (Bates et al., 2019, Roberts et al., 2017), notwithstanding that these parameters are typically more complex and more difficult to measure than are characteristics of individual taxa.

While the evidence for these effects is strong, and robust in a general sense, the effects vary in magnitude, persistence and significance across different MPAs as a function of geography, different taxa, the nature of the ecosystem, the level of protection provided and other characteristics of a particular MPA. These issues are briefly explored below.

2.2 Effects on biodiversity or properties of specific taxa

The primary function of MPAs globally is to conserve biodiversity and ecosystem function at the bioregional scale, through the establishment of MPAs, which usually include “no-take” or “sanctuary” zones where all forms of extraction (such as fishing, mining) are prohibited. Many studies have thus addressed the effects of MPAs on biota by comparing their abundance or other properties (size, reproductive characteristics, diversity, etc.) across management zones, that is in no-take zones vs. unprotected (fished) areas or partially protected MPAs. Much of this research globally has reported on the consequences of these restrictions to fishes (relative to research on other organisms). This is not surprising given the extent of impact of fishing on the world’s oceans (Díaz et al., 2019) and marine ecosystems (e.g., Eddy et al., 2015), the economic and socio-political debates around MPAs which are often centred on where, when, or how people can fish (Grip and Blomqvist, 2020) and that fish are likely to show the most immediate responses to restrictions on fishing in MPAs. Thus, studies of fishes are a pragmatic approach to the science of monitoring responses to MPA protection. Here, the focus for understanding the effects of MPAs on fishes is to understand their role as components of the ecosystem in terms of biodiversity, dynamics and function, rather than in a fisheries management context.

Global meta-analyses of the effects of no-take zones on fish communities have generally found that abundances inside reserves vs. unprotected reference sites were much greater, e.g. by ~200% (Lester et al., 2009; density), > %300 (Lester et al., 2009; biomass), > 600% (Sala and Giakoumi, 2018; biomass), and 40 – 200% (Soler et al., 2015), with variation depending on factors associated with the species considered, e.g. trophic level. In the meta-analysis of Lester et al. (2009) increases in fish size or diversity in reserves were on average not as great (25-30%), but more broadly increases in the size of fishes or the abundance of large fishes is a very common effect of no-take zones (Lester and Halpern 2008, Edgar 2011, Currie et al., 2012). Consequently, more recent studies of changes in fish communities inside no-take areas sometimes partition results between fishes greater *vs*. lesser than 20 cm in length (e.g., Stuart-Smith et al., 2017).

These overall effects of MPAs on fishes are well established and confirmed in numerous specific studies. Some authors (e.g. Hilborn, 2018a, 2018b) argue that the effects only manifest when areas outside the MPAs are heavily fished. However, Cinner at al. (2018) found that fish biomass inside marine reserves declined along a gradient of human impacts in surrounding areas; further, reserves located where human impacts were moderate had the greatest differences in fish biomass compared with openly fished areas. Sala and Giakoumi (2018) partitioned their results by fishing effort, but still found emergent effects of prohibiting fishing, and their findings were consistent with an earlier study by Lester et al. (2009). Soler et al. (2015; also see references therein) used population index as a proxy for fishing pressure and found that population was related to the effect of MPAs but the magnitude of the effect varied among trophic levels, with carnivores affected most strongly. Cinner et al. (2018) concluded that that reserves in low human-impact areas are most effective for sustaining ecological functions like high-order predation but reserves in high-impact areas close to large human populations can provide substantial conservation gains generally for fish biomass.

While many studies on the effects of MPAs are on fishes, there is also an extensive literature on effects on other taxa, ranging from microbes (Catania et al., 2017) to invertebrates (Edgar et al., 2009, 2012, 2017, Shears and Babcock, 2003) to habitat forming organisms such as corals or kelp (Bates et al., 2017, Ling and Johnson., 2012) to megafauna (Gormley et al., 2012). These studies, like those on fishes, typically compare size, abundance or diversity of organisms across different zones of MPAs. Meta-analyses of such studies often show strong effects of protection, particularly of no-take zones, on properties of invertebrates or marine macrophytes (Lester et al., 2009, Babcock et al., 2010. However, these effects vary depending on the taxa and trophic level considered, as would be expected given the nature of marine food webs. For example, protection from fishing should enhance the abundance of harvested species such as lobsters (Babcock et al., 2010, Edgar et al., 2017, Freeman et al., 2012), but is likely to decrease abundances of prey if MPAs enhance abundance of predatory fishes. In turn, benthic habitat forming organisms are likely to increase (Babcock et al., 2010, Bates et al., 2017, Edgar et al., 2009). These "indirect" effects are explored in more detail below in Sect. 2.3.

Some studies also link the impacts of MPA zoning with other activities that are regulated by MPA zoning, such as boating and/or recreational activities (e.g., Milazzo et al., 2004). For example, soft sediment communities and benthic habitat formers such as seagrass can have changes in diversity or abundance in areas where boating pollution, anchoring or mooring scours are present (Herbert et al., 2009, Sagerman et al., 2020 for marine vegetation). In a rare study of the microbial component of communities in MPAs, Catania et al. (2017) found that bacterial communities inside a protected area were distinct from those outside the protected zone and attributed this to a difference in boating activities.

Marine megafauna such as seabirds, turtles, sharks and mammals often have ranges and behaviour patterns that exceed the boundaries of MPAs (Critchley et al., 2018), but MPAs are still widely considered an important tool for their conservation, *via* protection of prey populations, reduction of mortality or by providing refuges from behaviour-altering activities (Williams et al., 2015). For example, Gormley et al. (2012) found that establishment of a Marine Mammal Sanctuary in New Zealand enhanced survival of an endangered dolphin, *Cephalorhynchus hectori,* via removal of mortality from gillnet fishing. There are also multiple studies documenting the effects of boating and diving on megafaunal behaviour (Hayes et al., 2017, Nowacek et al., 2001) which informs regulations on recreational activities such as boating and mooring in MPAs. Conservation of megafauna, especially top predator species, can also complicate intended MPA effects due to overlap between human and marine predator prey items which can increase human-wildlife conflicts (e.g. Vincent et al., 2016). MPAs should incorporate consideration of marine megafaunal range dynamics and behaviour into their design (Ashe et al., 2010, Williams et al., 2015) even if those ranges extend well beyond the boundaries of the MPAs.

2.3 Effects on ecosystem properties or processes, and on resilience to other stressors

Studies of the effects of MPAs on restoring ecosystem properties have identified the cascading effects of protection for trophic interactions (predation, herbivory) and the effects of MPAs on enhancing population, community or ecosystem resilience. Because one of the most common effects of no-take MPAs is to increase the abundance of large, predatory fishes or invertebrates, broader effects of MPAs often manifest through effects on trophic interactions (e.g., Babcock et al., 2010, Bates et al., 2017, Soler et al., 2015). There are a variety of mechanisms by which such trophic effects can occur, but the two most often cited ones result from a) the re-establishment of previously fished predators in no-take MPAs, enhancing predation on herbivores, which in turn enhances lower trophic levels - particularly macroalgae - through trophic cascades (Leleu et al., 2012, Bates et al., 2017), or b) by increased abundance and grazing by (previously fished) herbivorous fishes which reduces macroalgal suppression of corals (mostly for tropical MPAs, e.g. Mumby et al., 2006).

In a meta-analysis type study of multiple MPAs, Babcock et al. (2010) compared the direct effect of cessation of fishing on fishes and predatory lobsters with their indirect effects on lower trophic levels *via* trophic cascades. They found strong evidence for both direct (78% of studies) effects on fishes and lobsters and indirect (71%) effects of increased predation in MPAs on taxa such as abalone, urchins and macroalgae, though the persistence (stability) of such effects varied significantly. On average, significant indirect effects took over twice as long (13 years) to manifest, as did direct effects on fishes or lobsters (5 years). In Australia, fishing of large predatory lobsters outside of MPAs reduced the resilience of kelp beds against the climate-driven threat of the sea urchin *Centrostephanus rodgersii*, increasing the risk of a widespread shift to sea urchin barrens (Ling et al., 2009).

While Babcock et al. (2010) and others have examined the consequences of increased abundance of predators in MPAs, measures of change in the actual presumptive mechanism - predation rates - are rare. One of the few examples is the recent study by Rhoades et al. (2019), who showed that predation rates were 6.5 times greater in old, no-take (greater than 40 years) MPAs relative to new, predominantly partial-take areas (approx. 8 years). This difference was due not only to changes in abundance and size of predatory fishes, but to differences in predatory behaviour in fishes in the older MPAs.

A key issue for MPAs is whether they can enhance resilience of populations, communities or ecosystems to stressors other than fishing and the evidence for this is mixed (Bates et al., 2019). Bates et al. (2014) showed that community level resilience to tropicalisation was enhanced by protection from fishing in temperate marine reserves in Tasmania. Otherwise, many of the relevant studies are from coral reefs. Sweatman (2008) found that the frequency of *Acanthaster planci* outbreaks on reefs open to fishing was 3.75 times higher than on no-take reefs in the mid-shelf region of the Great Barrier Reef (where most outbreaks occur) and seven times greater than on open reefs if all reefs were included. Williamson et al. (2014) also showed that MPAs conferred greater resilience to climatic disturbances for populations of reef fishes in the Great Barrier Reef Marine Park. Mellin et al. (2016) used a 20-year time series from Australia's Great Barrier Reef to show that no-take MPAs can increase the resilience of coral reef communities to natural disturbances, including coral bleaching, coral diseases, outbreaks of crown-of-thorns starfish and storms (also see Olds et al., 2014).

In contrast, Hughes et al. (2018) found no effect of on coral bleaching inside *vs.* outside of no-take areas on the GBR during a major bleaching event, and subsequently argued that resilience starts to fail as perturbations become more extreme. Eakin et al. (2019; also see associated papers in this special issue of *Coral Reefs*) concluded that, "While … MPAs can protect reefs against local stressors, they neither protect reefs against marine heatwaves caused by climate change nor even provide significant aid in reef recovery." Graham et al. (2020) found that marine reserves can still provide resilience for coral reefs in the face of climate change, but the species and functional groups that they benefit are altered. This more nuanced view of resilience - in which some species win and some lose - is consistent with the "Protection Paradox" of Bates et al. (2019). This paradox arises when protection from one pressure is implemented (e.g. fishing) and vulnerable species recover, but these species may also be relatively more sensitive to other pressures such as severe climate events.

2.4 Effects of different levels of protection: no-take vs. partial protection

MPAs may provide for a range of levels of protection by containing multiple zones that afford different levels of protection or have a variety of purposes. The efficacy of these differing levels of protection is an important consideration when assessing the performance of MPAs, as well as in the actual characterisation of MPAs. Many, if not most, "protected areas" globally allow extraction of resources and are therefore most appropriately designated as "partially protected areas" (Zupan et al., 2018).

The literature is clear that partially protected areas are generally not as effective as no-take areas. For example, Lester and Halpern (2008) compared biomass, density, species richness, and size of organisms (for fishes as well as invertebrates and algae) in no-take marine reserves and adjacent partially protected and unprotected areas across a range of geographic locations worldwide. They concluded that partially protected areas may confer some ecological benefits relative to unprotected areas, however, they also found that no-take reserves generally show greater benefits in these parameters relative to partially protected sites nearby. In the meta-analysis by Sala and Giakoumi (2018), biomass of whole fish assemblages in marine reserves were, on average, 670% greater than in adjacent unprotected areas, and 343% greater than in partially protected MPAs. Edgar et al. (2018) compared continental and decadal scale trends in fisheries catches from underwater reef monitoring data for 533 sites around Australia and found that partially protected areas generally performed less well than fully protected areas in terms of biomass of large fish, but still performed substantially better than fished areas. However, Turnbull et al. (*in press*), focusing on broader socio-economic and ecological measures, found no effect of partially protected areas in southern Australia, relative to non-MPA sites.

Notwithstanding that partially protected areas generally at best have more limited conservation outcomes than fully protected areas, they can be important for addressing specific threats. For example, Habitat Protection Zones in the Great Barrier Reef Marine Park prohibit trawling to prevent habitat destruction. Pitcher et al. (2016) demonstrated that this has substantially arrested and reversed previous unsustainable trends for the taxa assessed and has led to a prawn trawl fishery with improved environmental sustainability. Protection through zoning is an important measure which acts to limit spatial expansion of the fishery and potential risk to the ecosystem (Pears et al., 2012).

2.5 NEOLI and variation in the effects of MPAs

There is large variation in the performance of MPAs globally, and this raises the critical question: What factors affect this variation? Edgar et al. (2014) synthesised thinking in this area in a meta-analysis which remains an influential paper in the field (~1000 citations). Their analysis of 89 MPAs worldwide showed that to be effective, in this case as defined by increases in fish biomass or species richness, MPAs needed to fulfil at least 4, and preferably all 5, of the following criteria: include **N**o-take zones, have effective **E**nforcement, be **O**ld (in place for >10 years), be **L**arge (>100 km^2) and be

Isolated by deep water or sand (thus NEOLI). Only 10% of the MPAs in their analysis had 4 or 5 of the criteria; most had only one or two and were not distinguishable ecologically from fished areas.

Many studies have expanded on this theme in the recent literature, concluding that MPAs are often not designed adequately and lack essential criteria for performance. The effects of the time needed for the MPAs to have effects is critical (e.g. Babcock et al., 2010), and depending on the system or taxa, effects may take decades to establish (e.g. Edgar et al., 2009). The importance of fully no-take sanctuary zones *vs.* other levels of protection has been repeatedly emphasised, but Costello and Ballantine (2015) found in a global survey that only 6% of 9000 MPA's are no-take. Costello and Ballantine (2015) also showed that the median size (chosen as the metric to avoid the biasing influence of a few, very large MPAs) of these no-take zones was 2.7 km^2. This is very small relative to the criteria in Edgar et al. (2014) and relative to the biology of many species, particularly large predatory fishes. Dwyer et al. (2020) used tracking data on shark movements and found that "the world's officially recorded coral reef-based managed areas (with a median width of 9.4 km) would need to be enforced as strict no-take MPAs and up to 5 times larger to expect protection of the majority of individuals of the five investigated reef shark species." This comment also highlights that compliance with regulations in MPAs, and the ability to enforce those regulations, can be weak (Campbell et al., 2012, Gill et al., 2017).

2.6 Effects on regional properties outside of marine parks

The sections above provide strong evidence for the effects of restrictions in marine parks on the properties of taxa or ecosystems within the parks (particularly for no-take areas). A broader question is: What effects do they have on ecosystems outside the parks? There are theoretical reasons to argue that populations of some taxa in MPAs can significantly contribute to populations outside of MPAs, depending on the life history of the organisms in question. A well-documented effect of MPAs for many species is to increase the proportion of larger, older individuals (Sect. 2.2). Modelling by Barneche et al. (2018) and Marshall et al. (2019) shows that because fishes inside no-take MPAs are usually larger, and reproduction in fishes scales hyperallometrically with size, the larger fishes in MPAs could contribute much more significantly to recruitment of fishes outside MPAs than has previously been assumed.

There is some empirical support for this spill-over or "subsidy" effect. Le Port et al. (2017; also references within) showed that a small (5 km^2) reserve in Northern NZ contributed 10% of newly settled juveniles to a much larger area (400 km^2). Harrison et al. (2012) used genetic parentage analysis in marine parks around Great Keppel Island to show that three no-take MPAs exported 83% of assigned coral trout recruits and 55% of snapper recruits. These reserves accounted for just 28% of the local reef area yet produced approximately half of all juvenile recruitment in both reserve and fished reefs within 30 km. Bonin et al. (2016) found that a network of no-take MPAs contained 75% of the potential breeders in a metapopulation of the anemonefish *Amphiprion melanopus*, with breeding adults in these reserves responsible for 79% of locally produced juveniles sampled in the study. Finally, Kerwath et al. (2013) argued that spill-over of adults and increased export of larvae from a temperate South African MPA was likely responsible for a doubling of CPUE of seabream in the adjacent fishery.

2.7 Temperate MPAs

Many (by area and number) MPAs are in tropical regions rather than in temperate or boreal ones (Marine Conservation Institute, 2020), and the taxa, structure and functioning of tropical and temperate ecosystems can be quite different. The NSW Marine Estate is largely temperate, merging into subtropical in the north of the state. If temperate MPAs differed in their effects from tropical ones, then conclusions from global studies may not be relevant in the NSW context. This however does not appear to be the case. Studies comparing temperate and tropical MPAs, or focusing only on temperate MPAs, still strongly support the effects of MPAs described above. Soler et al. (2015) compared the effects of tropical and temperate MPAs and found strong effects on fish biomass for both. Babcock et al. (2010) similarly found strong direct and indirect effects in both temperate and tropical MPAs. Stewart et al. (2009), in a meta-analysis of 34 temperate MPAs, found consistent effects on enhancing abundance and biodiversity for a range of taxa.

Several specific temperate systems are worth highlighting for their relevance to NSW. The Cape Rodney to Okakari Pt Reserve (also known as the Goat Island Reserve) in Northern New Zealand (NZ), established in 1977, was reviewed generally by Ballantine (2014) and its performance 25 years post establishment examined in detail by Shears and Babcock (2003; also see Babcock et al., 2010). They found strong evidence for positive effects of the Reserve - brought about by the re-establishment of a trophic cascade - with an increase in kelp cover due to a decrease in herbivorous sea urchins consistent with the increase in fish and lobster predators (Shears and Babcock 2003; also see Edgar et al., 2017 for other Northern NZ Reserves). Given the similarity in structure of the NZ system to ecosystems along the NSW coast (same dominant species of kelp *Ecklonia radiata*, similar importance of urchin-kelp dynamics and taxa of predatory fishes and lobsters), the performance of the Goat Island Reserve would seem useful in understanding effects of NSW MPAs.

Tasmania is a cold temperate system, rather than a warm temperate system like most of NSW, but Tasmanian ecosystems also share many structural features and dominant taxa with NSW. Barrett et al. (2007, 2009) analysed 10 years of surveys of four east coast Tasmanian no-take marine parks and associated fished reference sites starting immediately after the establishment of the parks (also see Edgar et al., 2009, Edgar and Stuart-Smith 2009 and Stuart-Smith et al. 2017 for additional analyses). Results were both taxon- and park- specific, but there were several clear emergent messages. In particular, an increase in large fishes and lobsters in the reserves relative to fished sites, a decrease in sea urchins (particularly *C. rodgersii*) and abalone, consistent with the re-establishment of a trophic cascade in the reserves (also see Ling et al., 2009). Less consistent was the abundance of kelp (*E. radiata*), which was more variable, and other taxa showed a variety of responses, with Barrett et al., (2009, 2007) highlighting the importance of time since establishment (also see Edgar et al., 2009), size of park, indirect vs. direct effects of removing fishing, and taxon specificity for understanding this variation.

Carr et al. (2019) provides an extensive and useful review on the body of work of a third temperate system of MPAs in California (USA).

3. MPAs in NSW

3.1 Management context and background

The NSW Government Marine Protected Areas Policy Statement recognises that MPAs directly address certain environmental, economic, and social threats, typically those that can be regulated within the boundary of the MPA itself. These threats include harvesting, loss of biomass, wildlife interactions and disturbance, fishing-related marine debris, climate change and those that impinge on resource use conflicts (NSW Marine Estate Management Authority, 2017). The policy recognises that some aspects of these stressors may also be addressed by alternative and/or complementary management options such as fisheries management regulations, education programs and land-use planning.

The current network of NSW Marine Parks was established based on CAR (Comprehensive, Adequate and Representative) principles to provide a mechanism for focussed management so as to maximise conservation of biodiversity, ecosystem function and ecosystem integrity at the bioregional scale, resulting in ~35% area of the NSW Marine Estate being included in Marine Parks. Aquatic Reserves have had a similar, but more limited role, protecting unique or locally important values. The Independent Scientific Audit of Marine Parks in New South Wales (Beeton et al., 2012) found that management of MPAs achieved their primary purposes by providing a high level of protection for threatened and vulnerable species, protecting a representative diversity of habitats from damaging activities and establishing a network of representative no-take MPAs where populations of biota and their habitat are conserved and ecosystem functions maintained. Management of NSW Marine Estate has evolved based on the recommendations of Beeton et al. (2012), and in particular there is now a more co-ordinated approach to managing threats and risks to the entire Marine Estate. The 2017 Marine Protected Areas Policy Statement reaffirms the NSW Government's commitment to maintaining the existing comprehensive network of marine protected areas in NSW and improving their management. The revised approach has an increased focus on threat and risk assessment as a basis for assessing and managing threats to biodiversity, aquatic ecosystems and community benefits of MPAs within the holistic management arrangements for the entire marine estate (e.g., the NSW Marine Estate Management Strategy; NSW Marine Estate Management Authority, 2017).

Against this background, current management actions applied in NSW MPAs to address key threats to biodiversity conservation and maintenance of ecological processes include:

- prohibitions on extractive activities (e.g. fishing, mineral exploration and mining)
- zoning, regulation and permits to mitigate the impacts of use, sources of pollution etc.
- education programs, signage and enforcement activities to achieve compliance with codes of practice, management rules and regulations
- site works and facilities to protect vulnerable sites and habitats (e.g. moorings and markers to protect shallow reef communities, seagrass from anchor damage etc.)
- coordination with other management agencies, commenting on land-use planning proposals and development applications etc., to achieve management outcomes for the MPA
- research and monitoring to improve understanding of the environment within the MPA and to improve management responses

Zoning of Marine Parks in NSW includes no-take (*Sanctuary)* zones, partially protected zones (*Habitat Protection, General Use*), and location-specific zoning that applies a range of protection measures (*Special Purpose zone*s). Management rules for Aquatic Reserves are specific to each reserve (NSW DPI 2020).

3.2 Overview of the literature

While as described above there are a variety of management actions applied to NSW Marine Parks, by far the majority of published studies on the biology or ecology of NSW MPAs are based on comparisons of species or community characteristics across different management zones. Studies typically compare such characteristics in no-take Sanctuary Zones *vs*. those in either General Use Zones or areas outside of the MPA, although some studies also include comparisons of partially protected Habitat Protection Zones. Studies also have examined species' mobility and behaviour in order to determine the adequacy of the size of protected areas, integrated other factors – habitat type, pollution, urbanisation – into assessments of the impact of zoning, or addressed methods for assessment. A small number of studies address other management actions, such as boating and mooring, or compliance and education. There are also studies in the "grey" literature (e.g., Environmental Impact Assessments) that address the effectiveness of these and other management actions but are beyond the scope of this review.

There has been a substantial increase in studies of MPAs in NSW since Beeton et al. 2012 (Figure 1), with 18 studies published prior to 2012 and 49 studies subsequently. This is not surprising, given a) the time needed for MPAs to have effects and thus warrant investigations of those effects (Babcock et al., 2010, Edgar et al., 2014) and b) that the establishment of the six NSW Marine Parks occurred between 1998-2006, with zoning regulations in the parks mostly coming into effect post-2000.

Relevant studies have been conducted in all six Marine Parks and in 10 of the 12 Aquatic Reserves, with numerous published studies for Batemans (BMP), Jervis Bay (JBMP), Port Stephens-Great Lakes (PSGLMP) and Solitary Islands Marine Parks (SIMP), but fewer in Cape Byron (CBMP) and Lord Howe Island (LHIMP) marine parks or on the smaller aquatic reserves. Studies of single MPAs and studies which included the network of Marine Parks were both common. Some studies also utilised a broader network of south-east Australian (NSW, Victoria and Tasmania) MPAs (e.g., Edgar et al., 2009, Stuart-Smith et al., 2017, Turnbull et al., *in press*). We again focus on studies in the last ten years, noting the review of earlier literature in Beeton et al. (2012), though where relevant or appropriate we refer to earlier literature.

3.3 Effects of NSW MPAs on biodiversity and properties of specific taxa

A range of taxa have been studied in NSW MPAs including fishes, invertebrates, shellfish, worms, sharks, seals and seaweeds. As with the global literature the most studied taxa were fishes, and often commercially or recreationally important species. 33 of the 67 studies in Figure 1 were exclusively on fishes and a further 12 included fishes as well as other taxa. Most studies compare no-take Sanctuary Zones *vs.* fished areas (within or outside of the Marine Parks), with some studies adding data from partially protected areas (Habitat Protection Zones). These studies show that there is typically a strong positive effect from protection in MPAs, particularly in Sanctuary Zones (also see Sect. 3.5).

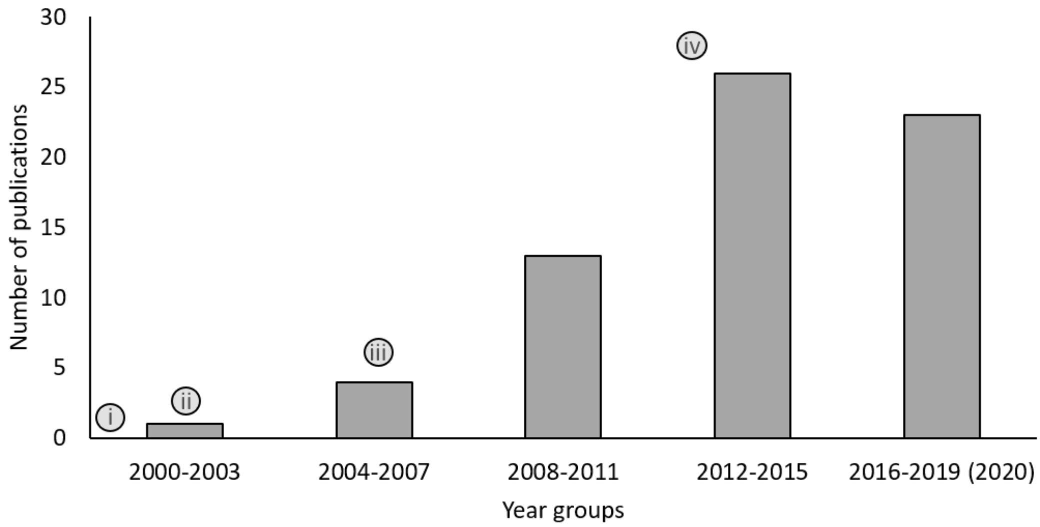

Fig 1. *Number of publications on the science of NSW MPAs using search terms "NSW Marine Parks Marine protected areas", and then curated manually to include only biological and ecological studies. Establishment of NSW marine protected areas and publication of Beeton et al. (2012) review shown for context: (i) seven Aquatic Reserves (ARs), including the Solitary Island AR were established between 1980 – 1998, prior to limits of the literature search. JBMP and SIMP, then LHIMP, were established in 1998 and 1999, then zoned in 2002 and 2004, respectively. (ii) six ARs were established in Sydney in 2002; CBMP was established in 2002 and zoned in 2006; (iii) PSMP was established in*

2005 and zoned in 2007, then BMP established in 2006 and zoned in 2007. (iv) Beeton et al. review published.

The most notable changes observed were on the abundance (biomass or density) and/or size distribution of fishes, relative to fished areas (e.g., McKinley et al., 2011, Kelaher et al., 2014, Kelaher et al., 2015a, Harasti et al., 2018a, Harasti et al., 2018b, Malcolm et al., 2018). Changes in diversity or overall fish community structure were also often observed, but here the direction or magnitude of the effect was more mixed. This is because of a shift in protected zones in community structure towards larger bodied and fished species in MPAs (Malcolm et al., 2015, Stuart-Smith et al., 2017; also seen globally Soler et al., 2015), as compared to fished areas where smaller and non-target fishes can be more common. This is likely due to the combined direct and indirect effects of fishing. That is, cessation of fishing directly increases larger fishes in Sanctuary Zones, but these may be predatory which in turn can cause a decrease in prey species.

Consistent with this, Harasti et al. (2014) found lower numbers of seahorses, but higher numbers of seahorse predators, in a no-take Aquatic Reserve *vs*. in fished areas. They suggested that with the implementation of MPAs, there will be 'winners and losers', with some species benefiting from no-take protection by increases in size and abundance while other species may exhibit different responses as a result of increased predation or interspecific competition.

Some earlier studies found relatively little effect of zoning (Edgar et al., 2009, Edgar and Stuart-Smith, 2009, Edgar and Barrett, 2012) but these studies were probably done too early in the history of the relevant Parks to expect much effect to be seen. The difference in fish assemblages between zones (Sanctuary Zones *vs*. fished areas) can also be habitat or place specific. For example, (Kiggins et al., 2019) found little effect of no-take zoning over seagrass habitat and suggested that this was due to the relatively low levels of prior fishing in the seagrass beds in which the Sanctuary Zones studied were situated.

Fewer studies have been done on the impacts of MPAs on taxa other than on fishes. Coleman et al. (2013) showed a mixture of effects for invertebrate and algal species five years after the establishment of BMP, with the strongest effects for a fished species, abalone. Glasby and Gibson (2020) investigated decadal changes in the cover of urchin barrens and macroalgal cover for the NSW coast. The study did not formally assess the effects of MPAs on urchin barrens, but the authors commented that they found no significant changes in cover associated with protection from fishing at sites in Batemans Marine Park or two Sydney Aquatic Reserves. The aerial photography used to collect the data could not distinguish between cover of the kelp vs. turfing alga, a critical habitat distinction in these systems (Filbee-Dexter and Wernberg, 2018).

Ferrari et al. (2018) found significant differences in key habitat-forming sponges and octocorals between Sanctuary Zones and General Use Zones on deep reefs across three MPAs but found no overall differences in community structure. There are relatively few studies on the effects of NSW MPAs on sediment communities, but Winberg and Davis (2014) showed significant shifts in sediment invertebrate assemblages in Sanctuary Zones in Jervis Bay Marine Park relative to control areas following cessation of bait harvesting. Interestingly, the effects were attributed to the decrease in sediment disturbance from bait collectors (trampling, etc.), rather than to reduction of removal of bait species *per se*. Sim et al. (2015) and Butcher et al. (2014) also found positive effects from Sanctuary Zones on species richness of sediment infaunal communities and abundance of mud crabs, respectively.

Edgar et al. (2009) and Edgar and Stuart-Smith (2009) included data from some NSW Marine Parks in their Australia-wide analyses of the effects of MPAs, and in some instances data on large invertebrates from NSW were explicitly analysed or presented separately (e.g. Figs. 5, 6 in (Edgar and Stuart-Smith, 2009). Changes were modest or variable, with conclusions constrained by the data mostly being collected relatively soon (< 7 years) after the zoning of the NSW Marine Parks came into effect. Greater changes were observed in later studies (Bates et al., 2017, Stuart-Smith et al., 2017)

3.4 Effects on ecosystem processes and resilience

Compared to the characterisation of differences in abundance, size or diversity of specific taxa, there are relatively few studies of NSW MPAs that address ecosystem, community or population *processes* that underly the conservation value of the parks.

A key property underlying such processes is connectivity, the extent to which separate populations or communities exchange individuals or genes, thus maintaining genetic diversity and facilitating resilience or adaptability of a species. Maintenance of connectivity in enabling regional persistence of populations or communities is a common rationale for establishing marine parks (Palumbi, 2003, Roberts et al., 2003). Coleman et al. (2011) studied connectivity for three species of habitat forming macroalgae (*E. radiata, Phyllospora comosa, and Hormosira banksii*) in Sanctuary Zones across four NSW Marine Parks (PSGLMP, BMP, JBMP, SIMP). Genetic evidence showed that the existing distribution of Sanctuary Zones was likely adequate to maintain connectivity among and within Parks for the two subtidal kelps, but that connectivity was low, with strong isolation by distance for the intertidal *H. banksia* which may put these populations at risk from some stressors. Coleman et al. (2017) further suggested that constraints on connectivity for kelp could affect genetic diversity and thus potentially resilience within individual Parks as oceans warm.

Grazing and predation are fundamental processes underlying ecosystem dynamics, but we have little understanding of the effects of MPAs in NSW on these processes. The study by Harasti et al. (2014) is consistent with the re-establishment of higher levels of predation (on seahorses) in Sanctuary Zones. In one of the few studies to measure these processes directly in NSW MPAs, Ferguson et al. (2016) compared abundance and grazing by herbivorous fishes (girellids and kyphosids) in JBMP Sanctuary ones *vs* fished areas. They found higher rates of grazing in Sanctuary Zones relative to fished areas, though the difference was not significant, likely due to low power. Most grazing was by one species, *Girella tricuspidata* (luderick) which was also larger and more abundant in Sanctuary Zones.

Predation, particularly *via* its role in large consumer (fishes, lobsters) - sea urchin - kelp trophic cascades, is a key ecosystem process for many temperate rocky shore ecosystems. The increased abundance of large lobsters (and other predators such as snapper) to the point where they reduce the density of urchins, leading to the re-establishment of kelp, is well established in northern New Zealand following decades of protection (Babcock et al., 1999, Shears and Babcock, 2003, Shears et al., 2006, Spyksma et al., 2017) as well as in other temperate kelp or seaweed dominated ecosystems (Pinnegar et al., 2000).

In NSW we have a poor understanding of the role that MPAs might play in allowing trophic cascades to establish or persist. Removal of predators in these systems would be predicted to result in urchin barrens (deforested areas), and there is evidence for long term (several decades) persistence of urchin barrens in NSW. This includes persistent barrens in a few of the NSW MPAs (Glasby and Gibson, 2020). However, we do not know if this is a historically natural feature of NSW coasts or a consequence of concurrent long-term decline in large urchin predators. We know that in some NSW MPAs potential urchin consumers – particularly snapper - have increased in size or abundance (Harasti et al., 2018b, Malcolm et al., 2018). But we do not know if large urchin predators (fishes and lobsters) in MPAs have re-established in sufficient size or abundance to effect urchin populations, following the historical reduction in both abundance and size of a number of key urchin predators in NSW, including blue groper (Young et al., 2014), old (large) snapper (Stewart, 2011) and lobsters large enough to eat *C. rodgersii* (Ling et al., 2009, Montgomery 1992).

We know of only one experimental study that has directly addressed the key question of whether actual predation in no-take areas is greater than in fished areas, Della Marta et al. (*in review*) who found that predation pressure was significantly higher in no-take reserves across Sydney than in either partially protected areas or fished areas.

3.5 Threatened, endangered and depleted species in NSW marine parks

While NSW Marine Parks aim to conserve all marine species occurring naturally in each bioregion, an emphasis in conservation generally is to conserve species that are threatened, protected, or endemic. Threatened and protected species present in NSW Marine Parks include the black rockcod, grey nurse shark, white shark, whale shark, whales, dolphins, turtles, seals and sea lions, waders and seabirds, a critically endangered marine slug, *Smeagol hilaris,* a critically endangered macroalga, *Nereia lophocladia*, and populations of the seagrass *Posidonia australis*. The range of two of these species is essentially restricted to locations within NSW Marine Parks (*N. lophocladia* in SIMP and *S. hilaris* in BMP). In contrast, others of these species have large home ranges stretching beyond park boundaries. However, marine parks can still potentially protect feeding, resting or breeding sites that may be seasonally important, and can improve management threats to their wellbeing or survival in the park.

There are few studies that assess the role of NSW Marine Parks in management of these species. Francis et al. (2016)'s review of the black rockcod, *Epinephelus daemelii* highlighted that its biology and behaviour make it vulnerable. Long-term data on this species is scarce, but abundance appears to have declined except in remote regions (e.g., Elizabeth and Middleton reefs) with extensive no-fishing areas. Francis et al. (2016) conclude that further prohibitions on fishing in key locations are likely to be important for the recovery and long-term survival of this species. MPAs on the NSW coast can play a role in this, though recovery can still take decades (Abesamis et al., 2014). The NSW DPI Priorities Action Statement for black rockcod recommends that information on their distribution, abundance and habitat preferences be considered during development and review of Marine Park Zoning Plans (NSW DPI 2020).

In a second example for the critically endangered grey nurse shark, *Carcharias taurus*, expansion of the NSW MPA network since 2002 resulted in many of the critical habitat sites for grey nurse sharks being incorporated into Sanctuary Zones. For example, Lynch et al. (2013) reported the re-establishment of an aggregation of grey nurse sharks at a previously abandoned aggregation site that had been incorporated into a Sanctuary Zoning at JBMP. Some aggregation sites in NSW MPAs remain in only partially protected zoning (Lynch et al., 2013) and it was recommended (Department of Environment, 2014) that due to the high rate of retained fishing gear reported in recent studies, the level of protection afforded by Marine Park zoning around grey nurse shark aggregation sites should be re-assessed and, in some cases, the zones expanded.

Grey nurse sharks are susceptible to a wide range of fishing gear and associated activities (Bansemer and Bennett 2010) and all forms of hook and line fishing (including catch and release fishing) have been listed as key threatening processes to threatened species (including grey nurse sharks) in NSW (http://archive.dpi.nsw.gov.au/?a=208341). However, Robbins et al.(2013) compared various types of fishing gear and concluded that the different gear types resulted in greater or lesser interaction risks when deployed around grey nurse shark aggregations; ranging from bottom-set baits which they found pose a high interaction risk, to trolling that they considered represents minimal direct risk to grey nurse sharks. A close-kin mark-recapture estimate of the population size and trend of east coast grey nurse shark reported by Bradford et al. (2018) indicated that there has been some recovery of the eastern Australian population, which they suggest may be as a result of the voluntary ban on capture by gamefishers in 1979, the NSW Government protection in 1984, and the implementation of a critical habitat classification. Notwithstanding a degree of recovery in the eastern Australian grey nurse shark population, Bradford et al. (2018) suggest that further work on the level of risk facing the recovering population would be required before it would be appropriate to alter the range of existing protective measures.

Though the emphasis in this paper is on the role of fishes in ecosystems, given the frequent enhancement of biomass of fish species in NSW Marine Parks (Table 1), Marine Parks can also potentially provide refuges for depleted and depleting fish stocks. There are a number of stocks of species or groups of fin fish, crustaceans, molluscs and sharks and rays in NSW coast that are either declined or declining. FRDC fisheries stock status reporting (Stewardson et al., 2018), indicates that of the 62 NSW stocks for which assessments had been completed: 7 are depleted and recruitment has been impaired, and; a further 3 stocks are classified as depleting, recruitment is not yet impaired, but fishing mortality is too high and moving the stock in the direction of becoming recruitment impaired. For one of these stocks, silver trevallies, Fowler et al. (2018a) notes that: "*Some protection to the Silver Trevallies (*Pseudocaranx *spp.) stock is afforded by marine parks in eastern Australia, but total fishing mortality is still likely higher than natural mortality*" (see also Fowler et. al., 2018b). A companion report for Australia's sharks (https://www.fish.gov.au/shark-report-card) makes similar comments regarding the role of marine reserves for conservation of crested hornshark, *Heterodontus galeatus,* and the Galapagos shark, *Carcharhinus galapagensis.*

3.6 Effects of different types of zones and partial protection

The best evidence for the effectiveness of marine parks globally or in NSW is for no-take MPAs, and many authors have argued that the presence of adequate no-take areas is the key to the effectiveness of MPAs. However, there are multiple zoning and management categories for NSW MPAs, and in NSW there is evidence for partially protected zones (Habitat Protection Zones) conferring some benefits in some places or for some species. Harasti et al. (2018b) found that the abundance and size of snapper, an important predator in coastal systems, in partial protection areas was intermediate between that of Sanctuary Zones and fully fished areas in the PSGLMP. Malcolm et al. (2015) also found an increase in abundance in partially protected areas for overall snapper abundance in the SIMP, but numbers of larger individual fish only increased in Sanctuary Zones. However, in a later study (Malcolm et al., 2018) found no difference in abundance of snapper and other target species between fully fished and partially protected areas in the SIMP.

Kelaher et al. (2014) found no benefits as measured by fish abundance from partially protected areas in the BMP and there are mixed results for other species/other parks. *Cheilodactylus fuscus* (red morwong) had higher abundance in sanctuary zones in BMP relative to partially protected areas or fished control sites (Coleman et al., 2013). However, Curley et al. (2013) found increased numbers of both red morwong and legal-sized *Acanthopagrus australis* (yellow-fin bream) in a very small partially protected Sydney Aquatic Reserve where spearfishing is prohibited, relative to fished control sites.

When comparing the effects of no-take zones with partially protected zones it is important to consider the likely outcomes of the different management regimes they are setting out to achieve. For example, a comparison of rocky reef fish abundance is unlikely to change, at least in the short term, between Habitat Protection Zones and General Use Zones if the focus of the Habitat Protection Zones is prohibiting activities impacting on sediment habitats such as trawling, anchoring in seagrass, harvesting of invertebrates but not fishing activities associated with rocky reefs (e.g., https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/656318/PSGLMP-Zoning-Map-Nov-2019.pdf). In a similar vein, the specifics of protection for individual species will affect any impacts of different zones. For example, in the Bronte-Coogee Aquatic Reserve collection of sea urchins is prohibited, but rock lobsters can be harvested (which is counter-intuitive if we are trying to manage effects of reduced predation on urchins on rocky reefs). These studies all suggest that the effectiveness of partial protection will depend on the specifics of the protection, the life histories and other characteristics of the organisms present, and the habitat type being protected (Zupan et al., 2018, Dwyer et al., 2020, Sect. 3.5 below).

However, it is also important to keep the goals of Marine Parks in mind when assessing the success of zoning. Most of the evidence cited above for the effectiveness of partial protection is for commercially or recreationally targeted species of fishes. In an assessment of the effectiveness of partially protected areas across temperate Australian MPAs, including NSW sites, Turnbull et al. (*in press*) found that partially protected areas overall provided no significant improvement over non-MPA sites for any of the broader social or ecological criteria assessed, and further argued that much of the evidence for the effectiveness of partially protected areas is for individual, targeted species of fish and thus does not necessarily speak to the broader ecological purposes of MPAs. The findings of McKinley et al. (2011) highlight a similar point (also see Beeton et al., 2012), that performance of NSW Marine Parks should be assessed against their primary purpose, with primacy given to conservation to achieve a more natural balance of biodiversity and maintenance of ecosystem processes, and that bolstering individual populations of economically valuable species should not in itself be a key measure of a marine park's success.

3.7 Interaction between the efficacy of MPAs and habitat type

Habitat type or structure has strong effects on species abundance or community structure and dynamics generally, including in NSW MPAs (Swadling et al., 2019, Rees et al., 2014, Rees et al., 2018a), and the complex relationship between organisms and their habitat is likely to affect the impact of MPAs. Several studies in NSW have addressed this complexity. Quaas et al. (2019) explicitly incorporated habitat variables into their study in PSGLMP. They found no overall difference in community structure or abundance of fishes between Sanctuary Zones and partially protected areas (fully fished areas were not included), but did find site to site differences as a function of geomorphology and habitat type, and concluded that the cover of canopy forming macroalgae may be an important determinant of fish communities in the Park. Strikingly, Rees et al. (2018b) found that by incorporating habitat complexity into a comparison of fished vs. no-take zones in they could increase the variance in kingfish (*Seriola lalandi*) abundance explained by more than an order of magnitude, from 3% to 65%.

In one of the relatively few studies in NSW to compare the effects of MPAs on fish communities in seagrass habitats (as opposed to rocky reefs), Kiggins et al. (2019) mostly found no differences in seagrass fish communities in Sanctuary Zones in JBMP vs. fished areas - in contrast to international findings for these communities. However, in an example of the complexity that can occur when assessing the effects of MPAs, they suggested that this was not a consequence of the effects of seagrass as a habitat type per se, but rather that historic levels of fishing in seagrass habitats in Jervis Bay were generally relatively low. Thus, differences between Marine Park zones would not have been expected. Consistent with this argument, the abundance of one fish species in seagrass habitat that was locally fished, the whiting *Haletta semifasciata,* was higher in Sanctuary Zones.

Finally, in the context of the increasing urbanisation of Australian marine systems, McKinley et al. (2011) found that the abundance of targeted fish species such as pink snapper were higher in Sanctuary Zones compared with other zone types in two MPAs. However, some targeted species were also more abundant in a nearby, more highly modified, estuary, suggesting that a higher abundance of commercially and recreationally important species does not always reflect natural conditions.

These studies all highlight that simple binary comparisons between no-take and fished areas, without taking into account critical factors of ecosystems such as species life histories, habitat type, structure or complexity, run the risk of obscuring – and most probably underestimating (Rees et al., 2018a) – the effectiveness of MPAs.

3.8 NEOLI considerations and NSW MPAs

As discussed above, the effectiveness of MPAs is strongly affected by their age since establishment, size, type of zoning, degree of enforcement/compliance and their degree of isolation (Edgar et al., 2014) and all these will impact on the efficacy of NSW MPAs. Earlier studies of the effects of NSW MPAs on fishes or invertebrates often showed no or quite variable impacts (Edgar and Stuart-Smith, 2009), whereas more recent studies with more time post-establishment tend to show more consistent effects of Sanctuary Zones in particular. Most studies post-2010 comparing Sanctuary Zones and fully fished areas outside of MPAs found some positive effects of Sanctuary Zones. This is consistent with the importance of the age of MPAs on their effectiveness in allowing for the re-establishment of previous food webs (Babcock et al., 2010). Coleman et al. (2015) found a positive relationship between the age of NSW Parks and the average trophic levels of fish, suggesting larger predators were re-establishing.

Compliance is also variable and at times apparently low in some NSW Marine Parks (Harasti et al., 2019 for PSGLMP), again affecting assessment of their performance. Increasing compliance in some NSW Marine Parks can enhance their effectiveness (Kelaher et al., 2015b), as is the case globally (McCook et al., 2010).

Size is a critical criterion for the effectiveness of MPAs, but there are relatively few explicit studies of the impact of the size of NSW MPAs, including that of no-take areas. Malcolm et al. (2016) showed that the size and age of no-take areas can interact; targeted fish species in the SIMP generally increased in abundance in no-take areas, but the response varied considerably depending on the size and age of the no-take areas. Curley et al. (2013) found excluding spearfishers from a small Aquatic Reserve (Gordon's Bay in Bronte-Coogee Aquatic Reserve) resulted in an increase in some fishes (red morwong and bream). Turnbull et al. (2018) concluded that small Aquatic Reserves were often not effective in achieving their aims, but argued that a network of small MPAs could be effective if they met a number of criteria; well located, in a sheltered area, have high structural complexity and thus multiple habitats, and enjoy strong support from the local community).

The adequacy of NSW MPAs as a function of their size will depend on the life history, genetic connectivity (Sect. 3.3) and behaviour of different species. Lee et al. (2015) suggested that smaller Aquatic Reserves could be effective in protecting blue groper, because of the relatively sedentary life history of this fish. More generally, the increased use of acoustic tagging technology for tracking fish movements has allowed mobility of fishes in a number of NSW MPAs to be assessed and compared to the size of Sanctuary Zones. Some species (*G. tricuspidata* [luderick], *Chrysophrys auratus* [snapper]) show strong site fidelity (Ferguson et al., 2013, 2016) and even small Sanctuary Zones can enhance the abundance of these species. Other tracked species exhibited philopatry (return to breeding sites, in this case within JBMP) across multiple years, but also moved hundreds of kms along the east coast of Australia outside of the park.

Such species-specific considerations need to be taken account when assessing the adequacy of the size of NSW MPAs (and habitats therein; Davis et al., 2017). However, the relatively small size of Sanctuary Zones in NSW is a concern. The average size of the 92 sanctuary zones in NSW is 6.16 km^2 and almost half (~45%) are smaller than 1 km^2 (CAPAD, 2018). These numbers exclude the mostly even smaller Aquatic Reserves, and contrast with the size of no-take areas recommended for effectiveness by Edgar et al. (2014), which are an order of magnitude (or more) higher at > 100 km^2.

3.9 Threats and risks

Beeton et al. (2012) proposed that Marine Park-specific risk assessments should be used to guide management actions commensurate with park objectives. Consequently, the NSW Government identified risk assessment as a matter to be considered in the development of Marine Park management plans (s49 of the Act). One of the objectives of this review was to document threats and risks identified by the literature; these may be threats and risks to the Marine Estate that may be reduced through management of MPAs, or threats and risks that may undermine the effectiveness of marine parks.

The NSW State-wide Threat and Risk Assessment (TARA) process was completed in 2017 (BMT WBM, 2017). It identified water pollution from diffuse sources and stormwater discharge as the number one threat, particularly to estuarine areas of the marine estate. Other priority threats included physical disturbance from clearing riparian vegetation, foreshore development, dredging and various on-water activities. Two other threats were considered highly cumulative or additive in nature and it was recommended that they should receive priority attention in the Marine Estate Management Strategy. These were fisheries, in terms of management of fish stocks and potential impacts on trophic structure and function, and the estuarine receiving environment and water quality as a whole (BMT WBM, 2017).

Changes to the biodiversity, ecosystem integrity and ecosystem functions of the NSW Marine Estate have occurred over a long period of time, with some localised impacts identified as far back as the 1800s (Novaglio et al., 2018). Notwithstanding those historical origins, both past and current threats continue to impact the Marine Estate. In our assessment, based on Beeton et al. (2012), the TARA (BMT WBM, 2017) and the further information presented above in this report, the highest current risks to biodiversity, ecosystem integrity and ecosystem function of the NSW Marine Estate are:

- Estuaries - water quality decline, development/disturbance (breakwaters and other structures, dredging, sand extraction, sedimentation, etc.), cumulative impacts of fishing (historic and current), climate change, and some increasing impacts from introduced pests; and
- Marine - cumulative impacts of fishing (historic and current), climate change, and some more localised impacts from coastal development/habitat disturbance.

These risks generally accord with the findings of the state-wide TARA (BMT WBM, 2017). However, a number of cumulative threats were identified by the TARA as requiring priority attention and are worth highlighting in the context of the role of MPAs in managing these consequent risks. These risks are: the potential impacts of fishing on fish populations, trophic structure and function; climate change, and; impact on threatened species.

The cumulative impact of fishing, both historic and current, has had measurable impacts across a range of harvested populations and subsequent impacts on trophic structure and function. These impacts include substantially reduced biomass of target species, truncated age structure due to a reduced number of older individuals in the populations, loss of larger size classes within populations, reduced age of maturity, reduced fecundity, reduced genetic diversity, and altered predator-prey relationships. These impacts are apparent both from comparison between no-take MPAs and fished areas (Malcolm et al., 2015, McKinley et al., 2011, Harasti et al., 2018b, Lee et al., 2015), and from studies and modelling of various populations and stocks (Audzijonyte et al., 2013, Harasti and Malcolm, 2013, Stewart, 2011, Stewardson, 2018). Impacts can occur from both commercial and recreational fishing (Novaglio et al. 2018).

MPAs, and in particular no-take Sanctuary Zones, address the cumulative impacts of fishing by re-establishing key aspects of ecosystem functioning. As discussed in previous sections of this review, there are a variety of mechanisms by which such effects can occur, but the most oft-cited ones result from the re-establishment of previously fished consumers, leading to a re-establishment of biodiversity and ecosystem properties through trophic interactions.

Climate change. The TARA identifies climate change threats as future risks (20-year timeframe). There is now however clear evidence in NSW (e.g., Scanes et al., 2020) and elsewhere in Australia - Wernberg et al., 2016) that significant changes and impacts from climate change are already occurring in our marine and estuarine environments. These changes are both gradual, often due to the increasing southward flow of the East Australian Current (EAC), and sudden, a result of extreme events such as marine heatwaves (Oliver et al., 2017, Holbrook et al., 2019). These impacts are affecting a wide range of species and habitats. Vergés et al. (2016) showed that northern NSW ecosystems (including in the SIMP) are becoming "tropicalised" with a loss of temperate kelp forests driven by the increasing southward incursion of tropical and subtropical herbivorous fish. Consistent with tropicalising ecosystems, Baird et al. (2012) identified a south-ward range expansion of *Acropora* species of hard coral in NSW. Wayte (2013) attributed the regime shift affecting the productivity of the eastern stock of jackass morwong *Nemadactylus macropterus* to long-term oceanographic changes (warming) and Morgan et al. (2019) identified and similarly suggested that a 400km poleward shift in the genetic transition zone of the East Coast Snapper (*C. auratus*) population was linked to the poleward advance of warmer and saltier water associated with the EAC.

Evidence for the ability of MPAs to enhance resilience of biodiversity, communities or ecosystems against climate change stressors is mixed (Sect. 2.3, 3.4). However, it is clear that the network of MPAs provides a unique opportunity to improve our understanding of the effects of climate change, and to disentangle those effects from the effects of fishing (Barrett et al., 2014, Bates et al., 2017).

Impacts on threatened Species. The literature has identified a number of ways in which NSW MPAs help to restore and protect populations of threatened, endangered and depleted species in NSW, including opportunities to improve the level of protection (section 3.5 above). Section 3.8 (NEOLI considerations and NSW MPAs) also identifies a number of limitations to the design and management of NSW MPAs that could be reviewed, both to improve the capacity of MPAs to address threats to biodiversity and ecosystem processes, and to reduce the risks to the integrity of the NSW MPA network.

4. Summary, knowledge gaps and conclusions

4.1 Evaluating the performance of NSW marine parks and Marine Protected Areas

Based on the *Marine Estate Management Act 2014* (cl. 22), and as discussed in the Introduction (Sect. 1), we concur with Beeton et al. (2012) that "the performance of the marine park system should be assessed against its primary objectives of conserving biodiversity and maintaining ecosystem integrity and function." (Beeton et al., 2012; Executive Summary). These objectives have informed this review and the following summary and discussion of knowledge gaps.

4.1.1 Summary of the science

There has been a substantial increase since Beeton et al. (2012) in the body of literature on the effects of NSW Marine Protected Areas on biological or ecological properties of NSW ecosystems and the species therein (see Fig. 1). Studies on the performance of MPAs in NSW now include all six Marine Parks and 10 of 12 of the smaller Aquatic Reserves. The more recent science reviewed here continues to support the findings of the Audit that the NSW network of Marine Parks, and in particular no-take Sanctuary Zones, support enhanced characteristics of individual species (abundance, size), biodiversity (in general or of specific taxa, noting that effects on biodiversity are more complex), with some emerging evidence of cascading effects on predator prey relationships (e.g., Harasti et al., 2014). This suggests that MPAs in NSW are beginning to establish the building blocks required for enhanced biodiversity, ecosystem functions and integrity.

4.1.2 Factors affecting the performance of NSW MPAs

These general conclusions are strongly supported. However, the strength or even direction of effects, and thus level of performance, varies from one location to another for a number of reasons (Edgar et al., 2014), including: the level of pre-existing fishing pressure and habitat disturbance in each location, time elapsed since protection was introduced, habitat type, the degree of compliance and level of illegal fishing, the relative level of other pressures at the location, the size of the area protected and how that interacts with the life history of the organisms the MPAs are trying to conserve (Ferguson et al., 2013).

4.1.3 Relevance of global and other Australian studies

There is an extensive global literature on the ecological effects of MPAs. Where studies are comparable, the effects reported for NSW MPAs are similar to those from the global literature, with some exceptions (e.g., Kiggins et al., 2019). This is particularly true for abundances and sizes of fishes and invertebrates, while the relatively few studies in NSW on ecosystem processes, dynamics or resilience make comparisons for these more complex parameters more difficult. None-the-less, the broader global and Australian literature can very usefully inform our understanding of NSW MPAs, particularly studies from MPAs in other temperate ecosystems with similar taxa and structure to NSW and which share modern approaches to management.

This is an important conclusion, because while the evidence base around NSW Marine Parks is increasing, many of the Parks are still young (Fig. 1) relative to the time needed for effects to manifest, and there are knowledge gaps for a number of critical issues (below). Thus, guidance for management of NSW MPAs will still often need to draw on learnings from elsewhere in Australia or from international studies.

4.1.4 Types of zoning

Consistent with evidence globally or in Australia, the strongest evidence for significant, positive effects by MPAs in NSW on biological and ecological parameters are for Sanctuary Zones. The often relatively small size of Sanctuary Zones in NSW MPAs, and their modest total area, is potentially concerning in this regard, as it may reduce their effectiveness. There is also evidence that partial protection confers some benefits in some instances (Harasti et al., 2018a), *via* for example the closure of areas in MPAs previously exposed to trawling. The effectiveness of partial protection (e.g., Habitat Protection Zones in NSW) will vary as a function of the provisions of the zone, the type of ecosystem, the life history of key organisms and many other factors. A better understanding of the effects of such factors on the effectiveness of different zoning in MPAs is a recognised need (Curley et al., 2013, Quaas et al., 2019) but remains a knowledge gap for NSW. This does not, however, diminish the role of Sanctuary Zones.

4.2 Knowledge gaps

There has been substantial research done on NSW MPAs (Fig. 1) relative to many global MPAs. However, not surprisingly given the scale of the NSW Marine Estate, there remain substantial knowledge gaps which limit our ability to optimally design and use the NSW MPA network. The amount of evidence for the effects of NSW MPAs on different properties of NSW marine ecosystems varies considerably. For example, there is more (usually much more) published evidence relating to:

- fishes *vs.* on other organisms;
- properties of individual species or taxa *vs.* on broader ecosystem properties or processes;
- open coasts or embayments *vs*. estuaries, and;
- rocky reefs *vs.* other habitats.

All of these points highlight knowledge gaps which can be substantial and are important targets for additional research. The disproportionate amount of information among different habitats highlighted by the last two dot points is notable. For example, although soft sediments in estuaries are a major habitat in NSW there are relatively few papers that compare sediment communities or key species in *vs.* out of Sanctuary Zones (e.g., Butcher et al., 2014,Winberg and Davis 2014), in comparison to dozens of studies on coastal rocky reefs. Estuaries are important areas of human use, commonly densely populated, and as a consequence can be focal points for conflict around the multiple use of coastal environments. They are also a focus for much of the broader Marine Estate Management Strategy's (MEMS) program, and thus further research on Marine Parks in estuaries would also inform the broader MEMS program.

There are many other specific examples where further research would be useful for managing NSW Marine Parks, but two of the general knowledge gaps listed above stand out:

4.2.1 Fishes vs. other organisms

67% of the studies in Figure 1 are on fishes, either exclusively or together (18%) with other organisms. This reflects a global paradox for studies of MPAs, which is that while the legislation for MPAs is typically written to support conservation values such as biological diversity or ecosystem function, studies of the impact of MPAs have often focused on the abundance or size of commercially or recreationally important fishes. This is not unsurprising in some respects; as regulating fishing is a major consequence of MPAs and we might expect fishes to be the first set of organisms to respond to the establishment of (for example) Sanctuary Zones.

However, it is problematic from at least two important perspectives. First, the key focus for assessing the effects of MPAs in NSW on fishes should be on their role as components of the ecosystem, not as components of fisheries' stocks. While acknowledging that MPAs may be used to conserve specific species of fishes (for example threatened and endangered species) in MPAs, we primarily need to understand their contribution to overall biodiversity, their function as consumers (Ferguson et al., 2016, Rhoades et al., 2019) and in other species interactions, and their role generally in ecosystem processes. Research is developing in NSW to fill this gap, but there are as yet very few studies in the literature.

The second gap that arises from a focus on fishes is that there are fewer studies on other organisms, particularly foundational habitat formers. Organisms such as kelp, corals, seagrasses, shellfish or sponges form the basic structure of coastal habitats, and in turn affect many of the other characteristics of those ecosystems, including fish communities (Harasti et al., 2018a). The importance of such foundation species for ecosystems is increasingly broadly recognised (Angelini et al., 2011), but our understanding of the impact of MPAs on these habitat formers in NSW is still not well known in NSW. The responses of foundation species to management actions are likely to take longer than for fishes (Babcock et al., 2010).

4.2.2 Broader ecosystem properties or processes

A second major gap is that there are few studies that address the role of MPAs on ecosystem processes or functions, as opposed to population, community or ecosystem structure. That is, we need to better understand how NSW MPAs affect the underlying dynamics of the system, which will drive the abundance, size structure or biodiversity of the organisms we are trying to conserve.

Two examples, discussed in more detail elsewhere in the review, illustrate this issue: i) predator driven trophic cascades and ii) resilience to climate change. With respect to the first issue, global and Australian evidence shows that no-take areas can enhance abundance of large predators, allowing kelp forests to re-establish. In NSW, although long term studies of algal and urchin barren abundance are emerging (Glasby and Gibson, 2020), other than a few studies relatively soon after the establishment of many NSW Marine Parks (Edgar et al., 2009, Edgar and Stuart-Smith, 2009, though see Stuart-Smith et al., 2017), we have little data that matches urchin, kelp and predator abundance at the same time and place over appropriate temporal and spatial scales. Moreover, we know of no published (noting Della Marta, *in review*) process studies that directly address the key mechanistic question of whether predation rates in MPAs (particularly in sanctuary zones) are greater than in fished areas, and sufficient to control urchin abundance and re-establish kelp forests.

Second, we know little about how removing one stressor (fishing) in NSW MPAs enhances resilience against other stressors, for example the consequences of climate change. This is a complex area of science, with evidence for and against enhanced resilience against ocean warming in no-take areas globally or elsewhere in Australia (Bates et al., 2019). Though studies are in progress (M. Coleman, *pers. comm*.), there is little published work yet on this issue in NSW. The "tropicalisation" now occurring in northern NSW (Vergés et al., 2016) may provide an ideal opportunity to address this issue, for example by addressing whether increased predation by large piscivores in sanctuary zones, or increased fishing of tropical migrants outside of sanctuary zones, can slow the warming induced southward advance of tropical and sub-tropical fishes.

4.2.3 Principles for filling knowledge gaps

Identification of these knowledge gaps addresses specific science that can be done to better assess the effects of MPAs. However, more general issues/principles for filling knowledge gaps are also worth briefly considering. First, experimental (manipulative) studies (e.g., Rhoades et al., 2019), rather than just observational or descriptive ones, are critical for an understanding of the effects of MPAs on ecosystem processes. Ideally – as with descriptive studies – these should be done across different zones in MPAs and in different habitat types (e.g., estuaries versus coastal). This would make more effective use of MPAs as scientific reference sites but may also require changes in regulatory or management guidelines. Second, given that NSW has a network of Marine Parks, there is an opportunity to use specific parks within that network to fill specific knowledge gaps. One such example follows from 4.2.2 above; that is, use the "tropicalisation" occurring in the SIMP to understand the potential for enhanced resilience against climate change in Marine Parks. Another example is to choose specific parks to understand and exemplify impacts on specific habitats, such as soft sediment communities.

Finally, while the following are not knowledge gaps that flow directly from the evidence reviewed above, three additional points are worth highlighting:

4.2.4 Social, cultural and economic evidence

While this paper focuses on biological and ecological studies that address the primary purpose of Marine Parks in NSW, MPAs in the State have a variety of additional purposes and values, particularly social, cultural and economic ones. An evaluation of social, cultural and economic parameters is beyond the scope of this review, but our understanding is that there is considerably less data on these issues than on biophysical or ecological ones (Yates et al., 2019). Additional studies in these areas are needed, both in their own right and for how they interact or align with biological and ecological considerations (Turnbull et al., *in press*. A review(s) of NSW MPAs and socio-economic parameters, analogous to this paper, would be a worthwhile addition to the evidence base for managing NSW MPAs, especially given the critical importance of these issues for the practical management of MPAs (Yates et al., 2019)

4.2.5 Additional management tools

The management of MPAs in NSW utilises a number of tools beyond restrictions on fishing *via* zoning regulations (Sect 3.1). These include, for example, restrictions/controls on boat anchoring, restrictions on damaging of habitat and aquatic vegetation, and public engagement *via* signage and education within Marine Parks. With the exception of studies of the impact and management of boat moorings (e.g., Demers et al., 2013; also see Macolino et al., 2019 and references therein), there is relatively little evidence that speaks to how these other management tools affect the ecological parameters of MPAs considered here. Additional evidence in this regard would be welcome.

4.2.6 Complementary management regimes

In their Audit, Beeton et al. (2012) recommended that "the current system of marine parks as established in NSW be maintained and mechanisms be found for enhancing the protection of biodiversity in the identified gaps, namely within the Hawkesbury and Twofold Shelf marine bioregions". The Audit also proposed a fully integrated approach to managing the NSW Marine Estate. Such an approach would include protected areas designated as Marine Parks or Aquatic Reserves that are zoned along the lines that are currently used for conservation of biodiversity and ecosystem function, fisheries or other resource management tools, management of pollution, and the range of other management approaches or tools noted early on in this paper. However, while an integrated approach is desirable and indeed underpins the overall MEMA strategy, the more recent science reviewed here since Beeton et al. (2012) supports the conclusions of the Audit, that is: that the current network of NSW MPAs, with effective zoning restrictions, established on a bioregional basis and applying the CAR principles, provides a critical component of an integrated approach to the management of the NSW Marine Estate. This network of MPAs enables conservation outcomes that would not otherwise be possible with other management regimes or tools.

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