

## PERSPECTIVE

# Marine protected areas can be useful but are not a silver bullet for kelp conservation

Karen Filbee-Dexter<sup>1,2</sup>  | Samuel Starko<sup>1</sup>  | Albert Pessarrodona<sup>1</sup>  |  
Georgina Wood<sup>1</sup> | Kjell Magnus Norderhaug<sup>2</sup> | Cristina Piñeiro-Corbeira<sup>3</sup>  |  
Thomas Wernberg<sup>1,2</sup> 

<sup>1</sup>School of Biological Sciences and Oceans Institute, University of Western Australia, Perth, Western Australia, Australia

<sup>2</sup>Institute of Marine Research, His, Norway

<sup>3</sup>BioCost Research Group, Facultad de Ciencias, and CICA – Centro Interdisciplinar de Química e Biología, Universidad de A Coruña, A Coruña, Spain

## Correspondence

Karen Filbee-Dexter, School of Biological Sciences and Oceans Institute, University of Western Australia, Perth, WA, Australia.  
Email: [kfilbeedexter@gmail.com](mailto:kfilbeedexter@gmail.com)

## Funding information

Australian Research Council, Grant/Award Number: DP220100650, FT230100214 and LP1931001500; Norges Forskningsråd; Xunta de Galicia, Grant/Award Number: ED481B-2021/095

**Editor:** M. Coleman

## Abstract

Kelp forests are among the most valuable ecosystems on Earth, but they are increasingly being degraded and lost due to a range of human-related stressors, leading to recent calls for their improved management and conservation. One of the primary tools to conserve marine species and biodiversity is the establishment of marine protected areas (MPAs). International commitments to protect 30% of the world's ecosystems are gaining momentum, offering a promising avenue to secure kelp forests into the Anthropocene. However, a clear understanding of the efficacy of MPAs for conserving kelp forests in a changing ocean is lacking. In this perspective, we question whether strengthened global protection will create meaningful conservation outcomes for kelp forests. We explore the benefits of MPAs for kelp conservation under a suite of different stressors, focusing on empirical evidence from protected kelp forests. We show that MPAs can be effective against some drivers of kelp loss (e.g., overgrazing, kelp harvesting), particularly when they are maintained in the long-term and enforced as no-take areas. There is also some evidence that MPAs can reduce impacts of climate change through building resilience in multi-stressor situations. However, MPAs also often fail to provide protection against ocean warming, marine heatwaves, coastal darkening, and pollution, which have emerged as dominant drivers of kelp forest loss globally. Although well-enforced MPAs should remain an important tool to protect kelp forests, successful kelp conservation will require implementing an additional suite of management solutions that target these accelerating threats.

## KEYWORDS

climate change, coastal darkening, conservation, macroalgae, marine heatwaves, nutrients, seaweed, top-down control

## A GLOBAL PUSH FOR MARINE PROTECTION

In 2023, the 198 nation members of the Convention of Biological Diversity ratified the Kunming-Montreal

Global Biodiversity Framework decision. This included the ambitious target of effectively protecting 30% of coastal areas—focusing on habitats of importance for biodiversity, ecosystem function, and services—by establishing systems of protected areas

**Abbreviation:** MPA, marine protected area

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2024 The Authors. *Journal of Phycology* published by Wiley Periodicals LLC on behalf of Phycological Society of America.

and other effective area-based conservation measures (Convention on biological diversity [CBD], 2022). This target follows a clear push to increase the amount of ocean contained in protected areas and to ensure that these protected areas encompass networks of a variety of habitats with high biodiversity (Duarte et al., 2020; Lubchenco & Grorud-Colvert, 2015). Kelp forests—the ecosystems formed by canopy-forming Laminariales and some other brown macroalgae—cover about a third of the world's coastlines (Jayathilake & Costello, 2021) and provide important ecosystem services and functions (United Nations Environmental Programme [UNEP], 2023). Despite their importance to coastal peoples, kelp forests are increasingly threatened by anthropogenic activities and have already experienced wide-scale declines over the past half century (Krumhansl et al., 2016; Wernberg et al., 2019). The escalating global loss of kelp forests has prompted calls for heightened conservation attention on these ecosystems (Feehan et al., 2021; Valckenaere et al., 2023), as demonstrated by the recent launch of the Kelp Forest Challenge, an initiative to protect 3 million hectares of kelp forests by 2040 (Eger et al., 2023).

Marine protected areas (MPAs) are a type of area-based management strategy involving a wide range of potential measures that restrict human activities in coastal or ocean areas, with the general aim of conserving and safeguarding ocean life (SDG4; Gissi et al., 2022). The degree of protection within a MPA can vary widely, ranging from no-access and no-take areas where some human activities are prohibited to partially protected areas where most activities are allowed to different degrees (Grorud-Colvert et al., 2021). Fishing is commonly regulated within no-take MPAs, along with other direct pressures such as harvesting, dredging, anchoring, dumping, and construction (Kriegl et al., 2021). Marine protected areas—and in particular, no-take marine reserves—can be effective at increasing abundances of fished or other harvested species and often support larger numbers of bigger and higher trophic level fish compared to exploited areas (Coleman et al., 2015; Gill et al., 2017; Pendleton et al., 2018). In fact, common measures of MPA effectiveness include total fish biomass, fish species richness, and number of large fishes, whereas measures such as habitat health or abundance of foundation species including kelps and seagrasses are less often considered (Edgar et al., 2014; Lester et al., 2009). Consequently, there is considerably less evidence that MPAs contribute toward habitat conservation and protection of marine foundation species beyond directly targeted species (Bruno et al., 2019; Strain et al., 2019).

Despite much-welcomed prospects of a strengthened ambition to conserve kelp forests, the conservation efficacy of policies aimed at rapidly increasing the extent of protection has been questioned (Agardy et al., 2003; Costello & Ballantine, 2015). Area-based

protection in the marine environment is known to generate variable conservation and socioeconomic benefits, as “protection” comes in a wide range of shapes and sizes (Kriegl et al., 2021; Relano & Pauly, 2023). The concept of area-based protection and the underlying mechanisms for its efficacy have been developed in terrestrial systems and applied often in marine systems to reduce overfishing. Moreover, MPAs have often been designed to maintain the status quo of a given ecosystem, but their conservation goals and pressures may become increasingly misaligned as novel threats emerge as dominant drivers of ecosystem change. For example, MPA planning or management typically is not designed to adapt to the effects of warming ocean temperatures and extreme climatic events (Jones et al., 2016), despite these events increasing in frequency and severity as well as their importance in shaping marine ecosystems worldwide (Wernberg et al., 2024). In the face of a global push to protect a greater area of the kelp forest biome, it is, therefore, pertinent to ask: Will more MPAs generate more meaningful conservation outcomes for kelp forests? Here we explore the effectiveness of MPAs for managing key drivers of kelp loss, including mitigating localized threats of kelp harvest, overfishing, nutrient pollution, coastal development, and invasive or range expanding species, as well as global threats associated with accelerating climate change. We discuss how conservation paradigms and protection targets may be challenged in the face of climate change and what new conservation tools may be needed to address large-scale threats such as rising ocean temperatures and marine heatwaves. We contend that, although protection remains a foundational solution in kelp conservation, protecting 30% of the world's kelp forests is not a silver bullet to ensure these habitats will persist and thrive in the coming century.

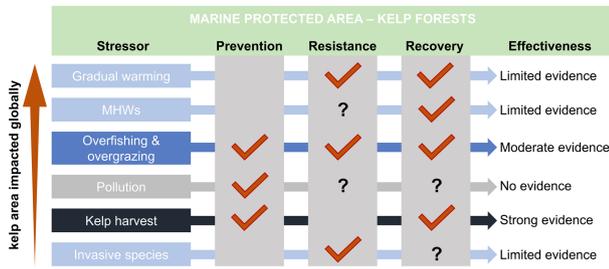
## CAN MPAS EFFECTIVELY CONSERVE KELP FORESTS?

The effectiveness of MPAs in conserving kelp forests has relied on the extent that local anthropogenic pressures directly or indirectly threaten kelp in the region and the extent that the MPA restricts damaging activities. Marine protected areas may benefit kelp directly, by limiting destructive kelp harvest, or indirectly, through increasing biomass of exploited predators of kelp consumers or restricting coastal development that causes poor water quality (Figure 1). In contrast, MPAs can be expected to have limited effectiveness against environmental stressors such as warming and marine heatwaves, which have regional manifestations and cannot be directly mitigated by restricting local human activity (Figure 1). Many threats to kelp forests can have cumulative impacts (Wernberg et al., 2019), so under

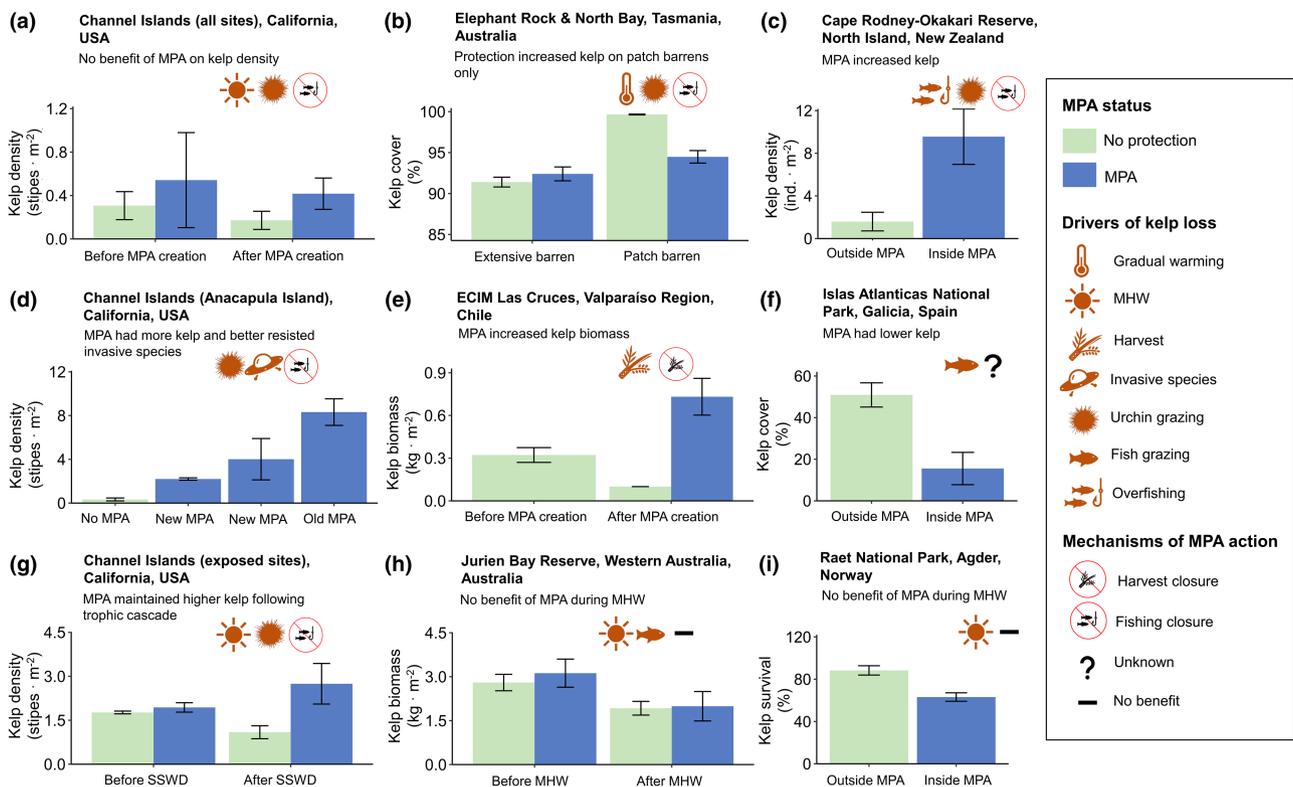
multi-stressor situations, area-based protection of kelp forests could be a way to alleviate pressure from one or more local stressors and build resilience to others (Roberts et al., 2017).

## MPA EFFECTIVENESS AGAINST DIRECT HARVESTING AND OVERFISHING

Globally, harvesting of wild kelp is a minor driver of kelp forest loss, but harvesting can be a locally or regionally important stressor in some areas (e.g., Chile, Norway, France, Japan, and Peru are responsible for 96% of the global wild kelp harvest; UNEP, 2023). Maine protected areas or other effective area-based conservation measures that prevent and/or manage the harvesting of kelp forests can have beneficial conservation outcomes in heavily harvested areas. For instance, areas closed to harvesting in Chile, Norway, and France support higher kelp biomass compared to areas without restrictions, over both short and long timescales (Castilla & Bustamante, 1989; Norderhaug et al., 2020; Sander et al., 2023). The establishment of no-take MPAs in Chile resulted in areas within MPAs having up to three times more biomass of kelp than nearby exploited areas, a difference that was maintained over 2 decades, with spillover of kelp to exploited areas ~5 years following protection (Castilla et al., 2007; Figure 2e). There are



**FIGURE 1** Marine protected areas mitigate different drivers of loss for kelp forests through prevention of stressors, resistance to stressors, or recovery following stressors. Ticks and designations of effectiveness are based on studies of kelp forests within MPAs, and do not include theoretical or modeled scenarios. The scale of kelp area impacted is approximate and based on global estimates of lost kelp areas and associated drivers summarized in Filbee-Dexter et al. (2022). Gradual warming and marine heatwaves often co-occur, so together these stressors are considered associated with the largest kelp area impacted. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 2** Examples of roles of MPAs in kelp conservation: (a) in California across MPAs in the Channel Islands (Malakhoff & Miller, 2021), (b) in Tasmania, within two experimental marine reserves (Ling & Keane, 2021), (c) in northern New Zealand within the Rodney-Okakari reserve (Peleg et al., 2023), (d) in California in one Channel Island (Caselle et al., 2018), (e) in Chile, in no-take MPAs (Castilla et al., 2007), (f) in Spain, in a newly established MPA (Barrientos et al., 2023), (g) in California, in the Channel Islands (Eisaguirre et al., 2020), (h) in Australia, based on kelp survival inside and outside of Jurien Marine Reserve (Wernberg et al., 2016), (i) in southern Norway, in six sites within Raet National Park compared to three reference sites outside (Filbee-Dexter et al., 2020). Drivers of kelp loss are shown in gray symbols (orange online) and mechanisms through which an MPA was effective are shown in black symbols. [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

also examples of kelp harvesting that cause little to no damage to the ecosystem. First Nations communities in British Columbia, Canada, use sustainable systems of traditional harvesting, and companies in South Africa and Namibia sustainably collect beach wrack, which has been shown to cause no declines in biomass or the health of the system (Krumhansl et al., 2017; Sander et al., 2023). This suggests MPAs may not increase kelp abundance in areas with sustainable harvesting practices.

Overfishing can deplete the abundance of top predators, releasing predator pressure on herbivores (e.g., sea urchins or herbivorous fish) that can then overgraze kelp (Filbee-Dexter & Scheibling, 2014; Steneck et al., 2002). Marine protected areas can be an effective conservation tool to prevent overfishing and rebuild predator populations, with cascading effects down the food chain and spillover effects to surrounding habitats (Harrison et al., 2020). This particularly applies to large no-take MPAs (e.g., marine reserves) with well-enforced compliance, that are over a decade old, and that are isolated by habitat boundaries (Edgar et al., 2014). Perhaps one of the most well-known examples of an MPA leading to protection and recovery of kelp forests is the Cape Rodney-Okakari reserve in northern New Zealand, an area where overfishing drove historical kelp declines (Peleg et al., 2023; Figure 2c). By mitigating fishing pressure, this MPA increased the fish and invertebrate predators of sea urchins, which in turn decreased urchin abundances and destructive grazing of kelp forests (Babcock et al., 2010; Leleu et al., 2012). Kelp forests in the reserve compared to nearby fished sites were more stable and abundant and increased in cover over the 22-year monitoring period, suggesting that long-term protection can increase resistance to grazing and enhance kelp recovery (Peleg et al., 2023). In Tasmania, there is evidence that protecting large predatory spiny lobsters could help prevent further shifts to sea urchin barrens (Ling, Johnson, Frusher, et al., 2009). In the California Channel Island MPAs, increases in the urchin predators California sheephead fish and spiny lobster led to reduced overgrazing in some sites and denser native kelp forests (Eisaguirre et al., 2020). This also increased resistance to invasion by *Sargassum horneri* compared to fished sites (Caselle et al., 2018) and suggests that restricted fishing can maintain and recover kelp forests and increase resistance to other drivers of change (Figure 2d). However, across all sites surveyed in the Channel Islands Long-term Ecological Monitoring, there have been no overwhelming increases in kelp forests nor clear overall reductions in urchin populations within MPAs compared to outside MPAs (Malakhoff & Miller, 2021; Figure 2a). Although here we focus on whether MPAs protect kelp foundation species, MPAs can also have strong impacts on associated fish communities (extensively reviewed by others, for example, Bosch et al., 2022;

Edgar et al., 2014; Ziegler et al., 2023), which can alter ecosystem functioning and enhance societal benefits of kelp forests within MPAs (Caselle et al., 2015).

The effects of predator protection on kelp forest abundance are often context-dependent and location-specific and depend on the effectiveness of MPAs in restoring predator populations and the strength of top-down control, as well as other factors (Malakhoff & Miller, 2021; Shears et al., 2008). As such, protecting predators may not always lead to effects consistent with a simple top-down trophic model. Marine protected areas may have limited capacity to rebuild large mobile finfish populations with ranges that greatly exceeds the area protected (Breen et al., 2015). There is little to no evidence that MPAs (even if fully enforced) can fully recover depleted coastal cod stocks (Morris et al., 2014), which drove the collapse of kelp forests in the 1960s and 1970s in the Gulf of Maine and Norway (Norderhaug et al., 2021; Steneck et al., 2013). There is evidence that MPAs can positively increase the size and abundance of coastal cod in some areas (Moland et al., 2013), yet complete closures of the fishery in Canada and USA have not recovered the stock. Sea otters are also other important predators of urchins (Estes et al., 1978), and their declines are linked to lost kelp forests in parts of Alaska, British Columbia, and Russia. Yet sea otter conservation strategies do not involve establishing protected areas but rely on hunting bans and reintroductions (Larson et al., 2015). Further, predator populations may take several years or even decades to rebuild to the extent necessary for trophic cascades to occur and recover kelp forests. Newly established MPAs around one Channel Island in California have not shown reduced grazing pressure and resistance to invasive species compared to long-term MPAs (Caselle et al., 2018). In Spain, kelp forests within a newly established and lightly protected MPA experienced higher fish (*Sarpa salpa*) grazing pressure compared with kelp forests outside, leading to unexpectedly lower kelp forest biomass within the MPA compared to reference sites (Barrientos et al., 2023; Figure 2f). The higher abundances of fish likely are not explained by the MPA, as these fish have low commercial interest in the region, so the mechanism for this decline in kelp is unclear (Barrientos et al., 2022). It is evident that MPAs without clear goals, with weak regulations, and which are not properly enforced (i.e., “paper parks”) will not recover kelp forests (Edgar et al., 2014; Grorud-Colvert et al., 2021).

The strength of top-down control by MPAs can be mediated by numerous biotic and abiotic factors (e.g., environmental stressors, food web complexity, prey behavior; Edgar et al., 2014, Grorud-Colvert et al., 2021). Comparisons among reserves and adjacent fished sites in New Zealand's North Island (including the Cape Rodney-Okakari reserve and five more recently established reserves) revealed variation in the effectiveness

of the MPA at rebuilding fish and invertebrate predators of urchins and therefore, the effectiveness of the MPA at rebuilding kelp forests was associated with regional and local-scale gradients of sediments and wave exposure (Edgar et al., 2017; Shears et al., 2008). Furthermore, across both reserve and non-reserve sites in northern New Zealand, the densities and extent of sea urchin barrens formed by the sea urchin *Centrostephanus rodgersii* has increased significantly over the past 22 years, which has coincided with ocean warming. This suggests that MPA-driven recovery of predators may not prevent outbreaks of destructive grazing by these subtropical species (Balemi & Shears, 2023). In Tasmania, experimentally increasing lobsters by establishing closed fishing areas and translocating ~1000 large lobsters to each area was not enough to recover the kelp forest in extensive barrens after 12 years (Ling & Keane, 2021; Figure 2b). This suggests that MPAs cannot easily recover the kelp once the ecosystem has shifted to a barrens state (Filbee-Dexter & Scheibling, 2014; Ling, Johnson, Frusher, et al., 2009). In some regions (e.g., the NE Atlantic, Western Australia), kelp forests are mainly structured by non-trophic factors (e.g., climate, wave exposure, reef complexity), and expectations for kelp recovery in MPAs designed to restrict fishing pressure may consequently be limited.

## MPA EFFECTIVENESS AGAINST REDUCED WATER QUALITY

Reduced water clarity (coastal darkening) and pollution are important drivers of kelp forest loss (Frigstad et al., 2023; Gorman & Connell, 2009; Tait et al., 2021). There is little to no evidence that MPAs protect kelp forests from these drivers. Marine protected areas may theoretically be effective in mitigating localized pollution by restricting certain polluting activities, such as aquaculture farming, sewage outlet discharge, and coastal developments that cause poor water quality. However, water quality issues in coastal areas tend to be highly influenced by pollutants derived from land-based sources, some of which are located upstream in watersheds and wetlands and can include urban, mining, industrial, and agricultural pollution (Mora & Sale, 2011). As a result, the ability of MPAs to mitigate poor coastal water quality and increased sedimentation is often limited (Beliaeff & Pelletier, 2011; Brodie & Waterhouse, 2012; Connell, 2007). For example, the abundance and species richness of seagrass meadows at 55 sites across the Philippines was not related to level of marine protection but significantly related to land-use practices due to impacts from farmland and urbanization (Quiros et al., 2017). Integrating catchment-wide management actions (e.g., restricting the use and runoff of agricultural pollutants, erosion management)

with local-based management within MPAs may be a more effective way to combat poor water quality (Connell, 2007; Sander et al., 2023) by, for example, designing MPAs to be adjacent to national parks where development and catchment issues are limited. Furthermore, some sources of poor water quality that have impacted kelp forests are not due to local human impacts but to broader climate change, such as increased sedimentation from extreme flooding, coastal erosion, melting glaciers, and crumbling permafrost (Davis et al., 2022; Filbee-Dexter et al., 2019). These drivers of kelp loss will not be effectively mitigated by area-based protection measures.

## MPA EFFECTIVENESS AGAINST CLIMATE CHANGE STRESSORS

Compared to threats of harvest and overfishing, MPAs are often less effective against the threat posed by broader-scale environmental changes, such as warming oceans and increased extreme events (Cooley et al., 2022). This is critical, as climate change has become the dominant driver of kelp loss globally, both through gradual changes in temperature and increases in the frequency and severity of marine heatwaves (Wernberg et al., 2024). At the warm range edges of kelp forests, where sea temperatures now regularly exceed thermal thresholds for kelp mortality (Coleman et al., 2022; Wernberg et al., 2024), protection will provide little benefit. In Australia, there was no difference in kelp survival inside and outside of a marine park during the 2011 marine heatwave (Wernberg et al., 2016; Figure 2h). In California, researchers observed no difference in kelp forest resistance or recovery to the 2014–2016 Northeast Pacific heatwave across a network of 124 MPAs (Smith et al., 2023). This contrasts expectations that MPA networks can promote recovery via spillover and dispersal from nearby populations (Harrison et al., 2020). In southern Norway, kelp forests within reserves did not have higher survival during a marine heatwave compared to outside reserves (Raet National Park; Filbee-Dexter et al., 2020; Figure 2i). Marine heatwaves are increasing in frequency and severity in these areas (Oliver et al., 2018), yet recovery trajectories of degraded kelp forests are often slow, suggesting effective rebuilding is unlikely. Protecting kelp forests from these stressors requires an immediate reduction of greenhouse gas emissions and an aggressive phase out of fossil fuels (Cooley et al., 2022). Moreover, other more transformative, active approaches, such as targeting climate refuges for protection (Arafeh-Dalmau et al., 2023) or using assisted migration or evolution instead of passive protection (Coleman et al., 2020), will likely be required to ensure that kelp forests remain resilient into a warming future. Conversely, establishing MPAs that

effectively protect kelp forests from other stressors may be one way to reduce greenhouse gas emissions and mitigate these climate change impacts, because kelp forests can store and sequester atmospheric carbon in some areas (Jankowska et al., 2022; Pessarrodona et al., 2023).

Kelp forests may still be protected from rising ocean temperatures if MPAs abate other stressors, which can increase resilience to some level of warming (Hamilton et al., 2022), but empirical evidence of MPA-fostered resistance to gradual warming is limited (Bates et al., 2019). Mass die offs of foundation species are regularly documented in MPAs around the world and the role of MPAs in building resilience to climate change has been debated for other marine ecosystems, such as coral reefs (Graham et al., 2020; Selig et al., 2012). Yet, there is some evidence that MPAs could protect kelp forests from climatic stressors by potentially increasing kelp resistance and resilience to the indirect effects of climate change, which arise when warming impacts kelp through climate-mediated shifts in competitors or grazers or increases in consumptive pressure (e.g., Ling, Johnson, Ridgeway, et al., 2009; Vergés et al., 2016). In these cases, maintaining a more intact food web (e.g., high predator biomass) can help to dampen these impacts through mechanisms similar to those described above for top-down control. Long-term monitoring from the Channel Islands, California, showed that outbreaks of sea urchin overgrazing following the 2014 marine heatwave and consequent die-off of sunflower sea stars were less common inside MPAs compared to outside MPAs (Eisaguirre et al., 2020). This resilience was because other sea urchin predators, namely California sheephead fish and spiny lobster, were more abundant inside MPAs, providing trophic redundancy that protected the kelp forest (Eisaguirre et al., 2020; Figure 2g). Multi-decadal records from reef surveys across Tasmania have shown an increase in seaweed forest canopy cover (including kelp species) following protection compared to an increase in turf cover and tropicalized reef communities in exploited regions, despite background warming occurring in both (Bates et al., 2017). This increase in kelp was attributed to more carnivorous fishes and lobsters and fewer herbivores within reserves compared to outside reserves, which prevented or reduced climate-driven shifts to turf algal reefs.

## RETHINKING KELP PROTECTION

Establishing MPAs is a low-risk strategy for kelp forest conservation and should continue to be considered a foundational management approach to mitigate the impacts of local stressors and increase kelp population resilience overall. Yet ongoing external stressors

largely prevent positive effects to kelp forests from MPAs in many areas. In these areas, reducing pollution and/or mitigating climate change are the most important actions for conserving kelp forests. The Kunming-Montreal Global Biodiversity Framework 2030 target describes effectively managing and conserving coastal ecosystems through systems of protected areas and other effective area-based conservation measures that are integrated into wider landscapes. Given the limitations of current MPAs in abating land-based water quality stressors for kelp forests, other area-based measures that span coastal and terrestrial boundaries, such as reduced terrestrial wastewater, will be critical to implement. Marine protected areas should also be designed to manage or mitigate the impacts of ocean warming, tropicalization, and/or increased severe events. Although principles that promote resilience to climate change, such as long-term goals and adaptive management, are often embedded in MPAs, explicit climate change mitigation and adaptation strategies are still uncommon (Lopazanski et al., 2023). Frameworks for designing “climate-smart” MPAs—which promote connectivity and gene exchange among populations, incorporate adjustments to MPA boundaries to reflect changing climatic conditions, target protection of blue carbon habitats that enhance CO<sub>2</sub> drawdown, and integrate knowledge of climate refugia that might enhance recovery potential—are beginning to emerge (Arafah-Dalmau et al., 2023; Coleman et al., 2013, 2017; Jankowska et al., 2022). However, these frameworks will still not be able to fully mitigate the impacts of climate change on kelp forests.

Importantly, to conserve kelp forests, MPAs must be implemented alongside a wider array of tools that include active interventions, such as restoration (CBD, 2022; Eger et al., 2022). Moreover, “future-proofing” measures, such as assisted migration and adaptation, are also likely to be key to mitigating the direct impacts of climate change over the next century (Coleman et al., 2020; Wood et al., 2019). Marine protected areas may facilitate and even enhance both the implementation and outcomes of these interventions. Choosing MPAs as restoration sites could improve survival and kelp recruitment by affording increased protection from other local stressors (Cebrian et al., 2021). Additionally, restoration initiatives can yield more co-benefits (e.g., enhanced fish stocks) in kelp forests within MPAs compared to those in unprotected areas (Hopf et al., 2022). Despite these benefits, the local-based targets and inflexibility in adjusting boundaries that are embedded in many MPAs management plans can hamper the implementation of novel management strategies. For example, requiring permits within MPAs can constitute a significant barrier to conducting kelp restoration activities in some

jurisdictions (Wood et al., 2024). A key challenge moving forward will thus be to ensure that MPA delimitation does not prevent other, perhaps more urgent and impactful measures where they are needed. This predominantly bureaucratic issue is somewhat analogous to the widespread issue of “paper parks” that have been established alongside increased marine protection mandates and ultimately weaken conservation impacts (Relano & Pauly, 2023). This illustrates the need to review MPA management plans, designs, and implementation frequently to ensure they adapt to climate change and best facilitate conservation targets.

## CONCLUSIONS

One of the major strategies for securing our ocean ecosystems is to protect 30% of marine areas by 2030. As one of the most widespread, valuable, and biodiverse coastal ecosystems, kelp forests have a key role to play in the global protection of biodiversity and ecological function. Yet, it is unclear how effective protection will be for maintaining and rebuilding kelp forests over the next century. Lack of monitoring and mapping of most of the world's kelp forests and mixed enforcement of MPAs make it difficult to assess the true effectiveness of protection of kelp. Yet, historically there are only a few examples of MPAs successfully recovering kelp or avoiding loss. Although it is evident that long-term protection can be beneficial to kelp forests, particularly in areas where there is strong top-down control, to date MPAs have had limited success in protecting kelp against poor water quality and appear to provide little to no immediate protection against the effects of climate change. Although we acknowledge the need for marine protection, only a strong reduction in fossil fuel emissions will prevent the impacts of climate change on kelp forests, which are increasingly becoming a main threat to these ecosystems globally. To conserve kelp forests, along with a range of other ecological assets supported by these ecosystems, we will need a different management toolkit, one that reduces land-based pollution and coastal darkening and boosts kelp resilience to climate change.

## AUTHOR CONTRIBUTIONS

**Karen Filbee-Dexter:** Conceptualization (equal); data curation (equal); funding acquisition (equal); supervision (equal); visualization (equal); writing – original draft (lead); writing – review and editing (lead). **Samuel Starko:** Conceptualization (equal); data curation (lead); visualization (equal); writing – original draft (supporting); writing – review and editing (equal). **Albert Pessarrodona:** Conceptualization (equal); data curation (supporting); writing – original draft (supporting); writing – review and editing (equal). **Georgina**

**Wood:** Conceptualization (equal); data curation (supporting); writing – original draft (supporting); writing – review and editing (equal). **Kjell Magnus Norderhaug:** Conceptualization (supporting); writing – original draft (supporting); writing – review and editing (equal). **Cristina Piñeiro-Corbeira:** Conceptualization (supporting); data curation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (equal). **Thomas Wernberg:** Conceptualization (equal); formal analysis (supporting); funding acquisition (equal); supervision (equal); writing – original draft (supporting); writing – review and editing (equal).

## ACKNOWLEDGMENTS

Open access publishing facilitated by The University of Western Australia, as part of the Wiley - The University of Western Australia agreement via the Council of Australian University Librarians.

## FUNDING INFORMATION

Australian Research Council LP1931001500, DP220100650 (TW, KF-D), FT230100214 (KF-D). Norwegian Research Council GEcoKelp (TW, KF-D, GW, KMN) BlueArc (KF-D, TW, KMN). Forrest Research Foundation (SS). Xunta de Galicia Grant ED481B-2021/095 (CP-C).

## ORCID

*Karen Filbee-Dexter*  <https://orcid.org/0000-0001-8413-6797>

*Samuel Starko*  <https://orcid.org/0000-0002-9604-9188>

*Albert Pessarrodona*  <https://orcid.org/0000-0002-6057-9937>

*Cristina Piñeiro-Corbeira*  <https://orcid.org/0000-0002-3355-3096>

*Thomas Wernberg*  <https://orcid.org/0000-0003-1185-9745>

## REFERENCES

- Agardy, T., Bridgewater, P., Crosby, M. P., Day, J., Dayton, P. K., Kenchington, R., Laffoley, D., McConney, P., Murray, P. A., Parks, J. E., & Peau, L. (2003). Dangerous targets? Unresolved issues and ideological clashes around marine protected areas. *Aquatic Conservation*, 13, 353–367.
- Arafeh-Dalmau, N., Olguin-Jacobson, C., Bell, T. W., Micheli, F., & Cavanaugh, K. C. (2023). Shortfalls in the protection of persistent bull kelp forests in the USA. *Biological Conservation*, 283, 110133.
- Babcock, R. C., Shears, N. T., Alcala, A. C., Barrett, N. S., Edgar, G. J., Lafferty, K. D., McClanahan, T. R., & Russ, G. R. (2010). Decadal trends in marine reserves reveal differential rates of change in direct and indirect effects. *Proceedings of the National Academy of Sciences of the United States of America*, 107, 18256–18261.
- Balemi, C. A., & Shears, N. T. (2023). Emergence of the subtropical sea urchin *Centrostephanus rodgersii* as a threat to kelp forest ecosystems in northern New Zealand. *Frontiers in Marine Science*, 10, 1224067.

- Barrientos, S., Barreiro, R., & Piñeiro-Corbeira, C. (2023). Paradoxical failure of *Laminaria ochroleuca* (Laminariales, Phaeophyceae) to consolidate a kelp forest inside a Marine National Park. *European Journal of Phycology*, 58, 72–82.
- Barrientos, S., Piñeiro-Corbeira, C., & Barreiro, R. (2022). Temperate kelp forest collapse by fish herbivory: A detailed demographic study. *Frontiers in Marine Science*, 9, 817021.
- Bates, A. E., Cooke, R. S. C., Duncan, M. I., Edgar, G. J., Bruno, J. F., Benedetti-Cecchi, L., Côté, I. M., Lefcheck, J. S., Costello, M. J., Barrett, N., Bird, T. J., Fenberg, P. B., & Stuart-Smith, R. D. (2019). Climate resilience in marine protected areas and the 'Protection Paradox.' *Biological Conservation*, 236, 305–314.
- Bates, A. E., Stuart-Smith, R. D., Barrett, N. S., & Edgar, G. J. (2017). Biological interactions both facilitate and resist climate-related functional change in temperate reef communities. *Proceedings of the Royal Society B: Biological Sciences*, 284, 20170484.
- Beliaeff, B., & Pelletier, D. (2011). A general framework for indicator design and use with application to the assessment of coastal water quality and marine protected area management. *Ocean and Coastal Management*, 54, 84–92.
- Bosch, N. E., Monk, J., Goetze, J., Wilson, S., Babcock, R. C., Barrett, N., Clough, J., Currey-Randall, L. M., Fairclough, D. V., Fisher, R., Gibbons, B. A., Harasti, D., Harvey, E. S., Heupel, M. R., Hicks, J. L., Holmes, T. H., Huvneers, C., Ierodiaconou, D., Jordan, A., ... Langlois, T. J. (2022). Effects of human footprint and biophysical factors on the body-size structure of fished marine species. *Conservation Biology*, 36, e13807.
- Breen, P., Posen, P., & Righton, D. (2015). Temperate marine protected areas and highly mobile fish: A review. *Ocean and Coastal Management*, 105, 75–83.
- Brodie, J., & Waterhouse, J. (2012). A critical review of environmental management of the 'not so Great' Barrier Reef. *Estuarine, Coastal and Shelf Science*, 104–105, 1–22.
- Bruno, J. F., Côté, I. M., & Toth, L. T. (2019). Climate change, coral loss, and the curious case of the parrotfish paradigm: Why don't marine protected areas improve reef resilience? *Annual Review of Marine Science*, 11, 307–334.
- Caselle, J. E., Davis, K., & Marks, L. M. (2018). *Marine management affects the invasion success of a non-native species in a temperate reef system in California, USA*. Blackwell Publishing Ltd.
- Caselle, J. E., Rassweiler, A., Hamilton, S. L., & Warner, R. R. (2015). Recovery trajectories of kelp forest animals are rapid yet spatially variable across a network of temperate marine protected areas. *Scientific Reports*, 5, 14102.
- Castilla, J. C., & Bustamante, R. H. (1989). Human exclusion from rocky intertidal of Las Cruces, central Chile: Effects on *Durvillaea antarctica* (Phaeophyta, Durvilliales). *Marine Ecology Progress Series*, 50, 203–214.
- Castilla, J. C., Campo, M. A., & Bustamante, R. H. (2007). Recovery of *Durvillaea antarctica* (Durvilliales) inside and outside Las Cruces Marine Reserve, Chile. *Ecological Applications*, 17, 1511–1522.
- Cebrian, E., Tamburello, L., Verdura, J., Guarnieri, G., Medrano, A., Linares, C., Hereu, B., Garrabou, J., Cerrano, C., Galobart, C., & Fraschetti, S. (2021). A roadmap for the restoration of Mediterranean macroalgal forests. *Frontiers in Marine Science*, 8, 709219.
- Coleman, M. A., Bates, A. E., Stuart-Smith, R. D., Malcolm, H. A., Harasti, D., Jordan, A., Knott, N. A., Edgar, G. J., & Kelaher, B. P. (2015). Functional traits reveal early responses in marine reserves following protection from fishing. *Diversity and Distributions*, 21, 876–887.
- Coleman, M. A., Cetina-Heredia, P., Roughan, M., Feng, M., van Sebille, E., & Kelaher, B. P. (2017). Anticipating changes to future connectivity within a network of marine protected areas. *Global Change Biology*, 23, 3533–3542.
- Coleman, M. A., Palmer-Brodie, A., & Kelaher, B. P. (2013). Conservation benefits of a network of marine reserves and partially protected areas. *Biological Conservation*, 167, 257–264.
- Coleman, M. A., Reddy, M., Nimbs, M. J., Marshall, A., Al-Ghassani, S. A., Bolton, J. J., Jupp, B. P., De Clerck, O., Leliaert, F., Champion, C., Pearson, G. A., Serrão, E. A., Madeira, P., & Wernberg, T. (2022). Loss of a globally unique kelp forest from Oman. *Scientific Reports*, 12, 5020.
- Coleman, M. A., Wood, G., Filbee-Dexter, K., Minne, A., Goold, H., Verges, A., Marzinelli, E., Steinberg, P. D., & Wernberg, T. (2020). Restore or redefine: Future trajectories for restoration. *Frontiers in Marine Science*, 7, 237.
- Connell, S. (2007). Water quality and the loss of coral reefs and kelp forests: Alternative states and the influence of fishing. In S. D. Connell & B. M. Gillanders (Eds), *Marine Ecology* (pp. 556–568). Oxford University Press.
- Convention on Biological Diversity. (2022). *Decision adopted by the conference of the parties to the Convention on Biological Diversity 15/4*. Kunming-Montreal Global Biodiversity Framework.
- Cooley, S., Schoeman, D., Bopp, L., Boyd, P., Donner, S., Ghebrehiwet, D. Y., Ito, S.-I., Kiessling, W., Martinetto, P., Ojea, E., Racault, M.-F., Rost, B., & Skern-Mauritzen, M. (2022). Chapter 3: Oceans and coastal ecosystems and their services. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of the WGII to the 6th assessment report of the Intergovernmental Panel on Climate Change, IPCC AR6 WGII* (pp. 379–550). Cambridge University Press. <https://doi.org/10.1017/9781009325844.005>
- Costello, M. J., & Ballantine, B. (2015). Biodiversity conservation should focus on no-take marine reserves: 94% of marine protected areas allow fishing. *Trends in Ecology & Evolution*, 30, 507–509.
- Davis, T. R., Larkin, M. F., Forbes, A., Veenhof, R. J., Scott, A., & Coleman, M. A. (2022). Extreme flooding and reduced salinity causes mass mortality of nearshore kelp forests. *Estuarine, Coastal and Shelf Science*, 275, 107960.
- Duarte, C. M., Agusti, S., Barbier, E., Britten, G. L., Castilla, J. C., Gattuso, J. P., Fulweiler, R. W., Hughes, T. P., Knowlton, N., Lovelock, C. E., Lotze, H. K., Predragovic, M., Poloczanska, E., Roberts, C., & Worm, B. (2020). Rebuilding marine life. *Nature*, 580, 39–51.
- Edgar, G. J., Stuart-Smith, R. D., Thomson, R. J., & Freeman, D. J. (2017). Consistent multi-level trophic effects of marine reserve protection across northern New Zealand. *PLoS ONE*, 12, e0177216.
- Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., Barrett, N. S., Becerro, M. A., Bernard, A. T. F., Berkhout, J., Buxton, C. D., Campbell, S. J., Cooper, A. T., Davey, M., Edgar, S. C., Försterra, G., Galván, D. E., Irigoyen, A. J., Kushner, D. J., ... Thomson, R. J. (2014). Global conservation outcomes depend on marine protected areas with five key features. *Nature*, 506, 216–220.
- Eger, A. M., Aguirre, J. D., Altamirano, M., Arafeh-Dalmau, N., Arroyo, N. L., Bauer-Civiello, A. M., Beas-Luna, R., Bekkby, T., Bennett, S., Bernal, B., Blain, C. O., Boada, J., Branigan, S., Bursic, J., Choi, C. G., Connell, S. D., Edward, C., Earp, H. S., Eddy, N., ... Vergés, A. (2023). *The kelp forest challenge: A collaborative global movement to protect and restore 4 million hectares of kelp forests*. Springer Science and Business Media B.V.

- Eger, A. M., Marzinelli, E. M., Christie, H., Fagerli, C. W., Fujita, D., Gonzalez, A. P., Hong, S. W., Kim, J. H., Lee, L. C., McHugh, T. A., Nishihara, G. N., Tatsumi, M., Steinberg, P. D., & Vergés, A. (2022). Global kelp forest restoration: Past lessons, present status, and future directions. *Biological Reviews*, *97*, 1449–1475.
- Eisaguirre, J. H., Eisaguirre, J. M., Davis, K., Carlson, P. M., Gaines, S. D., & Caselle, J. E. (2020). Trophic redundancy and predator size class structure drive differences in kelp forest ecosystem dynamics. *Ecology*, *101*, e02993.
- Estes, J. E., Smith, N. S., & Palmisano, J. F. (1978). Sea otter predation and community organization in the Western Aleutian Islands, Alaska. *Ecology*, *59*, 822–833.
- Feehan, C. J., Filbee-Dexter, K., & Wernberg, T. (2021). Embrace kelp forests in the coming decade. *Science*, *373*, 863.
- Filbee-Dexter, K., & Scheibling, R. E. (2014). Sea urchin barrens as alternative stable states of collapsed kelp ecosystems. *Marine Ecology Progress Series*, *495*, 1–25.
- Filbee-Dexter, K., Wernberg, T., Barreiro, R., Coleman, M. A., de Bettignies, T., Feehan, C. J., Franco, J. N., Hasler, B., Louro, I., Norderhaug, K. M., Staehr, P. A. U., Tuya, F., & Verbeek, J. (2022). Leveraging the blue economy to transform marine forest restoration. *Journal of Phycology*, *58*, 198–207.
- Filbee-Dexter, K., Wernberg, T., Fredriksen, S., Norderhaug, K. M., & Pedersen, M. F. (2019). Arctic kelp forests: Diversity, resilience and future. *Global and Planetary Change*, *172*, 1–14.
- Filbee-Dexter, K., Wernberg, T., Grace, S. P., Thormar, J., Fredriksen, S., Narvaez, C. N., Feehan, C. J., & Norderhaug, K. M. (2020). Marine heatwaves and the collapse of marginal North Atlantic kelp forests. *Scientific Reports*, *10*, 13388.
- Frigstad, H., Andersen, G. S., Trannum, H. C., McGovern, M., Naustvoll, L.-J., Kaste, Ø., Deininger, A., & Hjermann, D. Ø. (2023). Three decades of change in the Skagerrak coastal ecosystem, shaped by eutrophication and coastal darkening. *Estuarine, Coastal and Shelf Science*, *283*, 108193.
- Gill, D. A., Mascia, M. B., Ahmadi, G. N., Glew, L., Lester, S. E., Barnes, M., Craigie, I., Darling, E. S., Free, C. M., Geldmann, J., Holst, S., Jensen, O. P., White, A. T., Basurto, X., Coad, L., Gates, R. D., Guannel, G., Mumby, P. J., Thomas, H., ... Fox, H. E. (2017). Capacity shortfalls hinder the performance of marine protected areas globally. *Nature*, *543*, 665–669.
- Gissi, E., Maes, F., Kyriazi, Z., Ruiz-Frau, A., Santos, C. F., Neumann, B., Quintela, A., Alves, F. L., Borg, S., Chen, W., da Luz Fernandes, M., Hadjimichael, M., Manea, E., Marques, M., Platjouw, F. M., Portman, M. E., Sousa, L. P., Bolognini, L., Flannery, W., ... Unger, S. (2022). Contributions of marine area-based management tools to the UN sustainable development goals. *Journal of Cleaner Production*, *330*, 129910.
- Gorman, D., & Connell, S. D. (2009). Recovering subtidal forests in human-dominated landscapes. *Journal of Applied Ecology*, *46*, 1258–1265.
- Graham, N. A. J., Robinson, J. P. W., Smith, S. E., Govinden, R., Gendron, G., & Wilson, S. K. (2020). Changing role of coral reef marine reserves in a warming climate. *Nature Communications*, *11*, 2000.
- Grorud-Colvert, K., Sullivan-Stack, J., Roberts, C., Constant, V., Horta e Costa, B., Pike, E. P., Kingston, N., Laffoley, D., Sala, E., Claudet, J., Friedlander, A. M., Gill, D. A., Lester, S. E., Day, J. C., Gonçalves, E. J., Ahmadi, G. N., Rand, M., Villagomez, A., Ban, N. C., ... Lubchenco, J. (2021). The MPA guide: A framework to achieve global goals for the ocean. *Science*, *373*, eabf0861.
- Hamilton, S. L., Gleason, M. G., Godoy, N., Eddy, N., & Grorud-Colvert, K. (2022). Ecosystem-based management for kelp forest ecosystems. *Marine Policy*, *136*, 104919.
- Harrison, H. B., Bode, M., Williamson, D. H., Berumen, M. L., & Jones, G. P. (2020). A connectivity portfolio effect stabilizes marine reserve performance. *Proceedings of the National Academy of Sciences of the United States of America*, *117*, 25595–25600.
- Hopf, J. K., Caselle, J. E., & White, J. W. (2022). *No-take marine protected areas enhance the benefits of kelp-forest restoration for fish but not fisheries*. John Wiley and Sons.
- Jankowska, E., Pelc, R., Alvarez, J., Mehra, M., & Frischmann, C. J. (2022). Climate benefits from establishing marine protected areas targeted at blue carbon solutions. *Proceedings of the National Academy of Sciences of the United States of America*, *119*, e2121705119.
- Jayatilake, D. R. M., & Costello, M. J. (2021). Version 2 of the world map of laminarian kelp benefits from more Arctic data and make it the largest marine biome. *Biological Conservation*, *257*, 109099.
- Jones, K. R., Watson, J. E. M., Possingham, H. P., & Klein, C. J. (2016). Incorporating climate change into spatial conservation prioritisation: A review. *Biological Conservation*, *194*, 121–130.
- Kriegel, M., Elias Ilosvay, X. E., von Dorrien, C., & Oesterwind, D. (2021). Marine protected areas: At the crossroads of nature conservation and fisheries management. *Frontiers in Marine Science*, *8*, 676264.
- Krumhansl, K. A., Bergman, J. N., & Salomon, A. K. (2017). Assessing the ecosystem-level consequences of a small-scale artisanal kelp fishery within the context of climate-change. *Ecological Applications*, *27*, 799–813.
- Krumhansl, K. A., Okamoto, D. K., Rassweiler, A., Novak, M., Bolton, J. J., Cavanaugh, K. C., Connell, S. D., Johnson, C. R., Konar, B., Ling, S. D., Micheli, F., Norderhaug, K. M., Pérez-Matus, A., Sousa-Pinto, I., Reed, D. C., Salomon, A. K., Shears, N. T., Wernberg, T., Anderson, R. J., ... Byrnes, J. E. K. (2016). Global patterns of kelp forest change over the past half-century. *Proceedings of the National Academy of Sciences of the United States of America*, *113*, 13785–13790.
- Larson, S., Bodkin, J., & VanBlaricom, G. R. (2015). *Sea otter conservation*. Academic Press.
- Leleu, K., Remy-Zephir, B., Grace, R., & Costello, M. J. (2012). Mapping habitats in a marine reserve showed how a 30-year trophic cascade altered ecosystem structure. *Biological Conservation*, *155*, 193–201.
- Lester, S., Halpern, B., Grorud-Colvert, K., Lubchenco, J., Ruttenberg, B., Gaines, S., Airamé, S., & Warner, R. R. (2009). Biological effects within no-take marine reserves: A global synthesis. *Marine Ecology Progress Series*, *384*, 33–46.
- Ling, S., & Keane, J. (2021). *Decadal resurvey of long-term lobster experimental sites to inform *Centrostephanus control**. The Institute for Marine and Antarctic Studies.
- Ling, S. D., Johnson, C. R., Frusher, S. D., & Ridgway, K. R. (2009). Overfishing reduces resilience of kelp beds to climate-driven catastrophic phase shift. *Proceedings of the National Academy of Sciences of the United States of America*, *106*, 22341–22345.
- Ling, S. D., Johnson, C. R., Ridgway, K., Hobday, A. J., & Haddon, M. (2009). Climate-driven range extension of a sea urchin: Inferring future trends by analysis of recent population dynamics. *Global Change Biology*, *15*, 719–731.
- Lopazanski, C., Foshay, B., Couture, J. L., Wagner, D., Hannah, L., Pidgeon, E., & Bradley, D. (2023). Principles for climate resilience are prevalent in marine protected area management plans. *Conservation Letters*, *16*, e12972.
- Lubchenco, J., & Grorud-Colvert, K. (2015). Making waves: The science and politics of ocean protection. *Science*, *350*, 382–383.

- Malakhoff, K. D., & Miller, R. J. (2021). After 15 years, no evidence for trophic cascades in marine protected areas. *Proceedings of the Royal Society B: Biological Sciences*, *288*, 20203061.
- Moland, E., Olsen, E. M., Knutsen, H., Garrigou, P., Espeland, S. H., Kleiven, A. R., André, C., & Knutsen, J. A. (2013). Lobster and cod benefit from small-scale northern marine protected areas: Inference from an empirical before–after control–impact study. *Proceedings of the Royal Society B: Biological Sciences*, *280*, 20122679.
- Mora, C., & Sale, P. (2011). Ongoing global biodiversity loss and the need to move beyond protected areas: A review of the technical and practical shortcomings of protected areas on land and sea. *Marine Ecology Progress Series*, *434*, 251–266.
- Morris, C. J., Green, J. M., Snelgrove, P. V. R., Pennell, C. J., & Ollerhead, L. M. N. (2014). Temporal and spatial migration of Atlantic cod (*Gadus morhua*) inside and outside a marine protected area and evidence for the role of prior experience in homing. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*, 1704–1712.
- Norderhaug, K. M., Filbee-Dexter, K., Freitas, C., Birkely, S.-R., Christensen, L., Møllerud, I., Thømar, J., van Son, T., Moy, F., Vázquez Alonso, M., & Steen, H. (2020). Ecosystem-level effects of large-scale disturbance in kelp forests. *Marine Ecology Progress Series*, *656*, 163–180.
- Norderhaug, K. M., Nedreaas, K., Huserbråten, M., & Moland, E. (2021). Depletion of coastal predatory fish sub-stocks coincided with the largest sea urchin grazing event observed in the NE Atlantic. *Ambio*, *50*, 163–173.
- Oliver, E. C. J., Donat, M. G., Burrows, M. T., Moore, P. J., Smale, D. A., Alexander, L. V., Benthuysen, J. A., Feng, M., Sen Gupta, A., Hobday, A. J., Holbrook, N. J., Perkins-Kirkpatrick, S. E., Scannell, H. A., Straub, S. C., & Wernberg, T. (2018). Longer and more frequent marine heatwaves over the past century. *Nature Communications*, *9*, 1324.
- Peleg, O., Blain, C. O., & Shears, N. T. (2023). Long-term marine protection enhances kelp forest ecosystem stability. *Ecological Applications*, *33*, e2895.
- Pendleton, L. H., Ahmadi, G. N., Browman, H. I., Thurstan, R. H., Kaplan, D. M., & Bartolino, V. (2018). *Debating the effectiveness of marine protected areas*. Oxford University Press.
- Pessarrodona, A., Franco-Santos, R. M., Wright, L. S., Vanderklift, M. A., Howard, J., Pidgeon, E., Wernberg, T., & Filbee-Dexter, K. (2023). Carbon sequestration and climate change mitigation using macroalgae: A state of knowledge review. *Biological Reviews*, *98*, 1945–1971.
- Quiros, T. E. A. L., Croll, D., Tershy, B., Fortes, M. D., & Raimondi, P. (2017). Land use is a better predictor of tropical seagrass condition than marine protection. *Biological Conservation*, *209*, 454–463.
- Relano, V., & Pauly, D. (2023). The ‘Paper Park Index’: Evaluating marine protected area effectiveness through a global study of stakeholder perceptions. *Marine Policy*, *151*, 105571.
- Roberts, C. M., O’Leary, B. C., McCauley, D. J., Cury, P. M., Duarte, C. M., Lubchenco, J., Pauly, D., Sáenz-Arroyo, A., Sumaila, U. R., Wilson, R. W., Worm, B., & Castilla, J. C. (2017). Marine reserves can mitigate and promote adaptation to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 6167–6175.
- Sander, G., Karlsson, M., de Bettignies, T., Filbee-Dexter, K., Frangoules, K., Fujita, D., Gundersen, H., Greenhill, L., Pérez-Lloréns, J. L., Meyer-Rodrigues, C., Sundnes, F., & Vásquez, J. A. (2023). Approaches to managing kelp forests. In *Into the blue: Securing a sustainable future for kelp forests* (pp. 102–130). United Nations Environment Programme. <https://wedocs.unep.org/handle/20.500.11822/42255>
- Selig, E. R., Casey, K. S., & Bruno, J. F. (2012). Temperature-driven coral decline: The role of marine protected areas. *Global Change Biology*, *18*, 1561–1570.
- Shears, N. T., Babcock, R. C., & Salomon, A. K. (2008). Context-dependent effects of fishing: Variation in trophic cascades across environmental gradients. *Ecological Applications*, *18*, 1860–1873.
- Smith, J. G., Free, C. M., Lopazanski, C., Brun, J., Anderson, C. R., Carr, M. H., Claudet, J., Dugan, J. E., Eurich, J. G., Francis, T. B., Hamilton, S. L., Mouillot, D., Raimondi, P. T., Starr, R. M., Ziegler, S. L., Nickols, K. J., & Caselle, J. E. (2023). A marine protected area network does not confer community structure resilience to a marine heatwave across coastal ecosystems. *Global Change Biology*, *29*, 5634–5651.
- Steneck, R. S., Graham, M. H., Bourque, B. J., Corbett, D., Eerlandson, J. M., Estes, J. A., & Tegner, M. J. (2002). Kelp forest ecosystems: Biodiversity, stability, resilience and future. *Environmental Conservation*, *29*, 436–459.
- Steneck, R. S., Leland, A., McNaught, D. C., & Vavrinc, J. (2013). Ecosystem flips, locks, and feedbacks: The lasting effects of fisheries on Maine’s kelp forest ecosystem. *Bulletin of Marine Science*, *89*, 31–55.
- Strain, E. M. A., Edgar, G. J., Ceccarelli, D., Stuart-Smith, R. D., Hosack, G. R., & Thomson, R. J. (2019). A global assessment of the direct and indirect benefits of marine protected areas for coral reef conservation. *Diversity and Distributions*, *25*, 9–20.
- Tait, L. W., Thorat, F., Pinkerton, M. H., Thomsen, M. S., & Schiel, D. R. (2021). Loss of Giant Kelp, *Macrocystis pyrifera*, driven by marine heatwaves and exacerbated by poor water clarity in New Zealand. *Frontiers in Marine Science*, *8*, 721087.
- United Nations Environmental Programme. (2023). *Into the blue: Securing a sustainable future for kelp forests*. United Nations Environmental Programme.
- Valckenaere, J., Techera, E., Filbee-Dexter, K., & Wernberg, T. (2023). Unseen and unheard: The invisibility of kelp forests in international environmental governance. *Frontiers in Marine Science*, *10*, 1235952.
- Vergés, A., Doropoulos, C., Malcolm, H. A., Skye, M., Garcia-Pizá, M., Marzinelli, E. M., Campbell, A. H., Ballesteros, E., Hoey, A. S., Vila-Concejo, A., Bozec, Y. M., & Steinberg, P. D. (2016). Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. *Proceedings of the National Academy of Sciences of the United States of America*, *113*, 13791–13796.
- Wernberg, T., Bennett, S., Babcock, R. C., de Bettignies, T., Cure, K., Depczynski, M., Dufois, F., Fromont, J., Fulton, C. J., Hovey, R. K., Harvey, E. S., Holmes, T. H., Kendrick, G. A., Radford, B., Santana-Garcon, J., Saunders, B. J., Smale, D. A., Thomsen, M. S., Tuckett, C. A., ... Wilson, S. (2016). Climate-driven regime shift of a temperate marine ecosystem. *Science*, *353*, 169–172.
- Wernberg, T., Krumhansl, K. A., Filbee-Dexter, K., & Pedersen, M. F. (2019). Status and trends for the world’s kelp forests. In C. Sheppard (Ed.), *World seas: An environmental evaluation: Vol 3. Ecological issues and environmental impacts* (2nd ed., pp. 57–78). Academic Press.
- Wernberg, T., Thomsen, M. S., Baum, J. K., Bishop, M. J., Bruno, J. F., Coleman, M. A., Filbee-Dexter, K., Gagnon, K., He, Q., Murdiyarso, D., Rogers, K., Silliman, B. R., Smale, D. A., Starko, S., & Vanderklift, M. A. (2024). Impacts of climate change on marine foundation species. *Annual Review of Marine Science*, *16*, 247–282.
- Wood, G. V., Filbee-Dexter, K., Coleman, M. A., Valckenaere, J., Aguirre, D., Bentley, P. M., Carnell, P., Dawkins, P. D., Dykman, L. N., Earp, H. S., Ennis, L. B., Francis, P., Franco, J. N., Hayford, H., Ling, S. D., Lamb, J. B., Layton, C., Lis, E., Masters, B., ... Wernberg, T. (2024). Upscaling marine forest restoration: Challenges, solutions and recommendations from

- the Green Gravel Action Group. *Frontiers in Marine Science*. (accepted).
- Wood, G., Marzinelli, E., Coleman, M., Campbell, A., Santini, N., Kajlich, L., Verdura, J., Wodak, J., Steinberg, P. D., & Vergés, A. (2019). Restoring marine macrophytes into the future. *Marine and Freshwater Research*, *70*, 247–282.
- Ziegler, S. L., Johnson, J. M., Brooks, R. O., Johnston, E. M., Mohay, J. L., Ruttenberg, B. I., Starr, R. M., Waltz, G. T., Wendt, D. E., & Hamilton, S. L. (2023). Marine protected areas, marine heatwaves, and the resilience of nearshore fish communities. *Scientific Reports*, *13*, 1405.

**How to cite this article:** Filbee-Dexter, K., Starko, S., Pessarrodona, A., Wood, G., Norderhaug, K. M., Piñeiro-Corbeira, C., & Wernberg, T. (2024). Marine protected areas can be useful but are not a silver bullet for kelp conservation. *Journal of Phycology*, *60*, 203–213. <https://doi.org/10.1111/jpy.13446>