

Shortfalls in the protection of persistent bull kelp forests in the USA

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ABSTRACT

Kelp forests are one of the most productive ecosystems on earth, providing critical ecosystem services. Despite their global importance, their persistence in the face of human pressure and climate change is uncertain. We present a 38-year quarterly time series of satellite imagery that maps the distribution and persistence of surface canopy-forming kelp (dominated by the bull kelp, *Nereocystis leutkeana*) forests along eleven degrees of latitude in the western Pacific of the USA. We estimate kelp persistence as the fraction of years occupied by kelp canopy in the time series and evaluate the representation of kelp in marine protected areas (MPAs). While 3.6 % of kelp habitat is fully protected and 10.1 % is partially protected, only 0.7 % of the highly persistent kelp which may be indicative of climate refugia are fully protected. Regionally, the amount of kelp fully protected inside MPAs decreases from Central Northern California (8.0 %) to Oregon (5.9 %), Northern California (1.7 %), and Washington (0 %). Five years after the 2014–2016 marine heatwaves, kelp forests did not recover in California (~90 % loss for both regions), while Oregon and Washington remained near pre-heatwave values. The low amount of protection in Northern California is concerning and likely exacerbates the vulnerability of kelp and associated species to marine heatwaves. Meeting a target of protecting 10 % of existing kelp habitat will require a 2.5-fold increase in kelp representation in MPAs. Moreover, we propose protecting highly persistent kelp is a cost-effective approach to increase representation and efficacy of MPAs to support climate resilience of kelp forest ecosystems.

1. Introduction

Marine protected areas (MPAs) are a cornerstone of most coastal and marine conservation strategies (Gorud-Colvert et al., 2021). The protection of marine ecosystems has increased in the past decades (Maxwell et al., 2020), promoted by international agreements to expand area-based conservation, such as the Convention on Biological Diversity (CBD) Aichi Target 11 (CBD, 2010). The post 2020-global biodiversity framework (CBD, 2020), agreed upon at COP15 in December 2022, calls for the protection of 30 % of the oceans by 2030 through representative, and well-connected networks of MPAs and other effective area-based conservation measures while adapting to climate change. A central component of the post-2020 targets is habitat representation, and although many studies report the representation of critical habitat-forming species such as corals, seagrass, and mangroves (Maxwell et al., 2020), other essential marine habitats, such as kelp forests, remain

largely neglected (but see Arafteh-Dalmau et al., 2021). Information on their status and spatial distribution is needed.

Kelp forests are one of the most productive ecosystems on earth, comparable to terrestrial rainforests (Schiel and Foster, 2015). They dominate over 30 % of the world's rocky reefs, creating a complex three-dimensional habitat that sustains a diverse assemblage of species (Jayatilake and Costello, 2021; Schiel and Foster, 2015; Wernberg et al., 2019). Although there are >110 laminarian kelp species (Wernberg et al., 2019), only a few large species (e.g., *Macrocystis pyrifera*, *Nereocystis leutkeana*, *Ecklonia maxima*) form canopies that float on the surface and create extensive forests along the coastline. These surface-canopy forming species can be mapped by remote sensing, providing an opportunity to cost-effectively track their distribution and dynamics (Cavanaugh et al., 2021). Because extreme climatic events and other anthropogenic impacts are threatening kelp forests (Arafteh-Dalmau et al., 2019; Arafteh-Dalmau et al., 2020; Smale, 2020) and their capacity

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to provide ecosystem services worth billions of dollars to humanity (Smale et al., 2019; Smith et al., 2021; Eger et al., 2023), it is timely to use remote sensing to guide kelp forest protection and management (Cavanaugh et al., 2021).

As extreme climatic events are becoming more frequent and severe, securing the long-term persistence of kelp forest ecosystems requires area-based protection and climate adaptation strategies to address ongoing and future threats (Arafeh-Dalmau et al., 2021; Arafeh-Dalmau et al., 2020). Strategies include increased protection and management inside MPAs and protecting climate refugia for kelp forest ecosystems. MPAs can protect marine ecosystems from local threats such as fishing and thereby increase the resilience of kelp to climate stressors through different ecological paths (e.g., trophic cascades, ecosystem stability) (Edgar et al., 2017; Eisauguirre et al., 2020; Jacquemont et al., 2022; Ling et al., 2009; Roberts et al., 2017; Ziegler et al., 2023). For example, highly restrictive MPAs have effectively recovered or maintained over-exploited populations of sea urchin predators that otherwise can lead to sea urchins overgrazing kelp forests (Babcock et al., 1999; Hamilton and Caselle, 2015; Ling et al., 2009; Selden et al., 2017). Climate refugia are areas where the impacts of climate change may be less severe (Keppel et al., 2012) and kelp forests may persist or recover. Protecting climate refugia is a priority for conservation (Keppel et al., 2015) because these areas should support diverse assemblages of kelp-associated species. Nevertheless, identifying climate refugia at large spatial scales is challenging for dynamic ecosystems that are highly variable on seasonal, annual, and decadal timescales (Schiel and Foster, 2015). It requires using proxies, such as ecosystem attributes (e.g., persistence, resistance, or resilience) indicative of potential climate refugia (O'Leary et al., 2017). If we can map these ecosystem attributes for kelp forests, we can prioritize their protection.

Persistence refers to the presence of kelp forests through time, e.g. the fraction of years with kelp in a location (Young et al., 2016). Those kelp forests that have persisted despite climate change and human activity, considered as highly persistent, may be indicative of climate refugia (Arafeh-Dalmau et al., 2021). These areas are a priority for conservation because persistent kelp forests retain the habitat structure for other components of the community and can provide a source of spores for nearby less persistent kelp forests (Arafeh-Dalmau et al., 2021). Simulations and experiments in California have found that the loss of giant kelp (*M. pyrifera*) forests, due to multiple-year wave disturbance, simplifies food webs and decreases species richness (Byrnes et al., 2011; Castorani et al., 2018). Similarly, long-term kelp monitoring revealed that deforestation of kelp forests by sea urchins in the Channel Islands reduced sessile invertebrate diversity by 40 % and almost completely lost canopy fish assemblage (Graham, 2004). Empirical evidence from the sub-Antarctic giant kelp forests that are highly pristine (Mora-Soto et al., 2021), reveals that persistent kelp forests have stable ecological communities (Friedlander et al., 2020). However, despite the potential ecological benefits of protecting persistent kelp forests, as high-diversity systems can enhance ecosystem stability and resilience potential (Steneck et al., 2002), only one study has assessed their representation inside MPAs for giant kelp in California, USA, and Baja California, Mexico (Arafeh-Dalmau et al., 2021).

Along the northeast Pacific Ocean, bull kelp (*N. leutkeana*) forms forests with extensive surface canopy from northern California to Alaska. However, extreme marine heatwaves between 2014 and 2016 have severely impacted bull kelp forests in some regions (McPherson et al., 2021; Rogers-Bennett and Catton, 2019). The combined effect of the heatwave and the loss of a critical sea urchin predator (sunflower sea stars) due to a sea star wasting disease (Hamilton et al., 2021; Harvell et al., 2019; Hewson et al., 2014), have shifted many productive bull kelp forest ecosystems into sea urchin barrens in California, with reports of over 90 % loss in kelp coverage and \$47 million loss in fisheries in northern California (Rogers-Bennett and Catton, 2019). Compared to kelp in northern California, kelp forests in Oregon and Washington (in Washington both *N. leutkeana* and *M. pyrifera* can dominate) displayed

relative stability despite these marine heatwaves, although some kelp forests near human populations showed declines (Hamilton et al., 2020; Pfister et al., 2018; Tolimieri et al., 2023). For example, along the Olympic coast of Washington, kelp cover decreased by 50 % during the marine heatwaves but recovered within one year and steadily increased in the subsequent years to pre-heatwave coverage (Tolimieri et al., 2023). Given that climate projections suggest marine heatwaves will continue to increase in frequency and intensity (Cooley et al., 2022; Oliver et al., 2019), kelp forests will be increasingly at risk (Pörtner et al., 2022), which requires urgent and adequate climate adaptation strategies (Arafeh-Dalmau et al., 2020), such as increased protection inside MPAs and protecting potential climate refugia for kelp forest ecosystems.

The present study maps the distribution and persistence of surface-canopy forming kelp, dominated by *N. leutkeana* (except in Washington, see methods for more details), on the western Pacific coast of the USA from central California to Washington—spanning over eleven degrees of latitude—using a 38-year satellite time series. In this research, we quantified the representation of low, medium, and high persistent kelp found in two categories of MPAs (full and partial) across four regions: Washington, Oregon, Northern California, and Northern Central California. Because kelp forests are highly dynamic, we estimated the additional area of MPAs needed to meet kelp protection targets (e.g., the 10 % CBD Aichi target 11 for 2020) in any given year. Our work provides estimates of the shortfalls of kelp protection in the region that may be used to inform decision-making. Notably, we use an approach to account for kelp dynamics that will be useful for climate-smart MPA planning (Arafeh-Dalmau et al., 2022) and can be harnessed for other dynamic ecosystems and in other kelp forest-dominated regions.

2. Methods

2.1. Mapping surface canopy-kelp persistence

Our study area comprises the region where bull kelp (*Nereocystis leutkeana*) is the dominant canopy-forming kelp species in the western Pacific coast of the USA. The region extends from Half Moon Bay, California, USA in the south (~37.5°), to the border between USA and Canada in the north (~48.4°). The dataset maps canopy-forming kelp in western Washington, including the outer coast and most of the Strait of Juan de Fuca, from Cape Flattery (−124.72°) to Freshwater Bay (−123.6°) but does not include eastern and northern Washington: Puget Sound, San Juan Islands, and the Strait of Georgia. Although bull kelp dominates in California and Oregon, both bull and giant kelp (*M. pyrifera*) are equally abundant in many parts of Washington (Pfister et al., 2018). For this reason, in this study, we will refer to all canopy-forming kelp in our region as “kelp” and when discussing results, we will refer to bull kelp for California and Oregon, and bull and giant kelp in Washington.

Using a 30-meter resolution satellite-based time series, we mapped the distribution and persistence of kelp in our study area (Bell et al., 2020). The data provides quarterly estimates of kelp canopy from 1984 to 2021. This published dataset has been used to track kelp dynamics and can be visualized on kelpwatch.org (Bell et al., 2023). The dataset estimates kelp canopy from three Landsat sensors: Landsat 5 Thematic Mapper (1984–2011), Landsat 7 Enhanced Thematic Mapper+ (1999–present), and Landsat 8 Operational Land Imager (2013–present). Each Landsat sensor has a pixel resolution of 30 × 30 m and a repeat time of 16 days (8 days since 1999 in most years because two Landsat sensors were operational). We obtained a clear view of each pixel in the dataset ~15 times per year from 1984 to 2021 (mean = 14.6, SD = 8.4) and estimated the mean area for each quarter of a year. We used every Landsat image where at least part of the coastline was not obscured by cloud cover (we masked clouds using the pixel quality assurance band included with each image). This allowed for the maximum number of views of each kelp location. If a pixel was obscured by cloud cover it was

given a missing value. Relying on only completely cloud-free imagery would have reduced the number of views of kelp canopy in the time series and because kelp canopy can also be altered by tides and currents it is beneficial to obtain as many clear views as a possible.

We determined the presence and density of the kelp canopy on a subpixel scale using a fully automated procedure. First, we masked all land areas using a global 30-meter digital elevation model (asterweb.jpl.nasa.gov/gdem.asp). We organized the remaining pixels as seawater, cloud, and kelp canopy using a binary decision tree classifier trained with a set of pixels in the study area (Bell et al., 2020). Then we modelled each pixel as the linear combination of seawater and kelp canopy, using a Multiple Endmember Spectral Mixture Analysis (Roberts et al., 1998). For bull kelp canopies, these methods were validated using high-resolution aerial imagery from the Oregon Department of Fish and Wildlife (Hamilton et al., 2020) and kelp canopy shapefiles generated by the California Department of Fish and Wildlife (Cavanaugh et al., 2023). For giant kelp canopies, these methods were validated using a 15-year monthly dataset of kelp canopy biomass from the Santa Barbara Coastal Long Term Ecological Research project at two sites in Southern California (Bell et al., 2020; Cavanaugh et al., 2011) and a four-year dataset of high-resolution aerial drone imagery (McPherson et al., under review).

We characterized kelp persistence as the fraction of years occupied by kelp canopy (if a year had at least one quarter with a non-zero value for area) in each pixel (O_i) that the satellite detected kelp ($n = 68,858$) for the past 38 years. A pixel with zero value means the satellite never detected kelp forest in the timeseries (we did not include zeros in our analysis because they are not kelp habitat), while a value of one means it detected kelp for all 38 years (at least in one quarter of each year). Then, we used kelp persistence data to group pixels into three persistence classes. We classified pixels as low persistence in the 33rd percentile, with kelp found in <0.23 of years. Medium persistence among the 33rd and 66th percentile, with kelp found between 0.23 and 0.44 of years. High persistence over the 66th percentile, with kelp found over 0.44 of years. We obtained the vectorial maps of kelp distribution for the three persistence levels by rasterizing the data points and converting them to polygons in ESRI ArcGIS Pro (v10.8).

We also measured the response and recovery of kelp during and after the unprecedented 2014–2016 marine heatwaves, by comparing the average annual maximum canopy area during (2014–2016) and after the heatwaves (2017–2021) with a baseline period (2000–2013) (following Bell et al. (2023)). To estimate the annual maximum canopy area, we first summed the area of all kelp pixels in each region for each quarter of the year. If >25 % of pixels (30×30 m) did not have a cloud-free estimate during a quarter of a given year, that quarter of the year was assigned a missing value. We did not determine the annual maximum canopy area for a particular year if more than one quarter of a year had missing values (however, that was not the case for any year during 2000–2021). We estimated the annual maximum canopy area instead of the yearly mean canopy area because bull kelp, the dominant species in our study region, is mostly annual.

2.2. Kelp representation inside marine protected areas

We obtained data on MPA locations, boundaries, and types for Washington, Oregon, and California from the National Oceanic and Atmospheric Administration (NOAA, 2020 version, and Washington Department of Fish and Wildlife). We combined and merged MPAs based on the two levels of protection: full protection, where all extractive uses are prohibited (no-take marine reserves), and partial protection, where some restrictions apply to recreational and commercial fishing (multiple-use areas). We did not include National Marine Sanctuaries in our analyses, because there are minimal or no fishing restrictions. To estimate the representation of kelp habitats in MPAs, we calculated coverage through spatial intersections of MPAs (full and partial protection) and kelp forest persistence (high, medium, and low) for our

region. We divided our region into four areas, Washington, Oregon, Northern California, and Central Northern California. These four regions represent distinct biogeographic areas (Blanchette et al., 2008) where species composition varies because of oceanographic processes, or USA state borders. Note that our kelp mapping does not include Alaska or some parts of Washington that may have MPAs overlapping with kelp forests. We conducted the analyses for the entire region and separately for each of the four regions using ESRI ArcGIS Pro (v10.8). This study expands from a previous analysis that mapped the persistence of giant kelp forests and assessed their level of protection in the northeast Pacific ocean (Arafeh-Dalmau et al., 2021).

2.3. Probability of kelp representation inside marine reserves

We followed Arafeh-Dalmau et al. (2021) previous analysis of giant kelp persistence and estimated the representation of kelp habitats in marine reserves through time for each of the four regions and for the western Pacific coast of the USA. Present kelp is defined as the probability that a pixel will be occupied by kelp in any given year, thus maintaining the habitat structure they provide (Arafeh-Dalmau et al., 2021). Kelp habitat is defined as a pixel where the satellite detected kelp (at least once during the time series, $n = 68,858$). We estimate the probability of present kelp (P), for all pixels that are protected in marine reserves, as the average persistence value:

$$P = \frac{\sum_{i=1}^n O_i}{n} \quad (1)$$

where O_i is the fraction of years occupied by kelp habitat for protected pixel i and n the number of pixels with kelp. We then estimated the representation (percentage protection) of present kelp (R_p) as a product of the representation of kelp (R) and the probability of present kelp (P):

$$R_p = R \cdot P \cdot 100 \quad (2)$$

where R is the fraction of kelp protected in marine reserves, and P the probability of present kelp. R_p provides an estimate of the percentage of kelp protected and expected to be present in any given year.

2.4. Adjusting representation targets for present kelp

We followed Arafeh-Dalmau et al. (2021) and adjusted representation targets to protect present kelp for each of the four regions and the western Pacific coast of the USA. This method allows accounting for kelp dynamics and the likelihood of protecting present kelp when considering habitat representation targets. First, we estimate the probability of present kelp (P) for all kelp pixels, rather than probability of present kelp for protected pixels. Then, we adjust the representation targets to protect present kelp by applying a multiplier, M :

$$M = \frac{1}{P} \quad (3)$$

which adjusts the representation target (T_a):

$$T_a = T \cdot M \cdot 100 \quad (4)$$

where T is the representation target and M is a multiplier applied to adjust the representation target (T_a) for protecting present kelp. We can now ensure that the representation of present kelp (R_p) is equal to the representation target (T) (i.e., 10 % CBD Aichi target 11 for 2020).

2.5. Adjusting representation targets for specific persistence classes

The previous adjusted representation targets do not account for the classification of kelp based on their persistence. However, we can adjust representation targets for specific persistence classes. For example, we

can adjust the representation target to include only kelp with high persistence. We can then use the previous equation for each level of persistence (low, medium, high), leaving constant the representation target (T) (note that we substitute R_p for T from Eq. (2)) for low and mid persistence, and estimate the adjusted representation target for highly persistence kelp (T_h):

$$Tn = TP_l n_l + TP_m n_m + T_h P_h n_h,$$

$$\frac{Tn}{P_h n_h} = \frac{TP_l n_l + TP_m n_m}{P_h n_h} + T_h,$$

$$T_h = \frac{T(n - P_l n_l - P_m n_m)}{P_h n_h}, \quad (5)$$

where R_l is the representation of low, R_m medium, and R_h high persistence kelp. Then P_l is the probability of present kelp for low, P_m for medium, and P_h for high persistence kelp. Finally, n is the number of detected kelp pixels, n_l is the number of pixels with low, n_m with medium, and n_h with high persistence kelp. Note that we keep T constant. We can then estimate the multiplier required to adjust representation targets of high persistence kelp M_h :

$$M_h = \frac{T_h}{T}, \quad (6)$$

In cases where adjusting representation targets for highly persistent kelp is not enough to meet our target for present kelp (e.g., 10 %), we can adjust the representation target for medium and high persistent kelp combined (T_{mh}):

$$T_{mh} = \frac{T(n - P_l n_l)}{P_m n_m + P_h n_h}, \quad (7)$$

and the multiplier required to adjust representation targets of mid and high persistence kelp (M_{mh}):

$$M_{mh} = \frac{T_{mh}}{T} \quad (8)$$

2.6. Worked examples for adjusting the representation targets for present kelp

We estimate the probability of present kelp (P) for the western Pacific coast of the USA and the adjusted multiplier (M) required to protect 10 % (CBD Aichi target 11 for 2020 of present kelp) (R_p):

$$R_p = 0.1 * 0.39 * 100$$

where the probability of present kelp (P) is 0.39 and the representation target (T) is 0.1. By protecting 10 % of kelp, 3.9 % of the present kelp is protected in the western Pacific coast of the USA. We can now estimate the multiplier (M):

$$M = \frac{1}{0.39}$$

which suggests the need to apply a multiplier (M) of 2.55 to protect 10 % of present kelp in the western Pacific coast of the USA in any given year. We can then adjust the representation target (T_a):

$$T_a = 0.1 * 2.55 * 100$$

which suggests the need to protect 25.5 % of kelp habitat to ensure we protect 10 % of kelp expected to be present in any given year.

2.7. Adjusting representation targets for specific persistence classes

We also provide an example by estimating the adjusted representation target of high persistence kelp habitat, (T_h) required to represent 10 % of present kelp in the western Pacific coast of the USA:

$$T_h = \frac{0.1 (68858 - 0.15 * 25198 - 0.33 * 21251)}{0.72 * 22409} * 100$$

which suggests the need to protect 35.9 % of high persistence kelp habitat (including a fixed protection target of 10 % for low and medium persistence kelp) to meet representation target (T) and apply a multiplier for high persistence kelp (M_h):

$$M = \frac{0.359}{0.1}$$

of 3.59.

See values from Tables 1 and 3.

3. Results

In the western Pacific coast of the USA, only 3.6 % of kelp habitat is fully protected and 10.8 % is partially protected (Fig. 1a). However, by level of persistence, <1 % (0.7 %) of highly persistent kelp habitat is fully protected, with higher values for medium (4.2 %) and low persistence (5.8 %) (Fig. 1a). Washington has most of the persistent kelp habitat found in the western Pacific coast of the USA (66.7 %), while Northern California has the lowest (3.7 %) (Fig. 1b). We found important differences among regions in the area coverage of fully protected kelp habitat (Figs. 1c and 2), being highest in Northern Central California (8.0 %), followed by Oregon (5.9 %), Northern California (1.7 %) and Washington (0 %). We found a similar pattern for partially protected kelp habitat, except for Washington (9.5 %) (Figs. 1c and 2). Northern Central California also holds the highest percentage of fully protected persistent kelp habitat (3.4 %), followed by Oregon (3.1 %), Northern Central California (0.1 %) and Washington (0 %) (Figs. 1c and 2). Note that our kelp mapping does not include parts of eastern and northern Washington that have kelp habitat and partially protected areas.

We found an average persistence value of 0.39 for the western Pacific coast of the USA, which means that 39 % of the kelp distribution has kelp canopy present in any year. The average persistence value ranged from 0.62 (Washington) to 0.23 (Northern California) (Table 1). Our results indicate that only 1.4 % (instead of 3.6) of the detected kelp habitat is expected to be present and fully protected in any year, ranging from 2.3 % for Central Northern California to 0 % in Washington (Table 2). Adjusted representation targets suggest that fully protecting 10 % of present kelp habitat in each region requires, on average, an increase in the representation target by over three-fold (Tables 1 and 3) except Washington, which only requires 1.6 increase. However, the area required to meet these targets across our study area is smaller if highly persistent kelp habitat is prioritized for protection, decreasing from 25.5 % to 18.4 % (Table 3). Adjusting representation targets for Washington requires an increase of 1.7 in protecting highly persistent kelp habitat. In contrast, the low levels of persistence in the other regions require adjusting representation targets for both medium and highly persistent kelp habitat (Table 3).

Washington accounts for 36.5 %, Central Northern California for 28.4 %, Oregon for 18.3 %, and Northern California for 16.8 % of kelp coverage along our study region in the western Pacific coast of the USA (Fig. 1b). The time series reveals stability in kelp forest dynamics in the past 38 years in Washington and Oregon. However, Oregon had 3-fold higher area coverage from 1984 to 1991 compared to 1992–2021 (Fig. 1d). Central Northern California and Northern California had periods with high kelp coverage followed by multiple years with low values, indicating higher variability (Fig. 1d). The 2014–2016 marine heatwaves impacted kelp coverage in both regions in California. We report a loss of 85.6 % (± 12.8 % s.d) and 89.3 % (± 6.1 % s.d) in kelp area during the heatwave for Central Northern California and Northern California, respectively, while Oregon and Washington kelp coverage remained near pre-heatwave values with a 1.5 % loss (± 34.5 % s.d) and a 1.79 % increase (± 18.1 % s.d). In Central Northern California and

Table 1

Persistence of kelp for each region and for the western Pacific coast of the USA combined. P : probability of present kelp, n : number of detected kelp pixels. Subscript letters represent mean values of the low (l), medium (m), and high (h) persistence categories.

Region	P	n	P_l	n_l	P_m	n_m	P_h	n_h
Washington	0.62	25,149	0.19	2,190	0.34	6,140	0.77	16,819
Oregon	0.26	12,625	0.14	7,150	0.33	3,871	0.60	1,604
Northern California	0.23	11,533	0.14	6,836	0.33	3,767	0.55	930
Central Northern California	0.29	19,551	0.15	9,022	0.34	7,473	0.56	3,056
Western Pacific coast	0.39	68,858	0.15	25,198	0.33	21,251	0.72	22,409

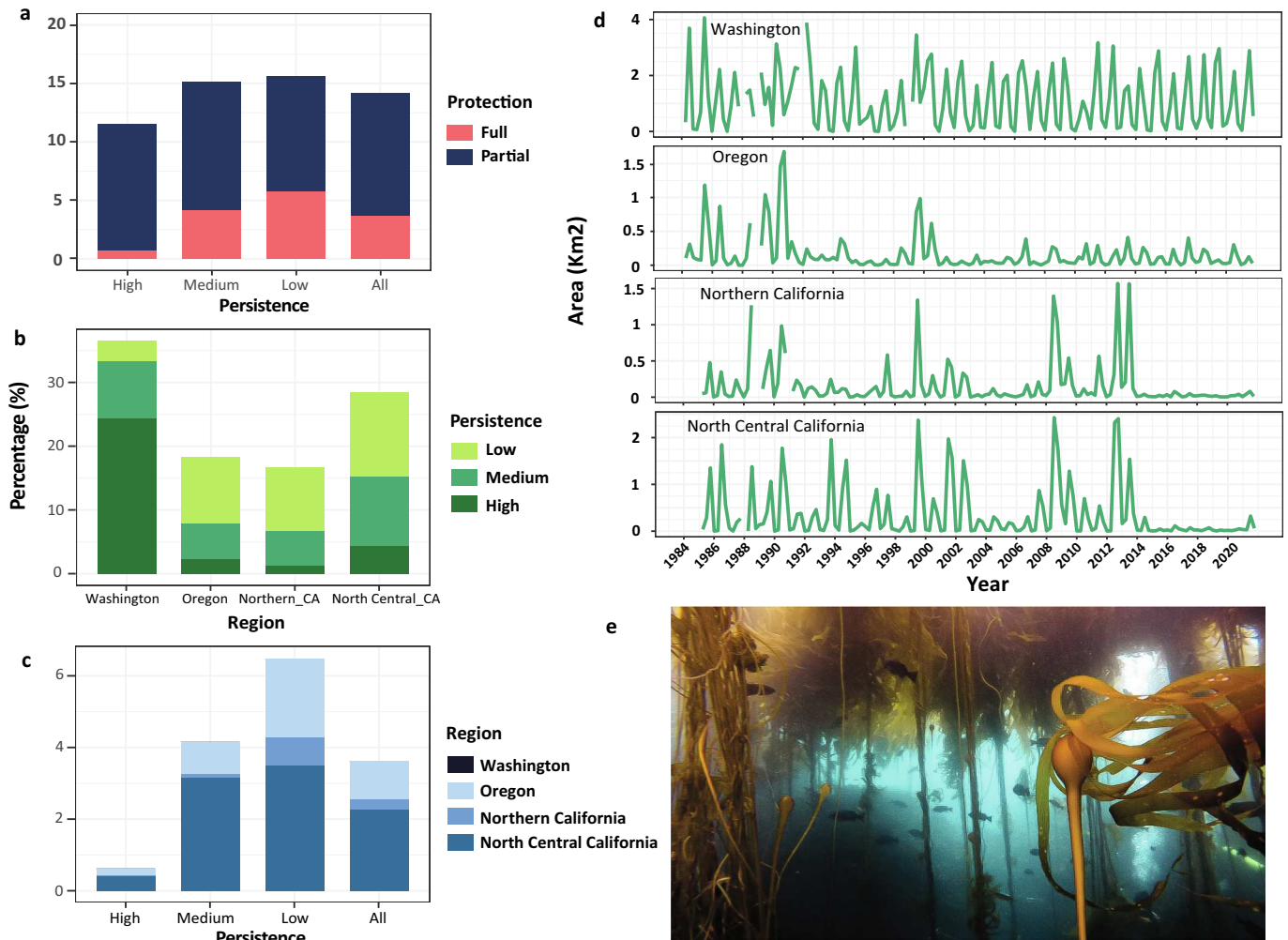


Fig. 1. Protected kelp by level of persistence in the western Pacific coast of the USA. Bar plots show the percentage (%) of the area of detected kelp by level of persistence **a)** fully and partially protected, **b)** contribution of the distribution of kelp persistence in the four regions, **c)** contribution of fully protected kelp in the four regions, **d)** time series of the area (km²) of kelp canopy detected in each quarter of a year for each region over the past 38 years, and **e)** example of a bull kelp forest ecosystem. Photo bull kelp credit: Steve Lonhart.

Northern California, kelp did not show recovery five years after the heatwaves, with 89.9 % (± 12.0 % s.d.) and 90.4 % (± 5.2 % s.d.) losses in these two respective regions. However, Oregon and Washington kelp coverage remained near pre-heatwave levels, with an increase of 8.6 % (± 62.1 % s.d.) and 13.8 % (± 13.6 % s.d.) (Fig. 3), respectively, but Oregon's yearly recovery was more variable.

4. Discussion

We found that only 3.6 % of kelp forests are fully protected on the western Pacific coast of the USA, which is far from approaching the Convention on Biological Diversity Aichi target 11 of effectively protecting 10 % of coastal areas by 2020 (CBD, 2010). This protection

shortfall is concerning because fully protected marine reserves are the most effective type of MPAs in conserving biodiversity (Edgar et al., 2014; Lester et al., 2009) and enhancing ecosystems' resilience and adaptive capacity to climate change impacts (Eisaguirre et al., 2020; Jacquemont et al., 2022; Micheli et al., 2012; Roberts et al., 2020; Roberts et al., 2017). Only Northern Central California nears the Aichi 11 target, and additional investments are needed in the other regions, especially Northern California and Washington. For example, the extent of kelp protection in marine reserves in Northern California is minimal (~ 1.7 %), despite that the existing network of MPAs in the region fully protects 5 % of the state's waters (Gleason et al., 2013).

The shortfalls in the protection of persistent kelp habitat in the USA (< 0.7 %) and particularly in Northern California, are also of concern

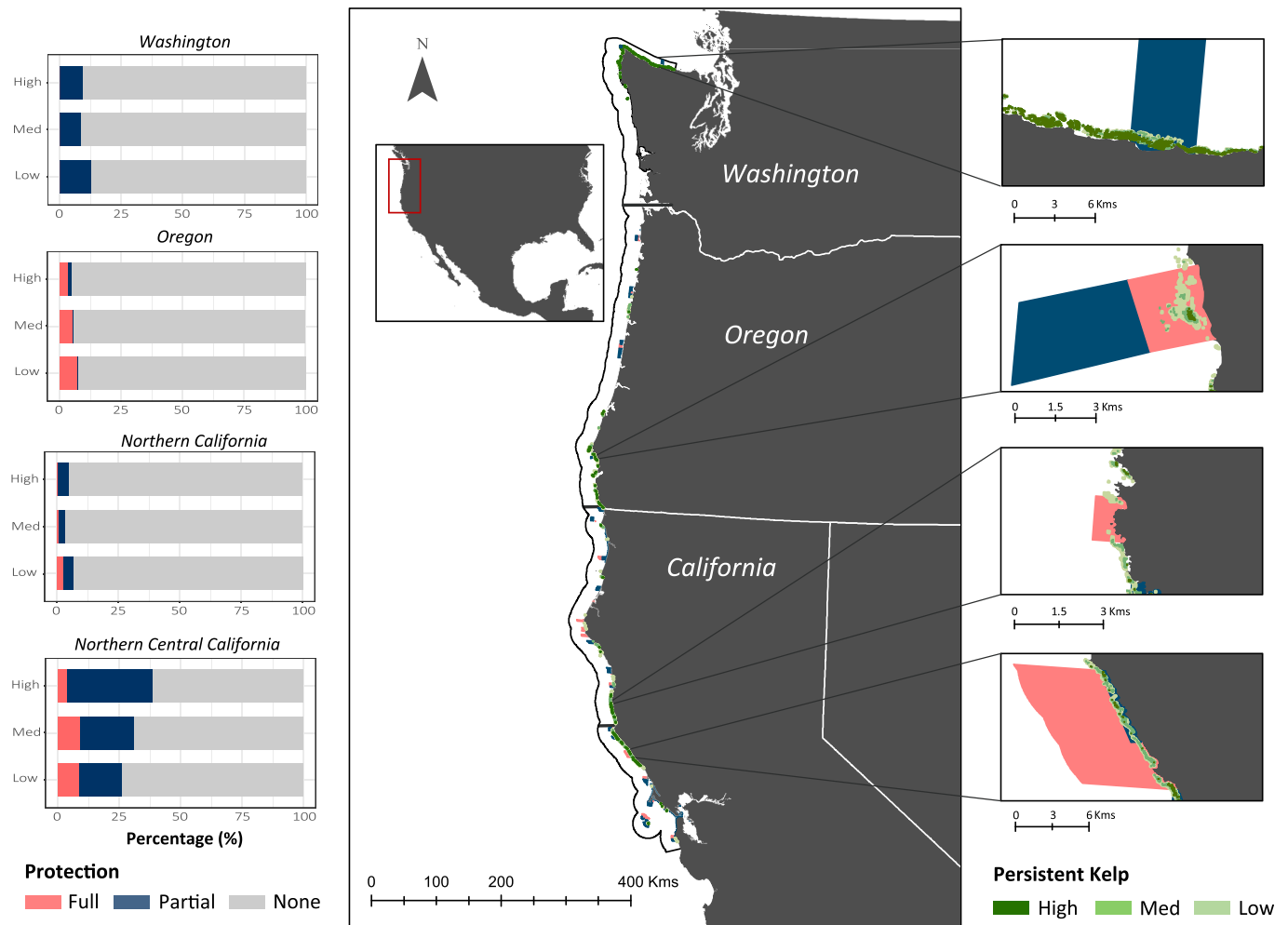


Fig. 2. The spatial distribution of kelp by level of persistence and marine protected areas by level of protection in the western Pacific coast of the USA. Left bar plots represent the percentage (%) of persistent kelp protected for the four regions. On right, fine-scale examples for each region. The buffer in the coastline represents the territorial seas for the area covered by the satellite-based time series and the dark horizontal lines the limits of each region.

Table 2

Representation of kelp inside marine reserves for each region and for the western Pacific coast of the USA combined. P : probability of present kelp, n : number of detected kelp pixels, R : protected kelp habitat inside marine reserves, and R_p : protected kelp habitat inside marine reserves expected to be present in any given year (based on the persistence metric, see methods for detail).

Region	P	n	R (%)	R_p (%)
Washington	–	0	0	0
Oregon	0.26	739	5.85	1.521
Northern California	0.23	197	1.71	0.39
Central Northern California	0.29	1,555	7.95	2.31
Western Pacific coast	0.39	2,491	3.62	1.42

because of the ~90 % loss of *Nereocystis leutkeana* forests five years after the 2014–2016 marine heatwaves. We found that only one marine reserve overlaps with highly persistent bull kelp habitat in Northern California, providing a minimal protection of 0.1 % in the region. In this region, many of the previously productive bull kelp forest ecosystems are today dominated by purple sea urchin barrens (McPherson et al., 2021; Rogers-Bennett and Catton, 2019). It remains an open question whether this ecosystem would have recovered after the marine heatwaves if adequately protected since the main sea urchin predator species in the region, the sunflower sea star (*Pycnopodia helianthoides*), was lost due to a sea star wasting disease (Hewson et al., 2014). However, our time series in California revealed high kelp variability with some

Table 3

Multipliers (M , M_h , and M_{mh}) required to adjust representation targets to protect 10 % of kelp expected to be present for each region and the western Pacific coast of the USA combined.

Region	M	Area (%)	M_h^a	Area (%)	M_{mh}^a	Area (%)
Washington	1.62	16.21	1.74	14.95	–	–
Oregon	3.87	38.7	–	–	5.16	28.06
Northern California	3.72	37.2	–	–	6.04	30.52
Central Northern California	3.14	31.4	–	–	4.31	27.80
Western Pacific coast	2.55	25.5	3.58	18.39	–	–

^a For M_h we kept constant the representation target for low and medium persistence (10 %), and for M_{mh} we kept constant the representation target for low persistence. Then we estimated the multiplier for specific persistence classes needed to meet the representation target of 10 %.

prolonged periods with low kelp coverage (i.e., 1992–1999, 2003–2008) before the loss of sea stars. These insights into bull kelp dynamics in California may indicate that other factors unrelated to marine heatwaves and sea star wasting disease have historically contributed to the low levels of kelp persistence.

Although marine reserves cannot directly mitigate marine heatwave impacts that surpass kelp forests' physiological thresholds for temperature and nutrient availability, they can minimize additional non-

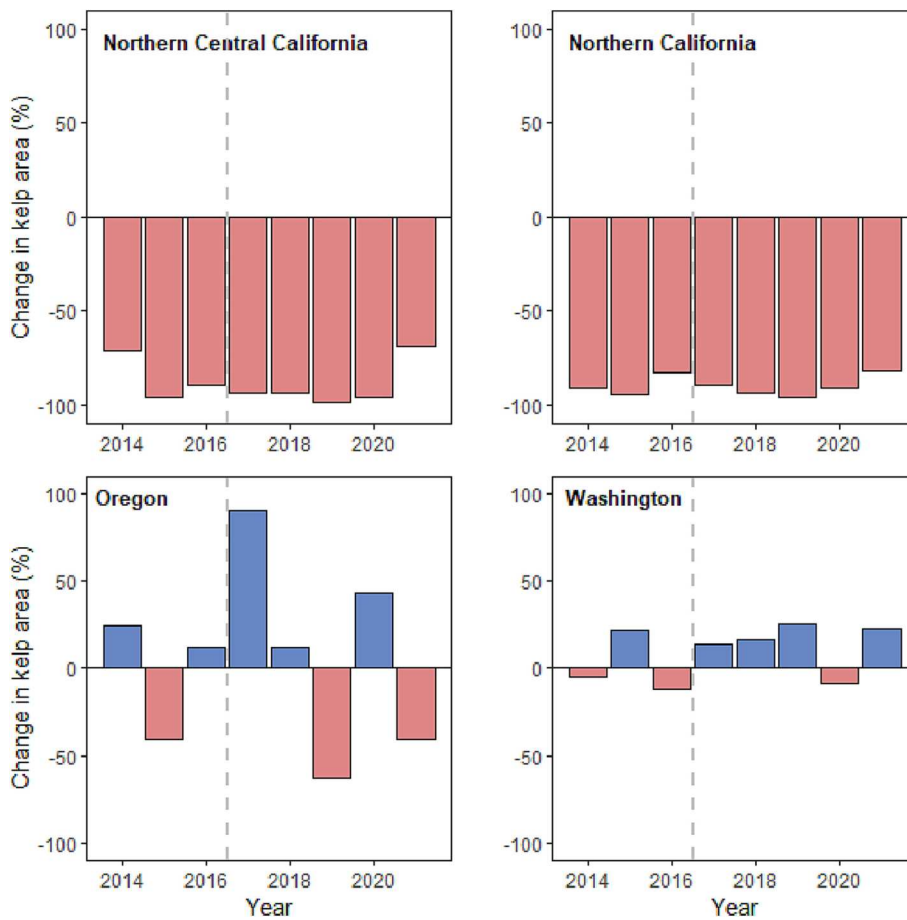


Fig. 3. Percentage change in the average annual maximum canopy kelp area during (2014–2016) and after (2017–2021) the marine heatwaves compared to the baseline period (2000–2013) in the western Pacific coast of the USA. Positive (blue bars) and negative values (red bars) represent years where the canopy area of kelp is above or below the baseline period, respectively. Dashed gray lines separate the years during and after the marine heatwaves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

climatic threats such as trophic cascades (Jacquemont et al., 2022; Roberts et al., 2017), by recovering overfished urchin predators that prevent productive kelp forests from shifting to sea urchin barrens (Eisaguirre et al., 2020; Ling et al., 2009). Full protection of kelp habitat in the region may promote the recovery or maintenance of overexploited populations (Eisaguirre et al., 2020), support ecosystem stability following marine heatwaves (Ziegler et al., 2023), and create positive multi-trophic effects that build resilience to climate change (Babcock et al., 1999; Edgar et al., 2017; Eisaguirre et al., 2020; Ling et al., 2009). Marine reserves may also support kelp forest resilience through other less-understood pathways (Babcock et al., 1999; Edgar et al., 2017; Eisaguirre et al., 2020; Ling et al., 2009). For example, more complex food webs in New Zealand's marine reserves have higher cover compared to non-reserve sites, regardless of the presence of known sea urchin predators (Babcock et al., 1999; Edgar et al., 2017; Eisaguirre et al., 2020; Ling et al., 2009). It is likely that marine reserves facilitate trophic cascades by recovering high biomass of less studied fish and invertebrates that predate on juvenile or adult urchins (Clemente et al., 2013; Hereu et al., 2005; Tegner and Dayton, 1981).

In addition, to increasing the protection of kelp forests inside MPAs, protecting California's remaining highly persistent kelp forests may be one of the few climate-adaptation strategies available. These areas are potential indicators of climate refugia for kelp forests (Arafeh-Dalmau et al., 2021; Cavanaugh et al., 2023), provide a wide range of ecosystem services by retaining the habitat structure of a productive ecosystem that sustains a diverse assemblage of species (Graham, 2004), and their protection is also a cost-effective approach for meeting protected area targets (Arafeh-Dalmau et al., 2021). Persistent kelp forests can also enhance ecosystem resilience at larger spatial scales if considered in the design of climate-smart networks of MPAs (i.e., MPAs that consider climate change). For example, strategically protecting persistent kelp

may enhance their resilience and maintain a source of recovery for impacted kelp habitats through spore supply and movement of species (Arafeh-Dalmau et al., 2022) and support the resilience of California's kelp ecosystems in the face of future changes.

Even though none of the kelp forests in Washington are fully protected (within our study domain), they harbor 66.7 % of the highly persistent kelp forests in our study region in the western Pacific coast of the USA. This high persistence may be explained by several factors (e.g., giant and bull kelp dominate in the region, while bull kelp dominates in Oregon and California), including that kelp forests in this region are in the central distribution of the species providing a greater population-level thermal safety margin (Pinsky et al., 2019). For instance, our analysis and previous work (Pfister et al., 2018; Tolimieri et al., 2023) show that kelp forests in Washington were resilient to the 2014–2016 marine heatwaves. The presence of sea otters along a part of the Washington coast, an active sea urchin predator, are likely supporting kelp forest persistence (Shelton et al., 2018). However, higher kelp forests declines have been observed near greater human populations in the eastern Strait of Juan de Fuca and Puget Sound in Washington (Pfister et al., 2018), suggesting that if kelp forests remain unprotected, they may be vulnerable to increasing anthropogenic pressure and future marine heatwaves, similar to other regions (Arafeh-Dalmau et al., 2019; Cavanaugh et al., 2019; Johnson et al., 2011; McPherson et al., 2021; Michaud et al., 2022; Rogers-Bennett and Catton, 2019; Smale, 2020; Wernberg et al., 2016).

Our analysis extends from a previous assessment for giant kelp (Arafeh-Dalmau et al., 2021) by including the other surface-canopy forming kelp species in the northeast Pacific. The levels of protection of kelp forests in this study were over two-fold lower than protection of giant kelp in California and Baja California (Arafeh-Dalmau et al., 2021). Notably, high levels of full protection of giant kelp were reported for

Central California (20.9 %) and Southern California (8.4 %) compared to the lower levels of bull kelp protection we report in Northern Central California (8 %), and Northern California (1.7 %). Given the state of California implemented a statewide network of MPAs, completed in 2012, the difference in protection between giant and bull kelp is concerning. Most of the human population in California is located from San Francisco to the south, and the planning face should have been more challenging where giant kelp dominates due to higher human competing interests. Our findings support the need to assess and identify gaps in habitat representation to guide decision-making for kelp forests.

We also report lower values of bull kelp persistence compared to giant kelp. The lowest average persistence value in the northeast Pacific Ocean for giant kelp (Arafeh-Dalmau et al., 2021) is much higher than the bull kelp persistence values for all regions except Washington where giant and bull kelp dominate. The life history of giant and bull kelp may give a plausible explanation for these differences: while giant kelp is a perennial species living for up to 7 years, bull kelp is an annual species. For example, it is less likely that the satellite will detect bull kelp than giant kelp because bull kelp usually dies in winter and grows in spring and summer, while giant kelp can be present throughout the year. However, we estimate kelp persistence yearly (see methods), which should capture the higher dynamics of bull kelp.

Considering that Washington's kelp persistence value is higher than the value of giant kelp persistence in any region, there may be other reasons for the lower values of bull kelp persistence in California and Oregon. For example, the lack of the main sea urchin predators. In Baja California and southern California, sheephead and lobsters predate on sea urchins, while central California and Washington have sea otters (Eisaguirre et al., 2020; Shelton et al., 2018) (although the abundance of these species varies in the regions). After the loss of sea stars, bull kelp forests of the northern portion of California and Oregon lack the main sea urchin predators, which, combined with the low levels of protection, may erode bull kelp resilience to human activities and marine heatwave impacts. The low values of persistence for bull kelp in Oregon and California support our recommendations for higher levels of protection for highly persistent bull kelp. In addition, although Oregon bull kelp forests remained near pre-heatwave values during and after the marine heatwaves, our analyses revealed high annual variability with years with low coverage. These insights may indicate that Oregon's kelp forests may be more vulnerable to future marine heatwaves than the less variable kelp forest in Washington.

We note that our findings are subject to some caveats. For example, our kelp canopy dataset may underestimate kelp canopies that cover less than ~15 % within a pixel (Hamilton et al., 2020) or canopies that are fringing the shoreline (Cavanaugh et al., 2021). Additionally, detection gaps associated with cloud cover and lack of available imagery may be present before two Landsat sensors were in orbit prior to 1999 (Bell et al., 2015). Moreover, ongoing methodological improvements have addressed most underestimation issues (for more details, see Bell et al. (2020), (McPherson et al., under review). Our work complements a previous study in southern and central California (Arafeh-Dalmau et al., 2021), and now the persistence and protection of kelp forests has been mapped and assessed in most of the western Pacific coast of the USA. Nevertheless, some parts of eastern and northern Washington or the state of Alaska that have kelp forests and MPAs have not been mapped or assessed. However, Alaska has the lowest proportion of marine area protected in the USA (0.6 %) (NOAA, 2020), and Washington lacks marine reserves protecting subtidal habitats. Thus, the low levels of protection reported here for the USA will remain similar and likely decrease when data for these regions is available and included. Moreover, these data gaps in kelp coverage in the USA will need to be addressed by increased funding. For example, those missing areas in Washington with low kelp coverage or are fringing the coastline may require other methods, such as aerial observations.

Another limitation is that the kelp canopy dataset does not distinguish between giant and bull kelp. Although there is a clear shift in

dominance for bull kelp north of San Francisco, there are some areas where both bull and giant kelp can form beds. For example, further south in Monterey Peninsula, it is common to find some patches of bull kelp in exposed areas, and many locations in Washington have both giant and bull kelp forests dominating. Decades of kelp mapping using low-flying aircraft in Washington reveal that giant and bull kelp have similar coverage in the outer coast and western Juan de Fuca strait and that giant kelp can be dominant in some years (Pfister et al., 2018). Future improvements in remote sensing for kelp detection will need to distinguish between bull and giant kelp. The same may apply to other regions where two surface-canopy-forming kelp species co-occur (e.g., *Ecklonia maxima* and *Macrocystis pyrifera* in South Africa). Regardless of such limitations, the findings of our study apply for mixed populations of bull and giant kelp, or other co-occurring species.

Even if the trend of increasing CO₂ emissions is reversed, extreme marine heatwaves are expected to become more frequent and intense in the following decades (Cooley et al., 2022; Oliver et al., 2019), which requires climate-adaptation strategies for kelp forest ecosystems. Protecting persistent kelp is one such strategy (Arafeh-Dalmau et al., 2021), but other measures will also be necessary, such as the restoration of degraded kelp (e.g., sea urchins removal, kelp out planting), the identification of genetically resilient kelp stocks, and the management of other anthropogenic impacts not mitigated by marine reserves (Arafeh-Dalmau et al., 2020; Eger et al., 2022; Wernberg et al., 2018). Importantly, we will need to test whether marine reserves support resilience for kelp forests to marine heatwaves, in some cases marine reserves may not provide the desired ecological outcomes (Bates et al., 2019; Malakhoff and Miller, 2021), and whether persistent kelp acts as climate-refugia and their interactive effects. Existing remote-sensing and kelp forest underwater datasets give an opportunity for researchers to test such hypothesis and provide the needed evidence for decision-makers.

Here, we build from a previous approach developed by Arafeh-Dalmau et al. (2021) and map and identify potential climate-refugia for kelp. We advise increased protection of highly persistent kelp as potential indicators of climate refugia, wide-ranging ecosystem services, and as a cost-effective approach to meet area-based targets. While more information becomes available for other kelp-dominated regions, our approach will support countries in assessing their progress at meeting representation targets for kelp forests and provide tools for their protection. We suggest other kelp-dominated areas replicate our efforts to help practitioners and researchers with the datasets, research, and tools needed for the global conservation of kelp forests.

CRediT authorship contribution statement

Nur Arafeh-Dalmau: Conceptualization, Methodology, Data curation, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Carolina Olguín-Jacobson:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing. **Tom W. Bell:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Fiorenza Micheli:** Conceptualization, Writing – review & editing. **Kyle C. Cavanaugh:** Conceptualization, Investigation, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The remote sensing kelp forest dataset is available at: <https://portal.edirepository.org/nis/mapbrowse?packageid=knbnlter-sbc.74.13>. The marine protected area dataset is available at:

<https://marineprotectedareas.noaa.gov/dataanalysis/mpainventory/>.

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