ARTICLE

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Southward decrease in the protection of persistent giant kelp forests in the northeast Pacific

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Kelp forests are globally important and highly productive ecosystems, yet their persistence and protection in the face of climate change and human activity are poorly known. Here, we present a 35-year time series of high-resolution satellite imagery that maps the distribution and persistence of giant kelp (*Macrocystis pyrifera*) forests along ten degrees of latitude in the Northeast Pacific Ocean. We find that although 7.7% of giant kelp is protected by marine reserves, when accounting for persistence only 4% of kelp is present and protected. Protection of giant kelp decreases southerly from 20.9% in Central California, USA, to less than 1% in Baja California, Mexico, which likely exacerbates kelp vulnerability to marine heatwaves in Baja California. We suggest that a two-fold increase in the area of kelp protected by marine reserves is needed to fully protect persistent kelp forests and that conservation of climate-refugia in Baja California should be a priority.

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Protected areas are a cornerstone for sustainability and bio-diversity conservation[1]. As a result, the past decade has seen an increase in the area of marine and terrestrial ecosystems protected[2], stimulated by international agreements that promote area-based conservation. The Convention on Biological Diversity Aichi Target 11 and the Sustainable Development Goal 14 [3,4] aimed to effectively protect at least 10% of ecologically repre-sentative coastal and marine areas by 2020, with an increased ambition to preserve 30% of oceans by 2030 [5,6]. A central com-ponent of Aichi Target 11 is that protection includes a repre-sentative sample of coastal and marine habitats: many studies and national reports assess the representation of species and habitats such as corals, seagrass and mangroves[2,7,8]. However, some essential habitats like kelp forests remain neglected and information on their status and spatial distribution is largely lacking.

Kelp forests are one of the most productive[9] ecosystems globally, comparable to coral reefs and terrestrial rainforests. Distributed along 25% of the world's coastlines, they create a complex three-dimensional habitat, which sustains a diverse community of species[9,10]. However, extreme climatic events, overfishing, pollution, and other anthropogenic impacts threaten the capacity of these ecosystems to continue to produce goods and services worth billions of dollars to humanity[9,11–14].

As marine heatwaves, hypoxic events, and other extreme epi-sodes are becoming more frequent and severe[15], ensuring the long-term persistence of species and ecosystems requires area-based conservation and adaptive strategies to address ongoing changes in climate and ocean chemistry[16]. One such strategy is protecting potential climate-refugia[17], areas where the impacts of climate change may be less severe[18]. For dynamic ecosystems like kelp that are highly variable on seasonal, annual, and decadal timescales[9], it is critical to use long-term, large-scale datasets[19] to understand their persistence, resilience, and resistance[20], and therefore identify potential climate-refugia areas. If we map kelp forests and know patterns of persistence, we can prioritize their protection.

California, USA, and the Baja California Peninsula, Mexico, share the largest canopy-forming kelp forest species, the giant kelp *Macrocystis pyrifera*[21,22] (Linnaeus) C. Agardh 1820 (hen-ceforth "kelp"). This transboundary region has recently been subject to extreme marine heatwaves that resulted in the loss of entire kelp forests[23,24], threatening the outcomes of conservation efforts that established a network of marine protected areas in California[25] and community-based marine reserves in Baja California[26]. Despite progress, recent reporting of marine habitat representation for both regions[7,8] neglect kelp, and the conditions and location of kelp forests that are potential climate change refugia are unknown. How can countries meet post-2020 targets to adapt to climate change and protect 30% of marine habitats by 2030 [5,6,16], if no such information exists?

Here we map the distribution and persistence of highly dynamic *Macrocystis pyrifera* forests in the Northeast Pacific Ocean—spanning over ten degrees of latitude—using a 35-year satellite time series[27]. We quantified the representation of low, mid, and high persistent kelp found in two levels of protection (full and partial) across four distinct regions: Central and Southern California, and Northern and Central Baja California (see "Methods" section). Finally, we adjusted representation tar-gets by calculating the additional area required to protect kelp that is expected to be present in any given year (see "Methods" section). We find uneven protection of persistent giant kelp forest across regions with <1% fully protected in the warm-distribution limit of the species in Baja California. We suggest that protection targets should increase by over two-fold the area required to protect present kelp in any given year.

Results

Results show that, across the Northeast Pacific Ocean, 7.7% of kelp is fully protected and 3.9% is partially protected (Fig. 1a). By level of persistence, 11.7% of highly persistent kelp is fully pro-tected, with lower values for mid and low persistence (Fig. 1a). By distribution, Central California has the highest amount of per-sistent kelp forest found in the Northeast Pacific Ocean (34.8%), while Northern Baja California has the lowest (13.5%) (Fig. 1b). In terms of protection by region, we found a decrease from north to south in the area coverage of fully protected kelp (Figs. 1c and 2), being highest in Central (20.9%) and Southern California (8.4%) and lowest in Northern and Central Baja California (~1%) (Fig. 2). We found a similar pattern for partially protected kelp (Figs. 1c and 2). Central California also holds the highest per-centage of highly protected persistent kelp (Figs. 1c and 2).

We found an average persistence value of 0.43, which means that 43% of kelp distribution has kelp present in any year on average in the Northeast Pacific Ocean. The average persistence value ranged from 0.57 (Central California) to 0.37 (Northern Baja California) (Supplementary Figs. 1 and 2). Our results indicate that only 4% (instead of 7.7%) of the detected kelp habitat is expected to be present and fully protected in any year in the Northeast Pacific Ocean, ranging from 12.8% for Central California to 0.29% in Central Baja California (Table 1). Adjusted representation targets suggest that fully protecting 10% of present kelp in each region requires, on average, an increase in the representation target by over two-fold (Tables 2 and 3). However, these targets are smaller when we consider the protection of highly persistent kelp, decreasing from 23.1 to 17.6% (Table 3).

Discussion

Fully protected marine reserves are more effective than partial protection in conserving biodiversity[28] and enhancing the resi-lience and adaptive capacity of ecosystems to climate impacts[29]. By fully protecting 7.7% of kelp, the Northeast Pacific Ocean appears to be approaching the Convention on Biological Diversity Aichi target 11 of effectively protecting 10% of coastal areas by 2020. However, only Central California meets the target and additional investments are needed in the other regions. This is particularly urgent for Mexico, where 22% of its exclusive eco-nomic zone is protected[7] but the extent of kelp protection in marine reserves in the coastal region of Baja California is extre-mely limited (~1%).

The uneven representation of persistent kelp in Baja California is of concern because the warm-distribution limit of the *Macro-cystis pyrifera* is found here. This region is subject to episodes of higher sea surface temperatures and lower availability of nutri-ents, limiting kelp biomass and area[30]. Kelp forests found near their warm-distribution limit are more impacted by extreme cli-matic events[24,30–32], suggesting that future climate-driven impacts could significantly diminish the coverage of kelp in Baja California. Protection of persistent kelp in the region can minimize other local stressors, such as indirect negative effects of fishing (through the removal of predators and release of herbi-vores that can over-graze kelp[33]), maintain sources for recovery of impacted habitat patches, and build the resilience required for these ecosystems to adapt and persist in the face of future changes. For this reason, fully protecting the highly persistent kelp forests that are exhibiting high resilience to climate varia-bility and extremes in Baja California is an urgent priority.

Unless the trend of increasing CO_2 emissions is reversed, extreme climatic events are expected to become more frequent and severe in the following decades[34], which will require science-based adaptation strategies in the Northeast Pacific Ocean. Pro-tecting persistent kelp is one such strategy, but other measures
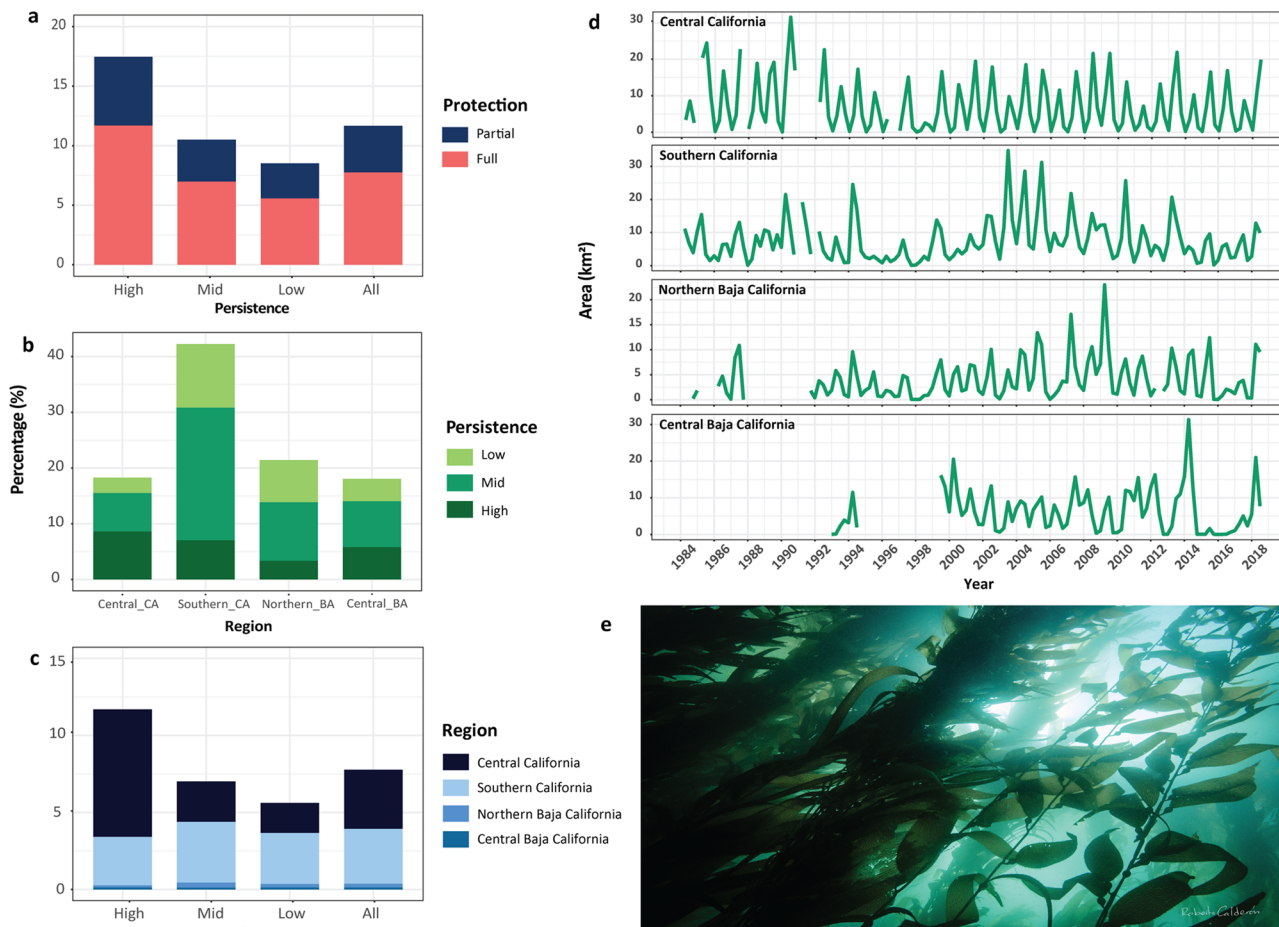
Fig. 1 Protected kelp by level of persistence in the Northeast Pacific Ocean and marine protected areas by level of protection. Bar plots (left) show the percentage (%) of the area of detected kelp by level of persistence **a** fully and partially protected, **b** contribution of the distribution in each region, **c** contribution of fully protected in each region. Time series (right) show **d** the area (km^2) of kelp canopy detected in each quarter of a year for each region over the past 35 years; **e** example of a giant kelp forest ecosystem.

will also be necessary, such as the restoration of degraded kelp, the identification of genetically resilient kelp stocks, and the management of other anthropogenic impacts not mitigated by marine reserves[11]. Importantly, we will need to test if persistent kelp acts as climate-refugia and understand the drivers and synergies (e.g., oceanographic features, human activities) which cause the high variability in local persistence (Fig. 1d), and how to integrate this information into the design of marine reserves. Moreover, climate-adaptation strategies in the Northeast Pacific Ocean will require transboundary coordination and collaboration among local stakeholders, non-governmental organizations, government institutions, and the scientific community[21,35–37].

Compared to less variable habitats like corals and mangroves, the highly dynamic nature of kelp forests[9] (Fig. 1d) poses unique challenges, rarely considered in conservation. Maps of kelp dynamics and persistence allow setting realistic and cost-effective habitat representation targets to protect kelp that is present in any given year. Not including this type of adjustments, can limit the amount of protected kelp that can provide the habitat structure for other community members.

Although the time-series dataset provided here for kelp canopy detection in the Northeast Pacific Ocean is the most comprehensive to date, some caveats remain. Examples include infrequent kelp overestimation at the intertidal interface (e.g., confusion with intertidal vegetation in some areas) and kelp detection gaps due to a lack of imagery or cloud coverage.

Moreover, ongoing methodological improvements have addressed most potential overestimation issues resulting from the movement of kelp beds and area underestimation due to wind, currents, and tides[27]. Gaps in years for Baja California could influence the persistence classification and estimation of protected kelp in marine reserves. Fewer downlink stations for Landsat and data storage issues during the 1980s and 1990s suggest that image availability is limited in areas outside of the United States. The fact that Northern Baja California has better coverage is probably a result of the proximity to California. Despite limitations, Central Baja California has over 20 years of data. In other data-limited regions, similar time series provided useful information on kelp canopy dynamics covering multiple cycles of marine climate oscillations, giving us confidence in our findings[38]. As new information and detection improvements become available, these data will be valuable for informing future marine reserve placement and evaluating progress at meeting international representation targets.

Here, we illustrate how to map and identify potential climate-refugia for kelp and other highly dynamic habitats. We advise increased protection of highly persistent kelp given their potential climate-refugia attributes, wide-ranging ecosystem services and as a cost-effective approach to meet area-based targets. Our effort should be scaled-up to map the global distribution and dynamics of kelp forests, which will require a globally coordinated effort. Only then, can countries assess their progress at meeting
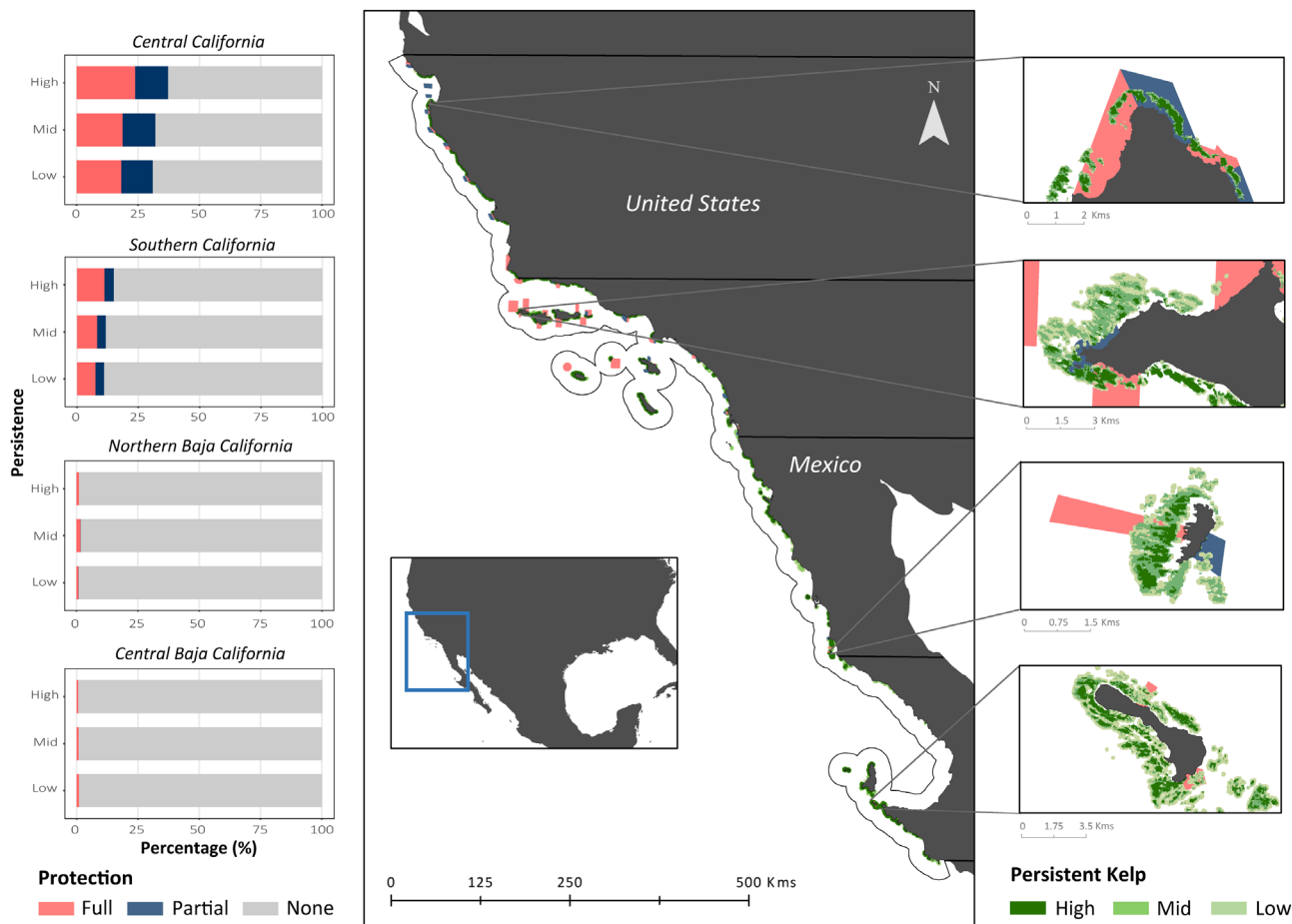
Fig. 2 The spatial distribution of kelp by level of persistence and marine protected areas by level of protection in the Northeast Pacific Ocean. Left bar plots represent the percentage (%) of persistent kelp protected per region. We provide fine-scale examples for each region. The buffer in the coastline represents the territorial seas and the horizontal lines the limits of each region.

Table 1 Probability of present kelp (P) and the number of detected kelp pixels (n) inside marine reserves for each region and for the Northeast Pacific Ocean combined. (R) represents the percentage (%) of fully protected kelp habitat and (R_p) the percentage (%) of kelp expected to be present and fully protected.

Region	P	n	R	R_p
Central California	0.61	15,567	20.93	12.83
Southern California	0.43	14,574	8.44	3.63
Northern Baja California	0.39	1,038	1.18	0.46
Central Baja California	0.43	513	0.68	0.29
Northeast Pacific Ocean	0.52	31,692	7.76	4.03

representation targets and support conservation and restoration actions for one of the world's most productive ecosystems.

Methods

Mapping kelp persistence. The study area for this analysis encompasses the region where *Macrocystis pyrifera* is the dominant canopy kelp species in the Northeast Pacific Ocean. The region extends from Año Nuevo Island in the north (latitude ~37.1°), California, USA, to Punta Prieta in the south (latitude ~27°), Baja California Sur, Mexico. We mapped the distribution of giant kelp canopy and characterized persistence using a 30-m resolution satellite-based time series covering our entire study area[27]. These data provide quarterly estimates of kelp canopy area across the study region from 1984 to 2018. We estimated giant 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). We downloaded all imagery as atmospherically corrected Landsat Collection 1 Level-2 products. Each Landsat sensor has a pixel resolution of 30×30 m and a repeat time of 16 days (8 days when two Landsat sensors were operational). Since Landsat imagery can be obscured by cloud cover, we obtained a clear estimate of kelp areas ~16 times per year from 1984 to 2018 (mean = 16.2, std = 4.1). The repeated observations across the time series avoid missing kelp canopy due to physical processes such as tides and currents. Multiple Landsat passes over seasonal timescales are successful at mitigating the effect of tide and tidal currents on Landsat kelp canopy detection[27].

While the pixel resolution of Landsat sensors is 30×30 m, we were able to observe the presence and density of kelp canopy on subpixel scales using a fully automation procedure. We first masked all land areas using a global 30 m resolution digital elevation model (asterweb.jpl.nasa. gov/gdem.asp) and classified the remaining pixels as seawater, cloud, or kelp canopy using a binary decision tree classifier trained on a diverse array of pixels within the study region[27]. We then used Multiple Endmember Spectral Mixture Analysis[39] to model each pixel as the linear combination of seawater and kelp canopy. This method can accurately obtain kelp canopy presence as long as kelp canopy covers ~13% of a 30 m pixel. These methods were validated using 15 years of monthly kelp canopy surveys by the Santa Barbara Coastal Long Term Ecological Research project at two sites in Southern California. We filtered errors of commission (such as free-floating kelp paddies) by removing any pixels classified as kelp canopy in <1% of the image time series.

We characterized kelp persistence as the fraction of years occupied by kelp canopy (at least during one quarter in a year) in each pixel (O_i) that the satellite detected kelp ($n = 408,906$) for the past 35 years. A pixel with zero value means the satellite never detected kelp forest (these values were not included); while a value of one means it detected kelp forest for all years. Then, we used kelp persistence data to group pixels into three persistence classes. We classified pixels as low persistence in the 25th percentile, with kelp found in less than 0.24 years. Mid persistence among the 25th and 75th percentile, with kelp found between 0.24 and 0.59 years. High persistence over the 75th percentile, with kelp, found over 0.59 years. To obtain the vectorial maps of kelp forest distribution for the three persistence levels, we rasterized the data points and converted them to polygons in ESRI ArcGIS Pro v10.8.

Table 2 Probability of present kelp (P) and number of detected kelp pixels (n) for each region and for the Northeast Pacific Ocean combined.

Region	P	n	P_l	n_l	P_m	n_m	P_h	n_h
Central California	0.57	74,624	0.17	9,605	0.41	29,670	0.81	35,349
Southern California	0.40	172,754	0.16	43,066	0.41	100,876	0.71	28,812
Northern Baja California	0.37	87,643	0.14	30,394	0.42	43,479	0.70	13,770
Central Baja California	0.46	73,885	0.16	16,412	0.43	33,719	0.71	23,754
Northeast Pacific Ocean	0.43	408,906	0.16	99,477	0.42	207,744	0.74	101,685

Low capital letters for the probability of present kelp (P) and the number of detected kelp pixels (n) represent low ($_l$), mid ($_m$), and high ($_h$) persistence categories.

Table 3 Multiplier (M) required to adjust fixed and unfixed (M$_h$) representation targets to protect 10% of detected kelp expected to be present for each region and the Northeast Pacific Ocean combined.

Region	M	Area (%)	$M_h{}^a$	Area (%)
Central California	1.76	17.6	2.13	15.4
Southern California	2.52	25.2	6.10	18.5
Northern Baja California	2.71	27.1	6.73	19.1
Central Baja California	2.17	21.7	3.35	17.6
Northeast Pacific Ocean	2.31	23.1	4.07	17.6

^{a}We kept constant the representation target for low and mid persistence (10%), and estimated the multiplier for highly persistent kelp needed to meet the representation target of 10%.

Kelp representation inside marine protected areas. We obtained data on marine protected area location, boundary, and type for California from the National Oceanic and Atmospheric Administration (NOAA, 2020 version) and for community-based marine reserves in the Baja California Peninsula from Comunidad y Biodiversidad, an NGO that has been supporting the local fishing cooperatives in establishing the voluntary reserves. We performed a spatial overlay analysis to estimate the representation of kelp habitats in marine protected areas. We performed the analysis using ESRI ArcGIS Pro v10.8, calculating coverage through spatial intersections of two marine protected area categories (no-take and multiple-use) and kelp forest persistence (high, mid, and low) for our region. We combined and merged marine protected areas based on the two levels of protection: no-take areas are the most restrictive type where all extractive uses are prohibited (full protection), and multiple-use areas where some restrictions apply to recreational and commercial fishing (partial protection). We divided our region into four areas, Central and Southern California, and Northern and Central Baja California. These four regions represent distinct biogeographic areas[40] where species composition varies because of oceanographic forcing, or geographic borders (USA and Mexico border). We conducted the analysis for the entire region and separately for each of the four regions.

Present kelp representation inside marine reserves. We estimate the representation of kelp habitats, in marine reserves, that are present, rather than just detected in the time series for each of the four regions and for the Northeast Pacific Ocean. We define present kelp as the probability that a pixel will be occupied by kelp in any given year, thus maintaining the habitat structure they provide. We define kelp as a pixel that the satellite detected kelp (at least once during the time series, $n = 408,906$). We estimate the probability of present kelp (P), for all pixels protected in marine reserves, as the average persistence value:

$$P = \frac{\sum_{i=1}^{n} O_i}{n}, \tag{1}$$

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

$$R_p = RP * 100, \tag{2}$$

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

Adjusting representation targets for present kelp. We adjust representation targets to protect present kelp for each of the four regions and for the Northeast Pacific Ocean. We first estimate the probability of present kelp (P) for all kelp pixels (rather than for protected pixels). Then, we adjust the representation targets to protect present kelp by applying a multiplier, M:

$$M = \frac{1}{P}, \tag{3}$$

which adjusts the representation target (T_a):

$$T_a = TM * 100, \tag{4}$$

where T is the representation target and M is the multiplier applied to adjust the representation target (T_a) to protect present kelp. Now we can ensure that the representation of present kelp (R_p) meets the representation target (T) (e.g., 10%).

Unfixed representation targets for present kelp. The previous approach uses fixed representation targets without accounting for the classification of kelp based on their persistence. However, we can adjust representation targets for specific persistence classes. As an example, we can only adjust the representation target for highly persistence kelp. We can then use the previous equation for each level of persistence (low, mid, high), leaving constant the representation target (R) (note that we substitute R for T from Eq. (2)) for low and mid persistence, and estimate the adjusted representation target for highly persistence kelp (T_h):

$$
\begin{aligned}
Tn &= R_l n_l + R_m n_m + R_h n_h, \\
Tn &= TP_l n_l + TP_m n_m + T_h P_h n_h, \\
T_h &= \frac{T(n - P_l n_l - P_m n_m)}{P_h n_h},
\end{aligned} \tag{5}
$$

where R_l is the representation of low, R_m mid, and R_h high persistence kelp. Then P_l is the probability of present kelp for low, P_m for mid, 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 mid, and n_h with high persistence kelp. We can then estimate the multiplier required to adjust representation targets of high persistence kelp M_h:

$$M_h = \frac{T_h}{T} \tag{6}$$

Worked example for adjusting the representation targets of present kelp. We estimate the probability of present kelp (P) for the Northeast Pacific Ocean and the adjusting multiplier (M) required to protect 10%[3] of present kelp (R_p):

$$R_p = 0.1 * 0.43 * 100,$$

where the probability of present kelp (P) is 0.43 and the representation target (T) is 0.1. By protecting 10% of kelp, only 4.3% of the present kelp is protected in the Northeast Pacific Ocean. We can now estimate the multiplier (M):

$$M = \frac{1}{0.43},$$

which suggests that we need to apply a multiplier (M) of 2.31 to protect 10% of present kelp in the Northeast Pacific Ocean. Finally, we can adjust the representation target (T_a):

$$T_a = 0.1 * 2.31 * 100,$$

which suggests that we need to protect 23.1% of kelp to ensure we protect 10% of kelp expected to be present in any given year.

Unfixed targets. We also provide an example by estimating the adjusted representation target of highly persistence kelp, (T_h) required to represent 10% of present kelp in the Northeast Pacific Ocean:

$$T_h = \frac{0.1(408906 - 0.16 * 99477 - 0.42 * 207744)}{0.74 * 101685} * 100,$$

which suggests that we need to protect 40.7% of highly persistence kelp to meet

representation target (T) and apply a multiplier for highly persistence kelp (M_h):

$$M_h = \frac{0.407}{0.1},$$

of 4.07.

See values from Table 2 in the main text.

Data availability

Code availability

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Author contributions
N.A.-D. conceived the idea with inputs from K.C.C., H.P.P., and F.M. N.A.-D. conducted the spatial analysis, K.C.C. led the kelp mapping with the support of K.C. and T.B. N.A.-D. wrote the manuscript with editorial input from K.C.C., H.P.P., A.M-V., G.M.-M., K.C., T.B., and F.M.

Competing interests
The authors declare no competing interests.

Additional information