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The importance of identifying and protecting coastal wildness

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Conservation of coastal biodiversity and associated ecosystem services requires protection and management for attributes of coastal wildness, which we define to include physical and ecological intactness and connectivity, native species and habitat diversity, and limited human disturbance. Coastal wildness is threatened by high demand for access to and development of coastal margins; sea level rise exacerbates this threat. As a case study, California (USA), a biodiversity hotspot, has a network of marine and terrestrial protected areas along the coast and strong coastal policy. While 35% of California's coast has wildness attributes, only 9% of California's coast is characterized as wild and also protected on both land and in the adjacent waters. A multi-tiered approach is needed to incorporate wild coast attributes into conservation planning and protection of coastal areas. A coastal wildness designation is needed, as well as policies that manage for wildness attributes in existing protected areas.

KEYWORDS

biodiversity, California, conservation, land-sea connectivity, protected area, policy, wilderness

1 Introduction

Coastal ecosystems exist as a narrow ecotone between marine and terrestrial realms and form the planet's longest distance of ecological interface linking land and sea. Coastal zones are defined here as the area within nearshore marine waters where light penetrates throughout (~50m depth) and the adjacent terrestrial areas dominated by ocean influences of tides and marine aerosols (Agardy et al., 2005). Accounting for less than 5% of Earth's land area, coastal ecosystems are highly productive and concentrate disproportionately high values for biodiversity and ecosystem services (Agardy et al., 2005). Coastal ecosystems are highly dynamic and globally threatened by changing climate, sea level rise, and development. Nearly 40% of the world's population lives within 100 kilometers of a coastline (Small and Nicholls, 2003; Center for International Earth Science Information Network (CIESIN) of Columbia University, 2006; Center for International Earth Science Information Network (CIESIN) of Columbia University, 2012). Consequently, many coastal habitats have been converted for development, commerce, and recreation (Halpern et al., 2008; Barbier et al., 2011; Wright et al., 2018). Today, just 15.5% of coastal areas worldwide can be considered ecologically intact and having low

anthropogenic pressure (Williams et al., 2022). Many of the remaining natural coastal areas are adjacent to human-altered landscapes, highly disturbed, and threatened by development (Neumann et al., 2015; Heady et al., 2018).

The narrow width and highly dynamic properties of coastlines can render them vulnerable at the local and landscape scale to anthropogenic impacts (Alvarez-Romero et al., 2011). Coastal ecosystems are physically and ecologically dependent on adjacent terrestrial and marine ecosystems to provide key inputs (such as trophic subsidies, nutrients, sand supply, freshwater supply) as well as to support wildlife connectivity across the land-sea interface. Consequently, connectivity, condition, and management of adjacent terrestrial and marine areas will affect the maintenance of the character of coastal habitats. Coastal ecosystems are inherently vulnerable to habitat loss, defaunation, and human disturbance due to their constrained location at the land-sea interface and dependence on inputs from both adjacent terrestrial and marine ecosystems (Williams et al., 2022). Land use, resource extraction, and infrastructure – even well inland in coastal watersheds – can disrupt freshwater inputs and flows, alter sand supply, and change erosional and depositional processes leading to an unraveling of coastal ecosystem processes and functions (Defeo et al., 2009; Alvarez-Romero et al., 2011; Merrifield et al., 2011). Coastal development, armoring, diking, dredging, beach grooming, and sand mining along the coast also affect physical processes and habitat quality for a variety of species (Schlacher et al., 2007; Dugan et al., 2008; Hubbard et al., 2014; Torres et al., 2017). Invasive species can alter species composition and structure of habitats, impact trophic dynamics, and alter nutrient and sediment loads to coastal areas (Byrnes et al., 2007; Williams and Grosholz, 2008). Wildlife use of coastal areas, such as resting and feeding areas for marine mammals and migratory birds and foraging grounds for top predators, can be significantly impacted by recreation and human disturbance (Lafferty et al., 2013; Larson et al., 2019). Overharvest of resources and trampling of intertidal and coastal habitats can reduce biodiversity, alter trophic structure, and affect wildlife use of the coast (Addessi, 1994; Crowe et al., 2000; Roy et al., 2003). Oil spills, toxic releases, and poor water quality can also significantly impact the condition of coastal areas (Crowe et al., 2000; Hughes et al., 2015; Bejarano and Michel, 2016).

Direct and indirect effects of climate change (e.g., sea level rise, coastal erosion, more frequent and intense storms, and changing ocean conditions) exacerbate these threats (Heady et al., 2018; Luijendijk et al., 2018; Lorie et al., 2020; Barnard et al., 2021) especially as coastal habitats are squeezed between rising sea levels and topographic or built environment constraints on their upward migration (Vitousek et al., 2017; Heady et al., 2018; He and Silliman, 2019; Leo et al., 2019; Barnard et al., 2021). Climate change is also altering storm frequency and intensity which can drive coastal erosion and coastal change (Zedler, 2010; Lehmann et al., 2018; Barnard et al., 2021). Changing ocean conditions, including rising temperatures, altered circulation patterns, increased acidity, and shifts in species distributions are already altering coastal marine ecosystems and will continue to do so well into the future (Hewitt et al., 2016; He and Silliman, 2019). In this light, shoring up coastal resiliency by protecting the most intact and wild areas becomes an even more urgent priority, as does prioritizing areas of the adjacent terrestrial realm for protection that will be needed to serve as coastal habitat strongholds in the future (Heady et al., 2018).

Coastal conservation efforts lag behind those for terrestrial and marine ecosystems (Jones et al., 2018). Indeed, most conservation planning processes still focus on either the terrestrial or marine realm in isolation and do not explicitly address the importance of conserving coastal biodiversity, ecological connectivity, and processes that span the land and sea interface (Beger et al., 2010; Alvarez-Romero et al., 2011; Harris et al., 2014). Coastal areas with intact physical and ecological processes, functions, and diversity provide myriad values to society (Barbier et al., 2011). They support numerous habitat types (such as rocky shores, sandy beaches, dunes, wetlands, and estuaries) and associated species; as well as nursery, foraging, and resting grounds for many species of economic and cultural importance (Beck et al., 2001; Neuman et al., 2008). Coastal areas are the physical and ecological connection between marine and terrestrial ecosystems and play a key role in nutrient, sediment, and water flows; they also buffer human communities from storm surge and sea level rise (Barbier et al., 2011; Arkema et al., 2013; Neumann et al., 2015). Protection of intact ecosystems can be an efficient means of conserving biodiversity, protecting ecosystems services, and slowing extinction rates as demonstrated in terrestrial and marine systems (Di Marco et al., 2019). To inform such efforts along coasts, however, planners need criteria for identifying intact coastal areas. Here we describe attributes of ecologically intact and functional coastal areas, which we further define below as areas of "coastal wildness".

We demonstrate how these attributes and considerations can be applied in conservation planning and management, using California (USA) as a case study. The state of California (USA) is an ideal study area for examining protection of coastal wildness with its long, ecologically diverse coastline, and history of coastal protection and strong coastal policy (Lester, 2013). About 68% of California's population of 38.4 million people lives within 48 km of the coast (NOAA Office for Coastal Management https://coast.noaa.gov/states/california.html). Conflicts between coastal access and coastal development led to the passage of the California Coastal Act in 1976, which provides for coastal conservation, coastal access for the public, and relatively strict regulations on coastal development. California has extensive terrestrial protected areas (e.g., national and state parks) along the coast, as well as a network of marine protected areas (MPAs) in nearshore waters (Gleason et al., 2013). Due to data limitations, our study focused on California's mainland coast, including San Francisco Bay, but not the coast on offshore islands. We note that California's islands are generally well-protected; their relatively robust populations of breeding pinnipeds and seabirds suggest the conservation values that can be retained by protection of coastal wildness.

We illustrate how lack of protection of coastal wildness represents a significant conservation gap, even in geographies with strong coastal policy and a system of coastal marine and terrestrial protected areas. Our analysis suggests that not only is greater investment in coastal conservation warranted, new

designations aimed at prioritizing and preserving wild coastal areas may also be necessary.

2 Materials and methods

We defined coastal wildness as areas that are largely physically and ecologically intact, with limited human disturbance, and containing (or having the potential to contain) the full complement of biodiversity expected for the associated habitat types in their unimpaired states (see also Kormos et al., 2016; Watson et al., 2016). We applied this definition to the mainland coast of California, USA. Using Geographic Information System (GIS) software, we defined a study area that spanned the mainland California coastline to 8 km inland of projected 1.5 m of sea level rise. Readily available spatial data were compiled and aggregated to a grid of 4 km^2 hexagons to best match the resolution of the data with the resolution needed for analyses. Data were also aggregated by regions, within these geographic bounds: North (Marin County and north to the Oregon border), Central (San Francisco south to Santa Maria), South (Santa Maria south to the border of Mexico), based on established terrestrial and marine ecoregional boundaries (e.g., Bailey, 2004; Spalding et al., 2007).

We characterized four attributes of wildness to identify areas with high ecological intactness, high physical intactness, high species and habitat diversity, and low human disturbance. (Table 1; see Supplemental Information for full methods and Table S1 for data sources).

- Ecological Intactness Index: was based on indicators of ecological function and connectivity including natural landscape blocks, counts of shorebird and marine mammal colonies, and haul out areas (Table S1). These indicators were ranked and summed in an additive model framework. Quintiles were taken from the distribution generated from the model to represent a rank-score for the index with a value of 1 as low ecological intactness and a value of 5 as high ecological intactness.
- Physical Intactness Index: was based on three indicators of the built environment along the coast including a landscape development intensity index taken from (Heady et al. (2018); sensu Brown and Vivas, 2005), percent of the shoreline armored, and counts of piers, jetties, and harbors (Table S1). These indicators were ranked and summed in an additive model framework. Quintiles were taken from the distribution generated from the model to represent a rank-score for the index with a value of 1 being high physical intactness and a value of 5 being low physical intactness.
- Habitat and Species Diversity Index: was based on a Rarity Weighted Richness Index (RWRI) taken from (Heady et al. (2018); sensu Albuquerque and Beier, 2015) which accounted for terrestrial species and habitat richness weighted for coastally dependent occurrences, with species weighted relative to statewide occurrences and habitats weighted relative to occurrence in the larger study area (Table S1). We aggregated 1km^2 RWRI index from Heady et al. (2018) into 4km^2 grid cells. Quintiles were taken from the distribution generated from the model to represent a rank-score for the index with a value of 1 as low species and habitat diversity and a value of 5 as high species and habitat diversity.
- Human Disturbance Index: was based on count of coastal access locations and density of built features, including roads and buildings (Table S1). These were ranked and summed in an additive model framework. Quintiles were taken from the distribution generated from the model to represent a rank-score for the index with a value of 1 as low human disturbance and a value of 5 as high human disturbance.

Each of the four attributes of wildness were mapped statewide, with quintile rank scores for each hexagon, showing broadscale patterns of ecological and physical intactness, diversity, and human disturbance (Figures S1–S4).

To characterize coastal wildness, we developed a "Coastal Wildness Index" based on the four attributes. Using an additive model, we combined indexed quintile scores with Ecological Intactness and Species/habitat Diversity contributing positively to wildness, and Human Disturbance and lack of Physical Intactness indices contributing negatively to a coastal wildness index (see Stein et al., 2009; Heady et al., 2015). We ranked the resulting coastal wildness index using quintiles with 1 representing low coastal wildness values and 5 representing high coastal wildness values; we considered areas with rank 4 or 5 to be 'wild coast'.

We then compiled spatial data on Conservation Management Status (CMS), Marine Protected Areas (MPAs) and ownership (federal, state, or private) to identify existing terrestrial and marine protected areas that could most likely support effective management and conservation of wildness attributes (Table S2; CMS dataset modified from Heady et al., 2018, data derived from the California Protected Areas Database CPAD, 2016 and other sources; see Heady et al., 2018 for data sources). We considered CMS category A (highly conserved) and B (conserved) to contribute most to the protection of wild coast attributes, with the more highly conserved category A likely providing more protection of wildness attributes. We then overlaid existing marine and terrestrial protected areas with the Coastal Wildness Index spatial layer to calculate and assess gaps in protection of wild coast areas. Additionally, we identified areas of wild coast that are publicly or privately owned (CMS category C and D), but not conserved, to identify potential opportunities for future conservation of wild coast.

3 Results

Approximately 35% of the California coastal study area can be characterized currently as wild coast (Figure 1; Table S3). This varies by terrestrial ecoregion, with about 39% of northern and central California regions having wild coast attributes (Figure S5; Table S3), including some well-known areas such as the King

TABLE 1 Attributes of coastal wildness, their description, and types of data that could be used to inform analyses.

Attribute	Description	Types of data
Ecological intactness	Intact and functioning ecological processes, functions, and relationships (e.g., contiguity of habitats; land-sea connectivity; population and metapopulation connectivity; breeding and nursery functions; functioning community dynamics; complete trophic structure; presence of top predators and predator redundancy)	• Terrestrial-marine connectivity (e.g., estuaries, river mouths, coastal habitats) • Habitat intactness • Marine mammal haul outs, seabird colonies • Presence of top predators
Physical intactness	Unfragmented natural landscape/seascape context, with intact abiotic processes (e.g., unimpeded flows and dynamics of water, sediments, and materials; nutrient levels within natural ranges; cross-ecosystem subsidies); absence of, or limited, coastal infrastructure.	• Habitat fragmentation • Intensity of built environment • Coastal armoring and structures (e.g., riprap, jetties, piers, harbors); coastal infrastructure (e.g., roads, railroads) • Barriers to fish passage, sediment, or water flows (e.g., dams, culverts) • Sea level rise models of projected landscape change
Biodiversity	Natural complement of biodiversity for given habitat types, with relatively high habitat diversity and abundant populations of diverse native species (including top predators and keystone species) across terrestrial, coastal, and marine realms	• Biodiversity indices (rarity-weighted species richness indices) • Habitat diversity • Presence of key species (rare and keystone species, top predators) • Nesting, roosting, nursery areas for key wildlife
Human Disturbance	Largely undisturbed by human activities or resource extraction	• Footprint of built environment • Road density • Coastal access points • Human use

Range-Lost Coast, and Big Sur. In southern California, 27% of the coast has wild attributes, including Vandenberg Space Force Base, the Point Conception area, Malibu-Santa Monica Mountains, and Camp Pendleton Marine Corps Base (Figure 1; Table S3). Some wild coast areas, especially in northern California, likely have proxy protection by their remoteness and low population density. Other areas, such as military lands in southern California, have some level of *de facto* protection from recreation and access but are subject to military uses and priorities.

Statewide, approximately 60% of the area characterized as wild coast is currently protected in CMS A or B, amounting to about 21% of the total California coastal area (Figure 2). Only about half of that, 11% of the total coastal area, is managed for values consistent with sustaining wild coast attributes in the most protected category (CMS A, highly conserved; see Figure S6; Table S3). Areas of wild coast with protection spanning the land-sea interface are limited. Only about a quarter (26.6%) of areas characterized as wild coast are protected terrestrially (in CMS category A or B) and adjacent to an MPA, amounting to about 9% of California's coastline (Figure 2; Table S3). Some parts of the wild coast area characterized as well protected on the marine side are adjacent to agriculture or development on the terrestrial side. Similarly, other wild coast areas with strong terrestrial protection lack protection of coastal and marine biodiversity in an adjacent MPA.

Remaining wild coast is distributed non-equally among regions of California. Of the 35% of the remaining wild coast, 13.5% is in the North Coast, 14% in the Central Coast, and 7.9% in the South Coast (Figure 1; Table S3). Levels of protection for remaining wild coast areas also vary by region with 'highly conserved' area (CMS A) of 29.3% of wild coast of the North Coast, 43.6% of Central Coast, and 10.6% of South Coast, and 'conserved' area (CMS B) of 2.5% of wild coast of the North Coast, 3.0% of Central Coast, and 5.0% of South Coast region (Figures 1, 2; Table S3).

We found that about 40% (1,974 km^2) of the area characterized as wild coast is in private ownership (Table S3; Figure S6). This amounts to about 14% of the total coastal area highlighting that even in a relatively well-conserved geography like coastal California there remain opportunities for conserving wild coast values through conservation easements or other mechanisms on land, especially where that can be paired with marine protection in nearshore waters.

4 Discussion

Ecologically intact and wild areas are essential for effective biodiversity conservation and resiliency in the face of global change, and areas with these attributes are poorly protected globally (Di Marco et al., 2019). Coastal areas with high wildness values have been undervalued by conservation planning and often fall in the cracks between terrestrial and ocean protection, management, and governance. California has some of the strongest coastal policy of any place in the world. Yet despite a robust policy framework and decades of conservation, we found that much of California's remaining wild coast is vulnerable to threats to biodiversity and ecosystem function. This is largely due to

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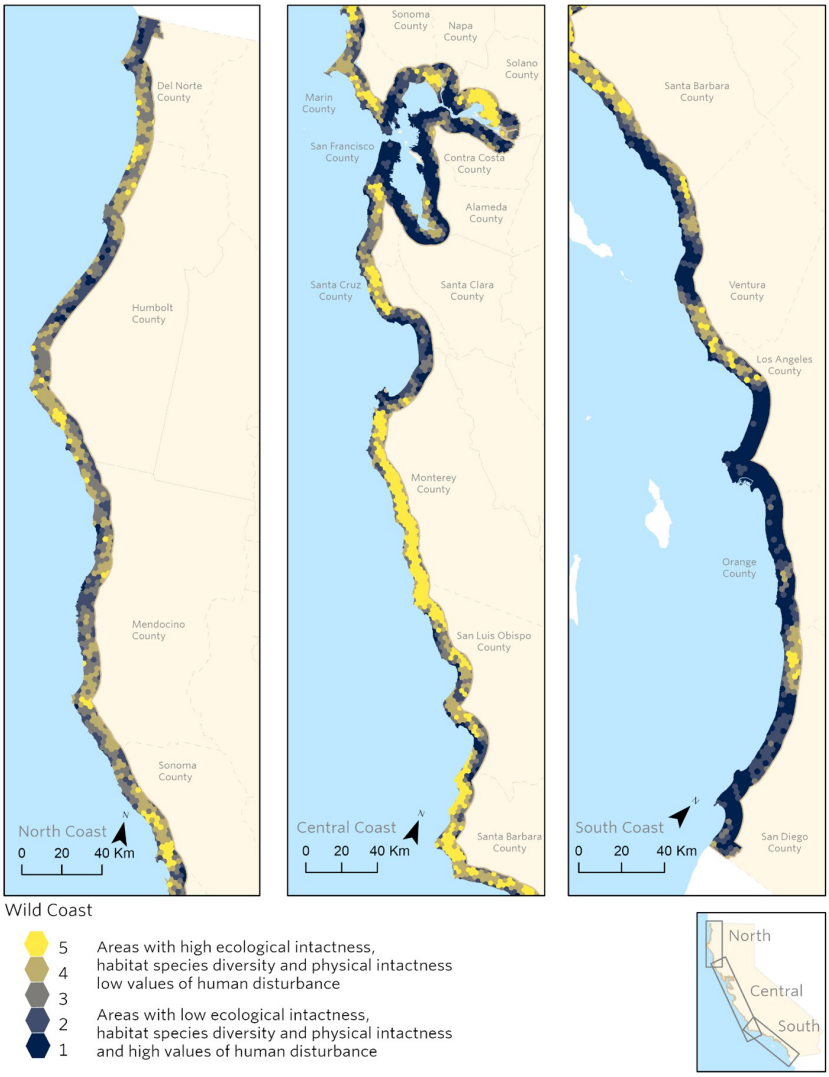

FIGURE 1
Areas along California with highly ranked (rank 4 & 5) wild coast attributes of ecological intactness, physical intactness, biodiversity, and low human disturbance highlighted in yellow.

the paucity of areas with management focus of protecting wildness attributes, the importance placed on providing public coastal access, and the lack of integrated marine-terrestrial conservation planning and management oversight.

Conservation of wild coastal areas urgently needs more attention in conservation planning, policy, and practice around the world, especially where there are opportunities for adjacent land-sea protection and management. With nearly half of the global population residing near the coast and increasing threats focused in coastal areas, we recommend a multi-tiered approach to conservation of wild coastal attributes based on four key elements:

4.1 Incorporate wild coast attributes in systematic conservation planning to identify remaining wild coast areas

As we have shown, attributes of wild coastal areas can be defined with biophysical, ecological, and anthropogenic criteria, and they can be mapped using data that are publicly available. Incorporating wild coast attributes into conservation planning efforts will help identify the location and extent of wild coastal areas for protection, restoration, and management, as well as optimize opportunities for integrated landscape and seascape conservation.

4.2 Protect existing and future wild coast areas

Wild coast areas may be protected through a combination of traditional protection and acquisition strategies, public policy, and management of wildness attributes. Coastal policy and investment in protection and management should explicitly include attributes of coastal wildness. Many coastal areas are quasi-protected with no legal long-term protection, policy, or management that focuses on the wildness attributes or the important connections to adjacent marine and terrestrial ecosystems. Formal protections, through designations and management that prohibits extractive uses and

development, may be needed on both the terrestrial and marine sides of the coast. In some areas, indigenous stewardship or co-management arrangements may be the best management approach. At the global scale, existing enabling conditions should be leveraged around opportunities for integrated landscape and seascape protection and to enhance wild coastal connectivity and functional networks of protected areas. Conserving wild coast attributes and the biodiversity and ecosystem services they confer will require policy and management explicitly focused on those goals.

4.3 Manage for wild coast attributes within and outside of wild coastal areas

Conserving wild coastal areas will require long-term and large-scale management. To conserve the fundamental attributes of wildness, wild coastal areas need to be managed to minimize human disturbance and to maintain and restore natural processes, ecological condition, and biodiversity, across the land-sea interface. Managing for wild coast conservation values within and outside of designated wild coastal areas will require a full range of approaches including habitat restoration, restrictions on access, permanent or temporary prohibitions on certain activities (e.g., resource extraction, hunting and harvesting species, dogs, motorized vehicles), and other tools to minimize human disturbance and abate the many threats to coastal biodiversity. Multi-benefit management of wild coast attributes also creates opportunities for traditional and cultural co-management. Managed public access programs (e.g., via docent led hikes), seasonal no entry areas, and other approaches can be used to provide wildness experiences and to cultivate support while facilitating wildness attributes by limiting impacts on wildlife from human disturbance.

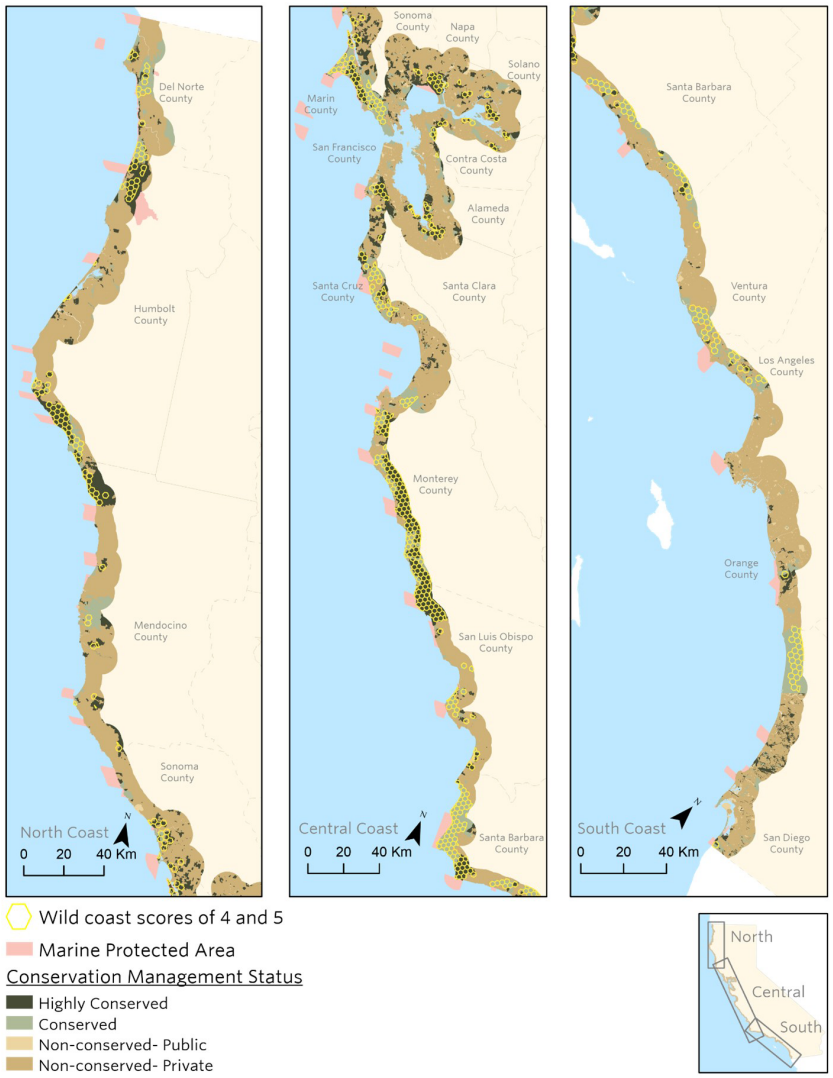

FIGURE 2
Terrestrial conservation management status, marine protected areas, and areas with wild coast attributes across three regions in California.

4.4 Build constituencies and effective policy for conserving wild coastal areas

Conserving wild coasts in the face of burgeoning coastal populations, climate change, and sea level rise will require engaging the public and growing constituencies to advocate for needed policies, governance, and funding. For example, providing low-impact wildlife viewing and wilderness experiences, managed public access, as well as quantifying the ecosystem service benefits of wild coastal areas (e.g., intact estuaries as nursery habitat for fisheries, extensive healthy coastal marsh to clean waters and sequester carbon, coastal resilience and storm protection, and aesthetic and recreation opportunities) are strategies with the potential to build constituencies for wild coasts. Wild coastal areas have been integral to humanity for millennia and there are opportunities to learn from traditional ecological knowledge, restore and extend indigenous connections to wild coast areas, and to engage indigenous or tribal contributions to management (Fletcher et al., 2021). As we have shown in the California example, existing protected areas designations are often inadequate for protecting wild coastal areas. This creates a need and opportunity for new designations for 'Areas of Coastal Wildness' that could be modeled on the U.S. 'Wild and Scenic Rivers' designation and create an important policy framing around constituency building, protection, and management of wild coastal areas (e.g., Rothlisberger et al., 2017 discuss US Wild and Scenic Rivers designation).

Wild coast areas are essential to conservation of biodiversity, ecosystem services, and coastal resilience, yet are undervalued and imperiled by population growth, development, habitat destruction, and climate change. Growing threats are squeezing out opportunities to effectively conserve the narrow strip of coastline that rings the earth's terrestrial environment. Conservation of these areas will require increased awareness of their importance, focused and effective policy, and perhaps new designations tailored to the unique challenges and attributes of these increasingly rare wild features. The California example shows that wild coasts can be vulnerable even in the context of relatively strong regulation, governance, and local, state, and federal protection designations. With a renewed focus by the state on protecting 30% of California's terrestrial and nearshore waters by 2030 (California Natural Resources Agency, 2022), there are opportunities for protection of the state's remaining areas of coastal wildness. We hope approaches such as the relatively simple framework for identifying wild coastal areas that we outlined here can be expanded upon to rapidly identify and protect the remaining wild coastal areas around the world before they are lost. The fate of numerous coastal dependent species depends on doing so.

Data availability statement

Data for the original contributions presented in the article are available on the Knowledge Network for Biodiversity (KNB) repository https://knb.ecoinformatics.org/view/urn%3Auuid%3A2f1c0de5-30ae-42b3-b05e-7214a5874115.

Author contributions

All authors contributed to the conceptualization of the article, contributed to the article writing and approved the submitted version. KE and WH led the analysis of the data. All authors contributed to the article writing and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcosc.2023.1224618/full#supplementary-material

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