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Co-occurrence of surf breaks and carbon-dense ecosystems suggests opportunities for coastal conservation

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Abstract

Surf breaks are increasingly recognized as socio-environmental phenomena that provide opportunities for biodiversity conservation and sustained benefits for local communities. Here, we examine an additional benefit from improved conservation of the ecosystems that host and surround surf breaks—their coincidence with carbon dense coastal ecosystems. Using global spatial datasets of irrecoverable carbon (defined as carbon stocks that, if lost today, could not be recovered within 30 years' time), surf break locations, ecosystem types, protected areas, and Key Biodiversity Areas, we identified 88.3 million tonnes of irrecoverable carbon held in surf ecosystems. Of this total, 17.2 million tonnes are found in Key Biodiversity Areas without formal measures of protection. These results highlight surf conservation as a potential avenue to simultaneously mitigate climate change, protect biodiversity, and promote sustainable development in coastal communities.

KEYWORDS

area-based conservation, biodiversity, climate change mitigation, mangroves, OECMs, protected areas, socio-ecological systems, surf conservation, surfing

1 | INTRODUCTION

Surf breaks[1] are increasingly recognized as a new asset class upon which conservation of adjacent marine and terrestrial ecosystems can be founded (Scheske et al., 2019, Touron-Gardic & Failler, 2022). Located along shorelines globally, surf breaks often occur in or near priority ecosystems for conservation, such as highly biodiverse coral reefs, mangroves, or tropical forests (Reineman et al., 2021). Currently, the surf tourism industry is valued at 31–65 billion USD (roughly 15–30 times the value of today's voluntary carbon market), with benefits driving growth in developing economies and individual surf breaks bringing as much as 35.3 million USD annually to some communities (Donofrio et al., 2022; Mach & Ponting, 2021). Despite their significant value, surf breaks and their surrounding environments are subject to numerous threats, including coastal development (Corne, 2009), degradation of habitats, and impacts from climate change such as sea level rise (Reineman et al., 2017; Sadrpour & Reineman, 2023). There is consequently widespread interest in developing models of coastal conservation that protect the marine and terrestrial ecosystems that host surf breaks from these threats (Manero, 2023; Orchard et al., 2023).

The coastal socio-environmental systems that host surf breaks—which we refer to here as "surf ecosystems"—not only house high levels of biodiversity (Reineman et al., 2021) but can also contain large amounts of carbon. For example, coastal vegetated ecosystems such as mangroves, seagrass beds, and salt marshes (commonly termed "blue carbon" ecosystems), are among the most carbon-dense ecosystems on the planet (Macreadie et al., 2021). Although less commonly found in direct association with surf breaks, blue carbon ecosystems can be found in lower energy portions of the same coastlines and contribute important value, such as control of sedimentation, shoreline protection, and support of fish nurseries, to the broader surf ecosystem. When carbon-dense ecosystems such as these are converted to other uses, they emit large amounts of carbon dioxide to the atmosphere, driving anthropogenic climate change. While the potential for expanding protection of biodiversity conservation in surf ecosystems has been examined (Reineman et al., 2021), we lack understanding of how much carbon is held in surf ecosystems, which is critical for aligning surf conservation with climate change mitigation efforts.

Expanded conservation of surf ecosystems (including both their marine and terrestrial components) could provide a range of ecosystem services and values in addition to conservation of biodiversity and climate mitigation (Barbier et al., 2011). Although direct links between the health of surf ecosystems and surf break quality are absent in the literature, there are many avenues by which their protection can contribute to the greater well-being of coastal socio-environmental systems. Coastal estuaries facilitate nutrient cycling, control sedimentation, and provide nurseries for fish populations (Gaylard et al., 2020). Healthy upland ecosystems can improve habitats by reducing erosion and sediment loads to littoral areas (Bartley et al., 2014; Lavergne et al., 2022), and these services can similarly reduce the potential for surfer illness through improved water quality (Grant et al., 2001). Coral reefs shape surf breaks (Mead & Black, 2001), but also provide fishing grounds, non-surfing recreational opportunities such as diving, and shoreline protections (Moberg & Folke, 1999). Moreover, all the foregoing ecosystems provide cultural and spiritual value to local communities across the globe (Millennium Ecosystem Assessment, 2005).

Coastal management models that employ surf breaks as assets for conserving surf ecosystems are emerging across the globe. For example, Conservation International and Save The Waves Coalition are collaborating in partnership with organizations, local communities, and governments to use high-quality surf breaks as anchors for the establishment of surf protected areas. Here, surf protected areas refers to the use of local legal frameworks and protected area approaches to protect surf breaks and their surrounding environment–including both the terrestrial and marine components. It is important to emphasize that under this model, surf breaks are not the sole point of focus but are considered in concert with the surrounding coastal environments. Conservation of surf ecosystems is already being pursued in a handful of countries through the establishment of Surf Protected Area Networks (SPANs), which legally protect biodiverse and carbon-dense coastal ecosystems. For example, 40 km^2 of marine, coastal, and terrestrial area has been protected in Chile through the Piedra del Viento Coastal Marine Sanctuary (hosting six surf breaks), and 68 ha of riparian ecosystems in the San Miguel Watershed of Mexico has been protected through the establishment of a state park (hosting five surf breaks).[2] In addition, over 30,000 ha of marine and coastal area has been protected through 10 surf protected areas on the island of Morotai, Indonesia, which we discuss further in a case study (see below). As surf conservation models like this gain traction globally, their proliferation must be guided by science to optimize their contributions to global goals for biodiversity conservation and climate mitigation (Bukoski et al., 2018; Swamy et al., 2017).

Here, we quantify the irrecoverable carbon—defined as ecosystem carbon stocks that, if lost today, could not be recovered within 30 years (Goldstein et al., 2020)—held within the terrestrial component of global surf ecosystems. We draw on a suite of geospatial data to delineate surf ecosystems, quantify their irrecoverable carbon stocks, and evaluate whether these portions of coastlines exist within protected areas or Key Biodiversity Areas. Given that our analysis is global in scope, we also present a case study to exemplify ongoing surf conservation efforts on Morotai Island of Indonesia and how consideration of irrecoverable carbon can be integrated into these discussions. Specifically, we describe the ongoing development of a SPAN within Indonesia, which hosts carbon-dense ecosystem types (including roughly one-fifth of the globe's mangroves) as well as many popular surf destinations. We detail the government mechanisms that act in support of Indonesia's SPAN, activities that are being undertaken by local partners, as well as potential opportunities to operationalize carbon financing.

In presenting our findings, we discuss the applications of our results for conservation-focused organizations, focusing on how to support expanded conservation of surf ecosystems. We anticipate that our study will (i) encourage adoption of surf conservation efforts more broadly, (ii) expand research efforts on the potential value of surf ecosystem conservation, and (iii) encourage prioritization of opportunities that expand both biodiversity conservation and protection of irrecoverable carbon in coastal regions. In addition to extending previous analyses of the biodiversity value of surf conservation (Reineman et al., 2021), our study contributes directly to the growing body of research on the social, cultural, and economic value of surf ecosystems (Manero & Mach, 2023; Román et al., 2022).

2 | METHODS

Our analysis is based on spatial intersections of six global datasets: (i) locations of surf breaks, (ii) coastal watersheds, (iii) biome/ecosystem types, (iv) protected areas, (v) Key Biodiversity Areas, and (vi) irrecoverable carbon stocks (see Table S1). The primary challenge of our analysis was delineating the boundaries of surf ecosystems. Defining what constitutes an ecosystem is complex (Post et al., 2007) and we do not attempt to establish a formal definition of a surf ecosystem here. Doing so would require incorporation of data sources and information that we do not have—such as interactions between physical and biological systems, cultural values, and land and sea management practices. Instead, we operationalized a spatial proxy of surf ecosystem boundaries based on an ecological understanding of terrestrial–marine interactions and the approaches of existing surf protected areas (Carlson et al., 2019; Rude et al., 2016).

Specifically, we used coastal watersheds that drain onto surf breaks as the basis of our analysis. This is analogous to a "ridge-to-reef" approach, which is common within the conservation field and is based on extensive research showing impacts of upland land use (e.g., pollution or sedimentation) on marine resources (Bainbridge et al., 2018; Carlson et al., 2019; Rude et al., 2016). Moreover, this approach mimics existing surf protected areas, such as the San Miguel State Park that protects the riparian oak watershed upland of the San Miguel surf break (see footnote 2). In some instances, conservation of entire watersheds will be possible; however, in most cases such extensive projects will be infeasible. We therefore constrained our analysis to the portions of watersheds that are within 1–3 km of coastlines, which proxy varying extents of the terrestrial portion of surf ecosystems. To delineate surf ecosystems, we extracted coastlines from the GADM database of country extents, buffered the coastlines by 1–3 km, and intersected them with a dataset of coastal watersheds (Figure 1). Given our preference for proximity to surf breaks, we use the 1 km coastline buffer as our base unit of analysis, but also present results for 2 and 3 km buffers to explore more expansive conceptualizations of surf ecosystems.

We obtained polygons of coastal watersheds from the HydroBASINS dataset (Lehner & Grill, 2013). HydroBASINS uses data on topography to map watersheds at twelve different scales for the globe, ranging from entire continents to local catchments. Our focus was on extents of coastline that associate with surf breaks and we therefore used the smallest (i.e., "level 12") watersheds. Watersheds were missing from the HydroSHEDS database for small islands and atolls in the Pacific, Atlantic, and Indian Oceans that host surf breaks ($n = 80$). For Hawaii, we used data on watershed extent from Hawaii's Department of Land and Natural Resources (Hawaii Department of Land & Natural Resources, 2006). We were unable to obtain watershed extent for other small islands and atolls and therefore manually digitized them. Expanding the watersheds dataset allowed us to capture the full extent of our global surf break dataset, but minimally increased the total footprint of our area of interest (<1%).

We selected coastal watersheds for our analysis by intersecting them with a global dataset of surf breaks, which we obtained from the Stormrider Surf Travel Guides' "The World Book", a travel guide created by Low Pressure Ltd. (Sutherland & Colas, 2018). This dataset has been curated over more than three decades of surf travel, verified by local surfers around the world, and is regularly updated with their contributions. In total, the Stormrider dataset describes 4830 surf breaks located across 113 countries. The dataset also includes a five-tier

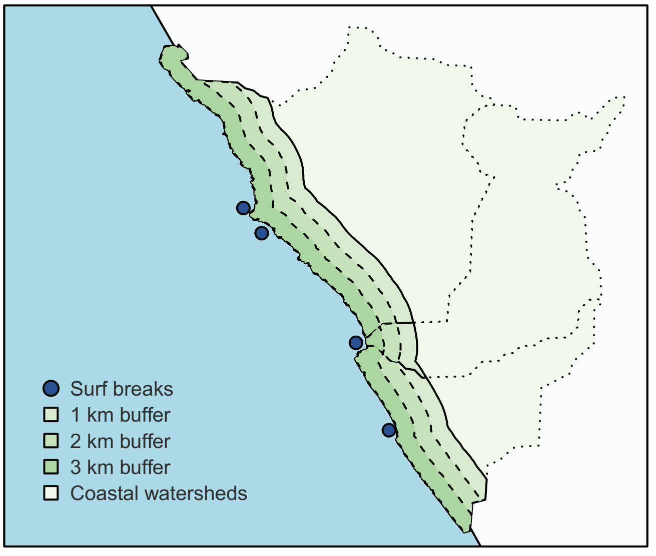

FIGURE 1 Example depiction of 1 km, 2 km, and 3 km buffers of coastlines and their relation to coastal watersheds upland of surf breaks. The coastline buffers are the delineation of "surf ecosystems" used in this study.

ranking of wave quality that ranges from "poor" to "world class." Ranking of wave quality entails high levels of subjectivity, given that waves provide different cultural values for individuals and communities, which may vary with experience level and personal preferences. Nevertheless, not all surf breaks will garner sufficient excitement to justify establishment of surf protected areas. We therefore performed a sensitivity analysis to understand how our results change when focusing on the most highly-rated waves (i.e., good, excellent, or world-class waves).

For each coastal watershed hosting a surf break (i.e., surf ecosystem), we then intersected several spatial datasets to quantify the total irrecoverable carbon held in different surf ecosystem types, as well as how much of this irrecoverable carbon was found in existing protected areas and Key Biodiversity Areas. First, we intersected the watersheds with a map of terrestrial biomes and ecoregions (Dinerstein et al., 2017), adjusted to include coastal ecosystem-specific maps of mangroves and salt marshes (Mcowen et al., 2017; Thomas et al., 2018). We were unable to obtain reliable maps of seagrass extent and unfortunately were not able to quantify irrecoverable carbon held specifically in seagrasses. Next, we intersected this map with protected area extents (UNEP-WCMC and IUCN, 2023) and a map of Key Biodiversity Areas (IUCN, 2016) to identify those ecosystems that are already under formal protection, and that coincide with priority areas for biodiversity conservation. Finally, we intersected this map with national boundaries to identify country-specific opportunities to expand protection of irrecoverable carbon in surf ecosystems (GADM, 2022).

To quantify climate-critical carbon stocks held within the terrestrial component of surf ecosystems, we used a map of irrecoverable carbon (Noon et al., 2022). Marine carbon stocks are primarily held in benthic soils, which are unlikely to be at high risk of loss within 1–3 km of the shoreline. Moreover, while a global map of benthic soil carbon now exists (Atwood et al., 2020), the spatial resolution is coarse and data are absent for many of the near-shore areas (i.e., within 1–3 km of the shoreline) we are considering (Atwood et al., 2020). We thus only considered terrestrial carbon stocks here (but note that tidal ecosystems such as mangroves and salt marshes are included). To calculate the irrecoverable carbon held within surf ecosystems, we overlaid our maps of surf ecosystems both in and outside of protected areas and Key Biodiversity Areas and characterized the irrecoverable carbon stocks using both average carbon density and total carbon stock metrics. Unless otherwise indicated, our results correspond to the portion of coastal watersheds that are within 1 km of a coastline; however, we also present numbers for the 2 and 3 km buffered coastlines as a sensitivity analysis. All processing and intersection steps were performed in Google Earth Engine and the {terra} package of Program R (Gorelick et al., 2017, Hijmans 2023).

3 | RESULTS

In total, we identified 88.3 million metric tonnes (Mt) of irrecoverable carbon across 28.5 thousand km^2 of surf ecosystems hosting 3602 surf breaks (Figure 2; Table 1). Of this total irrecoverable carbon, 17.2 Mt (20%) is found in Key Biodiversity Areas outside of existing protected areas. Regardless of protection and Key Biodiversity Area status, irrecoverable carbon was primarily found in mangroves (26.1%), tropical and subtropical moist broadleaf forests (24.0%), temperate broadleaf and mixed forests

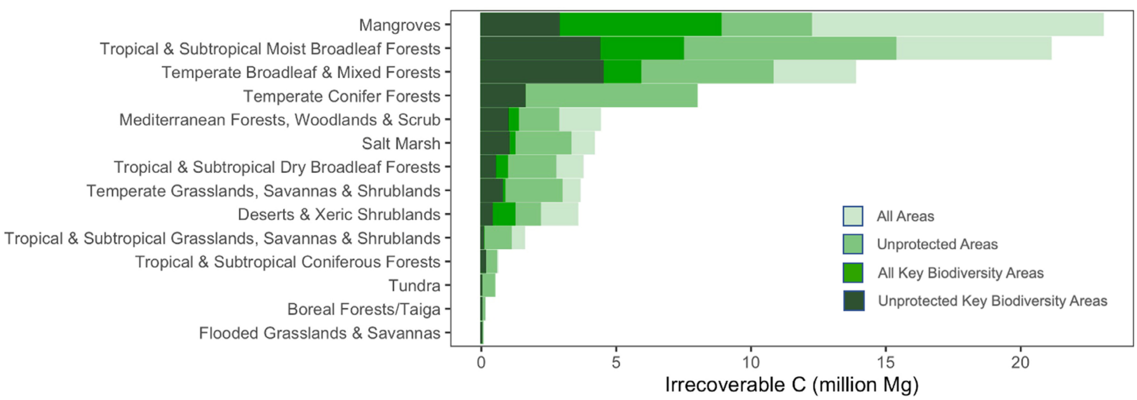

FIGURE 2 Irrecoverable carbon held in coastal watersheds within 1 km of surf breaks. The data are shown for all surf ecosystems ("All Areas"), all surf ecosystems outside of protected areas ("Unprotected Areas"), surf ecosystems that overlap with Key Biodiversity Areas ("All Key Biodiversity Areas"), and surf ecosystems that overlap with Key Biodiversity Areas but are outside of protected areas ("Unprotected Key Biodiversity Areas").

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TABLE 1 Number of surf breaks in protected areas and Key Biodiversity Areas summarized by the average irrecoverable carbon density of the coastal watershed in which the surf breaks are found.

		Protected area status	
		Protected	**Unprotected**
Key Biodiversity Areas	Within	Type I	Type II
		All: 92 (2.6%)	All: 502 (13.9%)
		<20: 59 (1.6%)	<20: 368 (10.2%)
		>20: 33 (1.0%)	>20: 134 (3.7%)
		>100: 10 (0.3%)	>100: 12 (0.3%)
	Outside of	Type III	Type IV
		All: 473 (13.0%)	All: 2351 (65.3%)
		<20: 250 (6.9%)	<20: 1512 (50.0%)
		>20: 223 (6.2%)	>20: 839 (23.3%)
		>100: 21 (0.6%)	>100: 65a (1.8%)

Note: We classify surf breaks into four different types: Type I, breaks within Key Biodiversity Areas and protected areas; Type II, breaks within Key Biodiversity Areas but outside of protected areas; Type III, breaks outside of Key Biodiversity Areas but within protected areas; and Type IV, breaks outside of both Key Biodiversity Areas and Protected Areas. We further disaggregate the number and percent of surf breaks by irrecoverable carbon density: all irrecoverable carbon densities ("All"), densities below the average irrecoverable carbon density across all surf ecosystems of 20 Mg C ha^{-1} (">20"), above this average density (">20"), and high carbon densities of >100 Mg irrecoverable carbon ha^{-1} (">100").

(15.5%), temperate conifer forests (9.1%), and mediterranean forests, woodlands, and scrub (5.0%) (Figure 2). Across all irrecoverable carbon densities, only 3% of all surf breaks are found inside Key Biodiversity Areas with formal measures of protection ("Type I." Table 1). A further 13% of surf breaks are located inside Key Biodiversity Areas, but outside of protected areas ("Type II," Table 1). Of this 13%, 223 surf breaks are associated with coastal watersheds with above average irrecoverable density, with 21 of these hosting more than 100 Mg irrecoverable carbon ha^{-1}.

Irrecoverable carbon density in surf ecosystems tends to be highest in the tropics and decreases with distance from the equator, with the exception of carbon-dense coastal forests in the Pacific Northwest region of North America (Figure 3a). However, total basinwide irrecoverable carbon, a function of both irrecoverable carbon stock density and size of coastal river-basins, is geographically widespread, with no clear relationship with latitude (Figure 3b).

Roughly half of all irrecoverable carbon in surf ecosystems is found in just five countries: the United States (18.4%), Australia (10.2%), Indonesia (10.2%), Brazil (4.6%), and Panama (4.3%) (Figure 4). However, the geographic distribution also depends heavily on biome type. For example, when considering mangroves only—a high-priority ecosystem type for conservation—roughly half of all surf-associated mangrove irrecoverable carbon is found in Brazil (10.9%), Panama (10.5%), Indonesia (9.8%), Gabon (9.3%), and the Philippines (6.4%). Opportunities to expand protection of irrecoverable carbon are concentrated in the United States (13.7 Mt C), whereas opportunities to expand protection of irrecoverable carbon in Key Biodiversity Areas are primarily found in Australia (3.2 Mt C), Indonesia (2.6 Mt C), and the United States (2.2 Mt C).

Our estimates of irrecoverable carbon found in surf ecosystems depended on our 1–3 km buffers of the coastline that we used to define surf ecosystems (Figure 5). Expanding our unit of analysis to include portions of coastal watersheds within 2 km of coastlines increased the total irrecoverable carbon to 147.6 million Mg C and total extent to 102.2 thousand km^2; whereas including portions of coastal watersheds within 3 km of coastlines held 191.7 million Mg C and covered 141.3 thousand km^2. However, the average irrecoverable carbon density decreased slightly (from 41.4 Mg C ha^{-1} to 39.4 Mg C ha^{-1}) when changing our coastline buffer from 1 km to 3 km. As expected, more expansive conceptualizations of what constitutes a surf ecosystem lead to greater total quantities of associated irrecoverable carbon.

When we integrated measures of surf break quality, we still found a large amount of irrecoverable carbon to be associated with good, excellent, or world class surf breaks (84.3 Mt C, or ~95% of the global total identified by this study). Surf ecosystems hosting excellent surf breaks held 32.2 Mt C, whereas surf ecosystems with world class surf breaks held 4.7 Mt C. For surf ecosystems with world class surf breaks, the average irrecoverable carbon density was 26 Mg C ha^{-1}, but a few individual surf ecosystems hosted greater than 100 Mg C ha^{-1}.

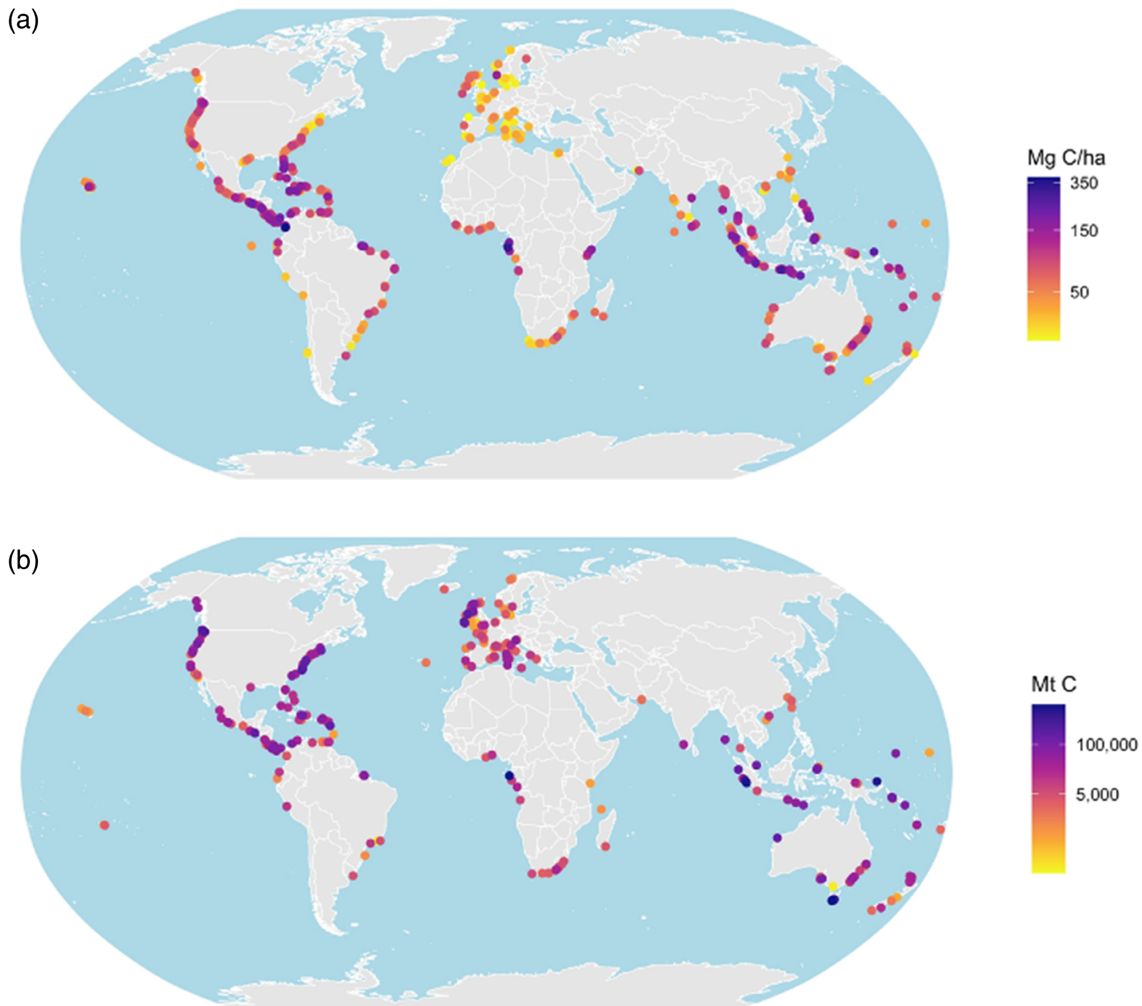

FIGURE 3 Average irrecoverable carbon density in (a) all surf ecosystems (b) and total irrecoverable carbon found in surf ecosystems that overlap with Key Biodiversity Areas but do not overlap with protected areas. Only surf ecosystems with average irrecoverable carbon densities >20 Mg C ha^{-1} are shown. Average carbon stocks are in Mg C ha^{-1} whereas total irrecoverable carbon stocks are in million metric tonnes of carbon (Mt C).

These were largely associated with islands dominated by mangrove forests in Indonesia.

4 | A CASE STUDY OF SURF PROTECTED AREAS IN INDONESIA

To exemplify what surf conservation looks like and how consideration of terrestrial carbon can be integrated into these programs, we present a case study from Indonesia here. Indonesia has an abundance of surf breaks and carbon-dense coastal ecosystems—as identified by our results—making it ideal for demonstrating the development of surf protected areas.

Within Indonesia, a grouping of national and international organizations are working with local partners to develop a network of surf protected areas (i.e., a SPAN). The surf protected areas are being developed using the Locally Managed Marine Area (LMMA) approach (Rocliffe et al., 2014), which is focused on developing and deploying locally-identified solutions and can be characterized by a five step process: (i) conceptualization, (ii) inception, (iii) implementation, (iv) monitoring and management, and (v) ongoing adaptive management (Kawaka et al., 2017). The surf protected areas in Indonesia vary in terms of their maturity, but generally are in the early stages of development, ranging from the conceptualization to implementation phases. No formal studies of the social or environmental outcomes of these programs exist yet; thus, we present information here based on our author teams' own experiences and apply the approach of our study to a local context.

As of March 2024, partners including the Indonesian LMMA Foundation and others have facilitated

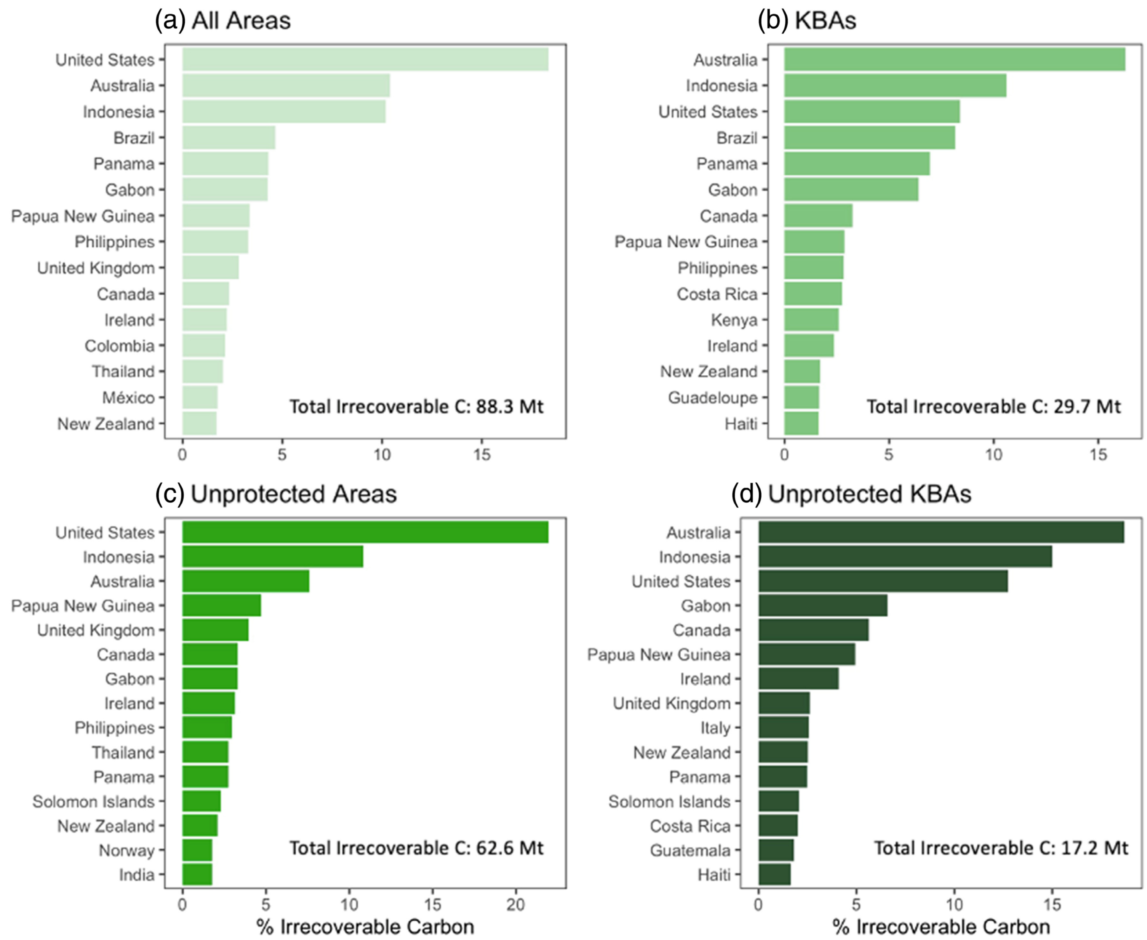

FIGURE 4 Distribution of irrecoverable carbon found in surf ecosystems by country. The data are shown in terms of percent of irrecoverable carbon for (a) all areas, (b) irrecoverable carbon found in Key Biodiversity Areas (KBAs), (c) irrecoverable carbon outside of protected areas, and (d) irrecoverable carbon found in KBAs, but outside of formally protected areas.

establishment of 23 surf protected areas across four islands: Biak and Supiori in Papua Province, Morotai in North Maluku Province, and Sumba in East Nusa Tenggara Province. The surf protected areas have been established in collaboration with Indonesian environmental organizations, local governments, and community-based partners. This approach supports community use of their legal authority to establish village regulations that protect their natural resources (in Bahasa Indonesia: *peraturan desa*), which was established by law Number 6, 2014 (*Undang-Undang Nomor 6 Tahun 2014*). Individually, these surf protected areas are small (~3000 to 4000 ha on average) and therefore locally adapted; however, they encompass substantial areas in aggregate (>60,000 ha to date).

Local communities are developing regulations for the surf protected areas that focus on improved management of both marine and terrestrial resources, including surf breaks, coral reefs, seagrass beds, beaches, mangroves, and coastal forests. The specific interventions undertaken parallel those found in other LMMAs more generally (Jupiter et al., 2014). For example, local communities have worked with local government to establish regulations that restrict destructive gear types or prevent overfishing, establish no-take areas, restrict coral and sand mining, and restrict harvesting of mangroves or conversion of other coastal forests. Moreover, community members within the surf protected areas have developed regulations on tourism and development, including restrictions on the sale of coastal land, regulations on new developments and visitor accommodation, management of waste, and establishment of fees to support conservation activities. These interventions focus on the broader stewardship of the surf ecosystem (including both marine and terrestrial components) and many—such as restrictions on mangrove harvesting—relate directly to strengthened protection of irrecoverable carbon stocks.

On Morotai Island, for example, a total of 25 surf breaks of significance have been identified, with 10 of

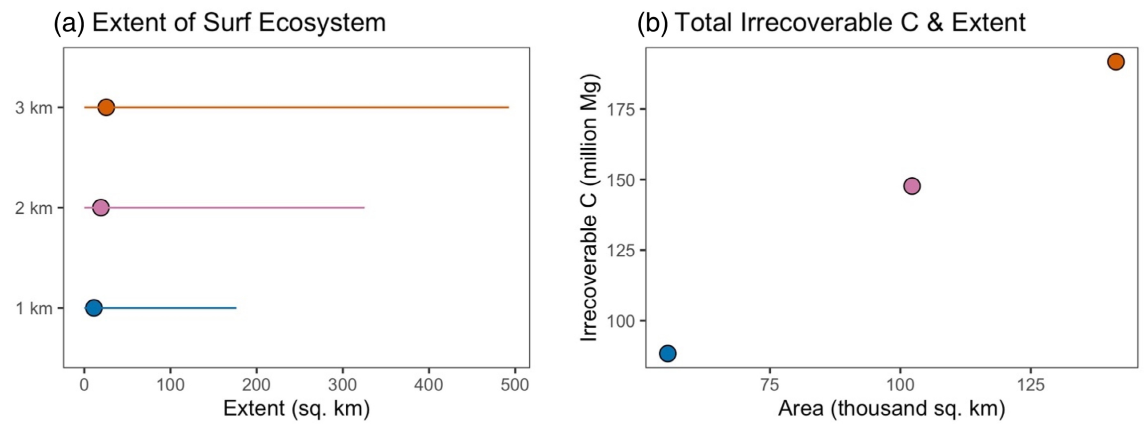

FIGURE 5 Comparison of (a) average extents of surf ecosystem across the three different coastline buffers (bars correspond to minimum and maximum surf ecosystem extent), and (b) total irrecoverable carbon and total extent for five different extents of surf ecosystem, or units of analysis taken in this study.

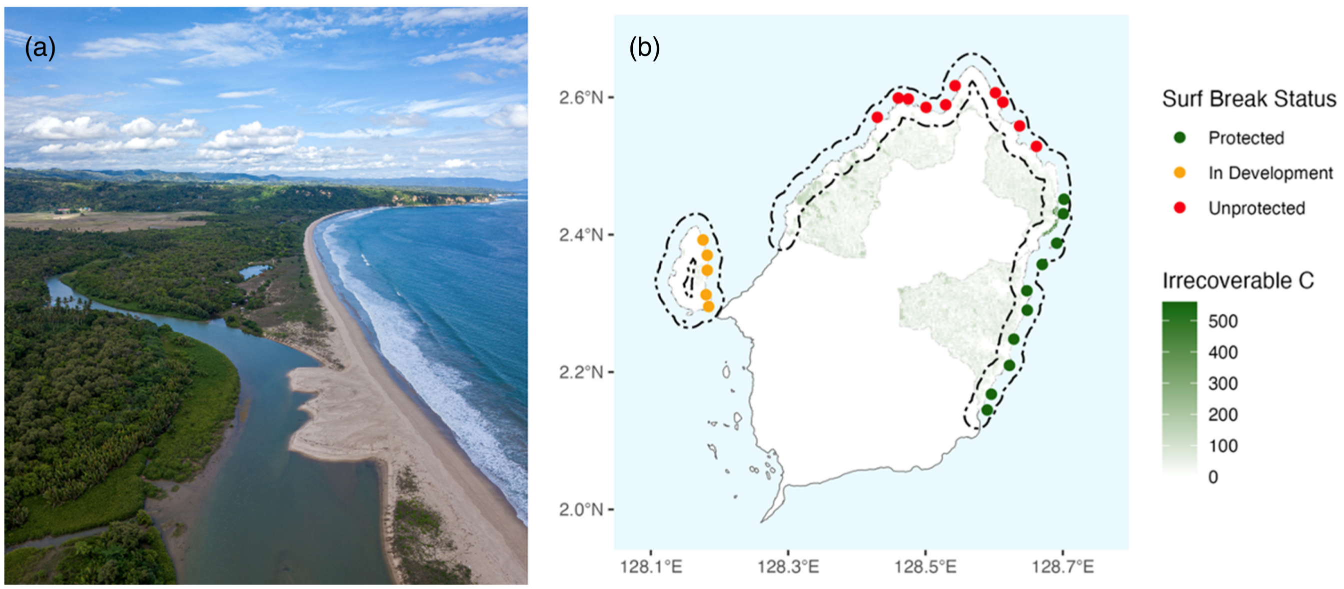

FIGURE 6 Example of (a) surf breaks and associated surf ecosystems of Sumba island (photo credit: Prastiano Septiawan), and (b) visualization of irrecoverable C, surf ecosystems, and protection status for surf breaks on Morotai Island, Indonesia.

these breaks now located in surf protected areas (Figure 6). Communities are now developing surf protected areas for an additional five breaks and are exploring the option of protecting the remaining 10 breaks. Using our approach for determining irrecoverable carbon stocks held in these surf ecosystems, we identify a total of 32,096 Mg C on Morotai Island within 1 km of the coastline (65,064 Mg C within 2 km of the coastline and 100,889 Mg C within 3 km of the coastline).[3] Of this total, 19,223 Mg C (60%) are within existing surf protected areas. Although this is a small proportion of the total surf ecosystem associated carbon held within Indonesia (roughly 9 Mt C), partners within the Indonesia SPAN are working to expand the network to other islands in Indonesia, strengthening locally developed stewardship of coastal resources across Indonesia. Moreover, our analysis identifies individual patches of mangroves within surf protected areas on Morotai Island with very high densities (>500 Mg C ha^{-1}) of irrecoverable carbon.

5 | DISCUSSION

Our results suggest significant opportunity for surf conservation to align with protection of climate critical carbon stocks. Globally, we identified 88.3 Mt of irrecoverable carbon held in surf ecosystems, which equates to roughly 1% of annual global energy-related CO_2 emissions today (Friedlingstein et al., 2022). Although this is a relatively small climate mitigation opportunity, our results and case study suggest that there may be key opportunities for surf ecosystem conservation at local scales. For example, 17.2 Mt of irrecoverable C (∼23%) are located within Key Biodiversity Areas without formal measures of protection, including nearly 200 surf breaks found in coastal regions with relatively high irrecoverable carbon densities (>20 Mg C ha^{-1}). Thus, there is the potential for surf conservation organizations that are engaged in the siting and establishment of surf protected areas to benefit from incorporating irrecoverable carbon stocks into their planning.

Accessing carbon finance streams to support surf ecosystem conservation can be operationalized through restoration of ecosystems or by mitigating legitimate threats of ecosystem conversion (Koh et al., 2021; Macreadie et al., 2022; Zeng et al., 2021). For avoided conversion projects, strong evidence that the ecosystem is at risk of loss is required (West et al., 2023). Identifying these opportunities requires additional local-scale analyses to identify surf ecosystems at risk of loss and where potential interventions can mitigate these risks, which we did not address in this scoping study. Our analysis included a large number of ecosystems types that extend beyond forests (e.g., salt marshes), and we lacked reliable maps of ecosystem conversion risk across these non-forest ecosystem types at a global scale. However, coarse estimates suggest substantial opportunities for conservation. At conservative carbon market prices today (10 USD per Mg CO_2), for example, mitigable threats to just 1% of irrecoverable carbon in surf ecosystems could present carbon finance opportunities of roughly USD 30 million. Other studies have already noted the relevance of mangrove conservation and other global blue carbon efforts for climate mitigation (Macreadie et al., 2022; Rogers et al., 2019), which aligns with our finding that irrecoverable carbon near surf breaks is primarily found in mangroves. Conservation projects that seek to value the carbon benefits of surf ecosystems can leverage existing surf-specific valuation frameworks (Manero & Mach, 2023) or more general frameworks such as the Ecosystem Accounting component of the United Nations System of Environmental-Economic Accounting (SEEA EA) (Edens et al., 2022; United Nations, 2021).

Governance arrangements for surf ecosystem conservation can take a variety of forms. Establishment of formal protected areas may be appropriate in some cases, whereas identification and recognition of other effective area-based conservation measures (OECMs) may be appropriate in others (Scheske et al., 2019). OECMs are being promoted currently in international policy circles (for example, the United Nations' Convention on Biological Diversity) as ways to broaden recognition and support of existing stewardship models that result in successful conservation outcomes (Dudley et al., 2018; Maxwell et al., 2020). While OECMs hold promise for broadening conceptualization of how conservation efforts are performed and who is engaged in these efforts (Gurney et al., 2021), surf conservation will benefit from a diversity of ecosystem conservation and protection approaches. For example, Indonesia is revising its conservation laws to incorporate coastal OECMs while also incorporating surf break locations into its ongoing marine protected area planning (Gurney et al., 2021; Scheske et al., 2019).

While protection of marine resources in proximity to surf breaks is easily understood, conservation of the terrestrial component of surf ecosystems is more complex. Here, we used an ecologically informed unit of analysis, the portion of coastal watersheds within 1 km of a coastline, as a way of linking terrestrial ecosystems to surf breaks. Not all land use activities within a coastal watershed are likely to impact a given surf break; however, we envision surf conservation areas as coastal landscapes that broadly support local communities and biodiversity conservation, while also benefitting from surf recreation. This view aligns with many efforts to protect surf breaks, which focus on surrounding terrestrial landscapes in practice and in legal regime (Ball, 2015; Orchard et al., 2023), as well as management strategies in the face of climate change (Sadrpour & Reineman, 2023). When viewed as such, it is apparent that a substantial footprint is necessary to harbor significant opportunities for sustainable resource use, ecosystem service provisioning, and biodiversity conservation. Nevertheless, additional research is needed on the scale at which upstream land activities adversely impact coastal resources, including surf breaks.

Our results quantify the potential of protecting terrestrial irrecoverable carbon through surf ecosystem conservation, albeit with several limitations. First, we focused on irrecoverable carbon (Noon et al., 2022), which is only a fraction of the total carbon held in surf ecosystems. While irrecoverable carbon should be prioritized given resource and time constraints, any carbon lost due to ecosystem conversion will impact the climate. Moreover, we did not consider carbon stocks in marine systems. As described in the methods, the majority of marine carbon stocks are found in benthic soils (Atwood et al., 2020), which are at lower risk of disturbance relative to carbon held in biomass and soils of terrestrial ecosystems. Global datasets of benthic soil carbon (Atwood et al., 2020) represent significant scientific advances but are ill-suited for our study, which focused at relatively small spatial scales in close proximity to coastlines.

Additionally, we used the WDPA (UNEP-WCMC and IUCN, 2023) to locate existing protected areas, but these data do not reflect the quality of the protection that currently exists for any given surf ecosystem. Extensive research on the effectiveness of protected areas generally shows that protected areas play important roles for conservation of habitat and protection of carbon stocks, including irrecoverable carbon (Duncanson et al., 2023; Geldmann et al., 2013; Zupan et al., 2018). Thus, the protected areas in our analysis likely play an important role in conserving surf ecosystems; however, they may also have more variable degrees of effectiveness when considering broaders sets of socio-ecological criteria (Geldmann et al., 2013). Moreover, carbon financing may help resolve funding issues for current ineffective protected areas (Sreekar et al., 2024). Regulations such as national laws may also provide additional protection for surf ecosystems and would complicate a detailed analysis of protected area effectiveness. We therefore excluded a detailed examination of protected area effectiveness from our study, but there is substantial opportunity for additional research on the topic at local scales. We encourage future research on these topics, which will help operationalize conservation of surf ecosystems.

6 | CONCLUSIONS

International initiatives such as the United Nations Decade of Ocean Science for Sustainable Development are promoting science-based stewardship of global coastlines today. Conservation of surf ecosystems is a growing avenue for supporting local communities and conserving biodiversity and—as our study shows here—strengthening protection of climate critical carbon stocks. Our study quantified irrecoverable carbon within global surf ecosystems and, using a case study in Indonesia, exemplified how surf protected areas are being developed in pursuit of conversation-related goals. Realizing the potential of surf ecosystem conservation will ultimately require collaborative projects between conservation practitioners, governments, and local communities—thereby offering opportunities to empower local stakeholders and make conservation efforts more equitable. We encourage further research that explores the potential of surf ecosystems as a conservation asset, including both expanded assessments of their contributions to global goals as well as local and regional scale analyses that guide targeted conservation efforts.

AUTHOR CONTRIBUTIONS

Conception: Jacob J. Bukoski, Scott R. Atkinson, Marissa Anne S. Miller, and Kellee Koenig. *Manuscript draft*: Jacob J. Bukoski, Scott R. Atkinson, Marissa Anne S. Miller, Diego A. Sancho-Gallegos, Mara Arroyo, Kellee Koenig, Dan R. Reineman, and John N. Kittinger. *Data analysis*: Jacob J. Bukoski.

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CONFLICT OF INTEREST STATEMENT

Scott R. Atkinson, Marissa Anne S. Miller, Diego A. Sancho-Gallegos, and Mara Arroyo are employees of surf conservation organizations. The remaining authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All datasets used in this analysis are publicly available, with the exception of the surf break dataset. We have provided access links for all public datasets as of the time of publication, as well as all relevant reference information in Table 1.

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ENDNOTES

[1] Surf Breaks are nearshore coastal areas where waves break due to a unique combination of seafloor and coastal geomorphology that allows for surfing—i.e., the act of people riding waves.

[2] The Save The Waves Coalition. https://www.savethewaves.org/span/.

[3] These estimates are based on a global dataset of irrecoverable carbon and are therefore a first pass estimate. More accurate estimate of site-level carbon stocks would require standard methodologies, such as field sampling or locally adapted models.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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