Leveraging surf breaks to expand conservation of carbon-dense coastal ecosystems

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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 conserving 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 priority areas for conservation (Key Biodiversity Areas), we identified 961 million Mg of irrecoverable carbon held in surf ecosystems. Of this total, 223 million Mg 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. Innovative and equitable conservation models that extend beyond excluding humans from nature will be critical to achieving these goals.

Introduction

Surf breaks are increasingly recognized as a new asset class upon which marine and coastal ecosystem conservation goals can be founded [1,2]. 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 [3]. 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 million USD annually to some communities [4,5]. Despite their significant value, surf breaks and surrounding ecosystems are subject to numerous threats, including coastal development [6], degradation of habitats, and impacts from climate change such as sea level rise [7,8]. There is consequently widespread interest in developing coastal management models that protect surf breaks and their surrounding environments from these threats [9–11].

Surf ecosystems—the land-to-sea interface that creates the conditions for breaking, rideable waves, and the flora and fauna and human communities dependent upon it—not only house high levels of biodiversity [3], but can also contain large amounts of carbon, elevating their priority for global efforts to mitigate climate change. 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 [12]. When carbon-dense ecosystems are converted to other uses, they emit large amounts of carbon into the atmosphere, driving anthropogenic climate change. While the potential for expanding protection of biodiversity conservation in surf ecosystems has been examined [3], we lack understanding of both how much carbon is currently held in surf ecosystems as well as what proportion of it is currently at risk and therefore of interest to climate change mitigation efforts.

Expanded conservation of surf ecosystems could provide a range of ecosystem services and values in addition to conservation of biodiversity and climate mitigation [9,13]. Although direct links between non-physical components of surf ecosystem health 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 [14]. Healthy upland ecosystems can improve habitats by reducing erosion and sediment loads to littoral areas [15,16], and these services can similarly reduce the potential for surfer illness through improved water quality [17]. Coral reefs shape surf breaks [18], but also provide fishing grounds, non-surfing recreational opportunities such as diving, and shoreline protections [19]. Moreover, all the foregoing ecosystems provide cultural and spiritual value to local communities across the globe [20].

Coastal management models that employ surf breaks as assets for conservation are emerging across the globe. For example, Conservation International and Save The Waves Coalition are collaborating in partnership with local communities and governments to use high-quality surf breaks as anchors and motivators for the protection of larger surrounding surf ecosystems. This approach has led to the development of Surf Protected Area Networks (SPANs) in Indonesia and Costa Rica, which legally protect biodiverse and carbon-dense surf ecosystems. As surf conservation models like this gain traction globally, their proliferation must be guided by science to optimize their contributions to global biodiversity conservation and climate change mitigation goals [21,22].

Here, we examine global opportunities to strengthen and expand protection of irrecoverable carbon—defined as ecosystem carbon stocks that, if lost today, could not be recovered within 30 years [23]—held within surf ecosystems. We draw on a suite of geospatial data to quantify the potential climate mitigation benefits of expanded protection of these climate-critical ecosystems. Further, we present a case study from Indonesia to illustrate how these concepts and strategies can be operationalized for conservation at local scales. In presenting our findings, we discuss the applications of our results for conservation-focused organizations, focusing on how to support the broader uptake of surf breaks as conservation assets. 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.

Methods

Our analysis is based on spatial intersections of six global datasets: i) locations of surf breaks, ii) coastal river basins, iii) biome/ecosystem types, iv) protected areas, v) Key Biodiversity Areas, and iv) irrecoverable carbon stocks (see Table S1 of the Supporting Information). All processing and intersection steps were performed in Google Earth Engine and the {terra} package of Program R [24,25]. We describe our methods in brief here whereas a full description is provided in the supplementary material.

We obtained a global dataset of surf breaks from the Stormrider Surf Travel Guides' "The World" Book, a travel guide created by Low Pressure Ltd. [26]. 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. The dataset is among the best publicly available compilations of surf breaks globally, and is considerably more comprehensive than those used in prior global analyses (Reineman et al. 2021).

We conducted our analyses using coastal river basins (i.e., coastal watersheds) as the unit of analysis. River basins are ecologically informed areas of interest for our study, given that land use and land cover change within river basins can directly and indirectly impact coastal resources, including surf ecosystems. To identify coastal river basins for our analysis, we selected basins from the HydroSHEDS database (Lehner & Grill, 2013) that intersected with surf breaks. HydroSHEDS provides river basins at multiple geographic scales. We present results for the "level 10" basins, which were deemed a compromise between proximity to surf breaks and sufficient extent to harbor substantial conservation opportunities. However, we also re-ran our analyses for levels 8-12 (with 12 being the smallest geographic extent) to examine the sensitivity of our results to this choice.

For each coastal river basin, we 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 coastal river basins with a map of terrestrial biomes and ecoregions [28], adjusted to include coastal ecosystem-specific maps of mangroves and salt marshes [29,30]. Next, we intersected this map with protected area extents [31] and a map of Key Biodiversity Areas [32] 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 a map of national boundaries to identify country-specific opportunities to expand protection of irrecoverable carbon in surf ecosystems [33].

To quantify climate-critical carbon stocks held within surf ecosystems we used a map of irrecoverable carbon [34]. We overlaid our maps of surf ecosystems both in and outside of protected areas and Key Biodiversity Areas and summed the irrecoverable carbon data held within each of these areas.

Results

In total, we identified 961 million metric tonnes (Mt) of irrecoverable carbon across 427 thousand km^2 of surf ecosystems and in association with 4,563 surf breaks (Figure 1 & Table 1). Of this total irrecoverable carbon, 223 Mt (23%) 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 Tropical & Subtropical Moist Broadleaf Forests (27.1%), Temperate Conifer Forests (19.5%), Temperate Broadleaf & Mixed Forests (16.3%), Mangroves (10.9%), and Mediterranean Forests, Woodlands, and Scrub (9.1%) (Figure 1). 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 15% of surf breaks are located inside Key Biodiversity Areas, but outside of protected areas (“Type II”, Table 1). Of this 15%, 184 surf breaks hold above average irrecoverable density, with 10 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 2a). 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 2b).

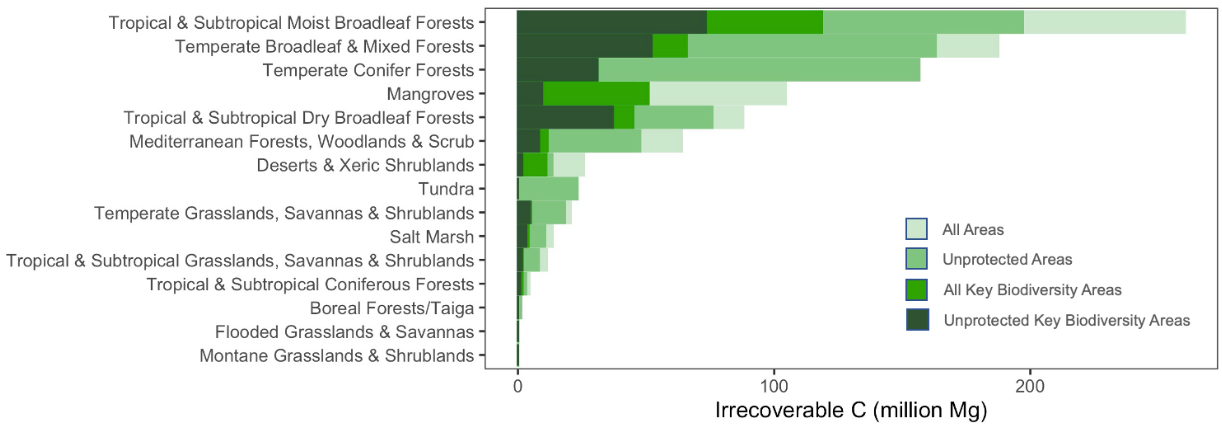

Figure 1 | Irrecoverable Carbon held in surf ecosystems. The data are shown for all surf ecosystems ("All Areas"), all surf ecosystems outside of protected areas ("Unprotected Areas"), surf ecosystems that overlap with Key Biodiversity Areas ("All Key Biodiversity Areas"), and surf ecosystems that overlap with Key Biodiversity Areas but are outside of protected areas ("Unprotected Key Biodiversity Areas").

Table 1 | Number of surf breaks in protected areas and key biodiversity areas summarized by the average irrecoverable carbon density of the coastal river basin in which the surf breaks are found. We designate these 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, including: 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").

		Protected Area Status	
		Protected	*Unprotected*
Key Biodiversity Areas	*Within*	Type I All: 132 (3%) < 20: 93 (3%) > 20: 39 (3%) > 100: 5 (5%)	Type II All: 688 (15%) < 20: 514 (16%) > 20: 174 (13%) > 100: 10 (9%)
	Outside of	Type III All: 583 (13%) < 20: 380 (12%) > 20: 203 (15%) > 100: 14 (13%)	Type IV All: 3160 (69%) < 20: 2200 (69%) > 20: 960 (70%) > 100: 79 (73%)

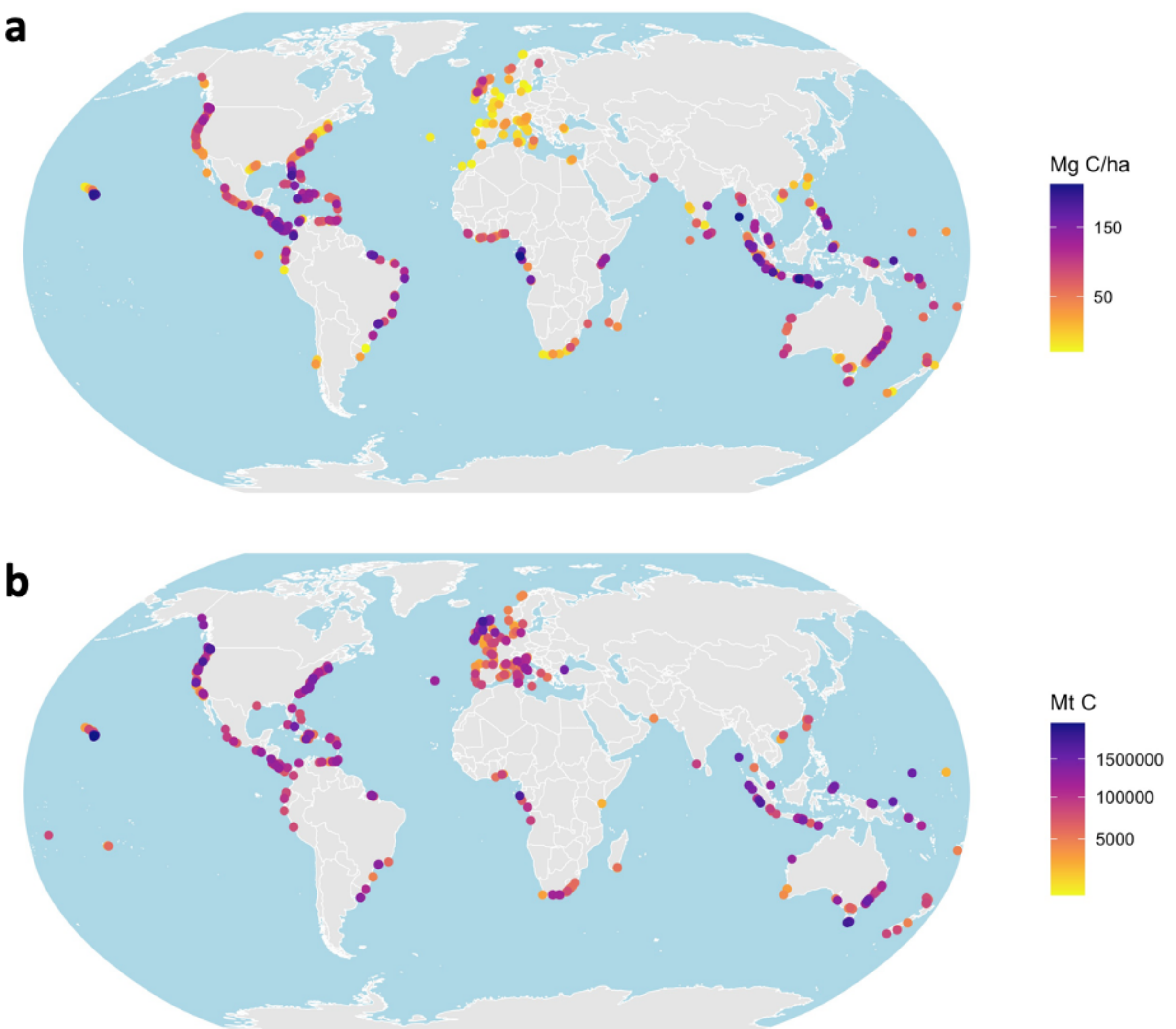

Figure 2 | Average irrecoverable carbon density in all surf ecosystems (a) and total irrecoverable carbon found in surf ecosystems that overlap with Key Biodiversity Areas but do not overlap with protected areas (b). Only river basins with average irrecoverable carbon densities > 20 Mg C ha^{-1} are shown. Average carbon stocks are in Mg C ha^{-1} whereas total irrecoverable carbon stocks are in million metric tonnes of carbon (Mt C).

Roughly half of all irrecoverable carbon in surf ecosystems is found in just five countries: the United States (29.1%), Australia (7.9%), Indonesia (7.7%), the United Kingdom (6.1%), and Brazil (5.5%) (Figure 3). 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 irrecoverable carbon is found in Brazil (31.5%), India (8.8%), Gabon (7.0%), Panama (6.9%), and Indonesia (4.9%). Opportunities to expand protection of irrecoverable carbon are concentrated in the United States (270.4 Mt C), whereas opportunities to expand protection of irrecoverable carbon in Key Biodiversity Areas are primarily found in the United States (88.7 Mt C), Australia (24.4 Mt C), and the United Kingdom (21.2 Mt C).

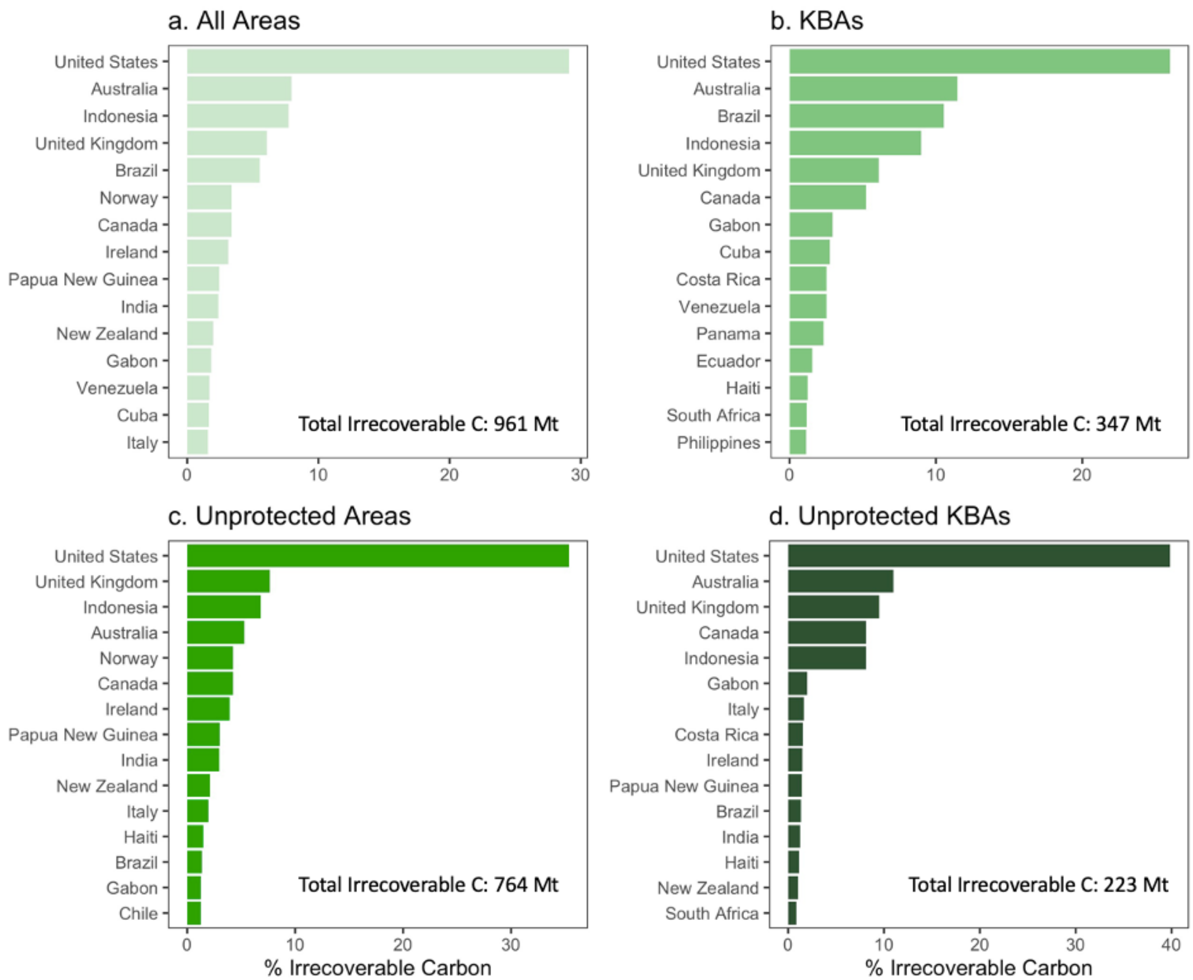

Figure 3 | Distribution of irrecoverable carbon found in surf ecosystems by country. The data are shown in terms of percent of irrecoverable carbon for a) all areas, b) irrecoverable carbon found in Key

Biodiversity Areas (KBAs), c) irrecoverable carbon outside of protected areas, and d) irrecoverable carbon found in KBAs, but outside of formally protected areas.

Our estimates of irrecoverable carbon found in surf ecosystems varied depending on the coastal river basin "level" used (Figure 4). Altering our unit of analysis from "level 10" to "level 12" (the smallest footprint of coastal river basins available) decreased total irrecoverable carbon to 865 million Mg C (9.9% decrease) and total extent to 375.6 thousand km^2 (11.9% decrease); whereas "level 8" coastal river basins (the geographically most extensive level considered) held 2.7 billion Mg C (182% increase) and covered 1.1 million km^2 (158% increase). In other words, our results do not change substantially when selecting smaller coastal river basin sizes but change greatly when selecting larger river basin sizes.

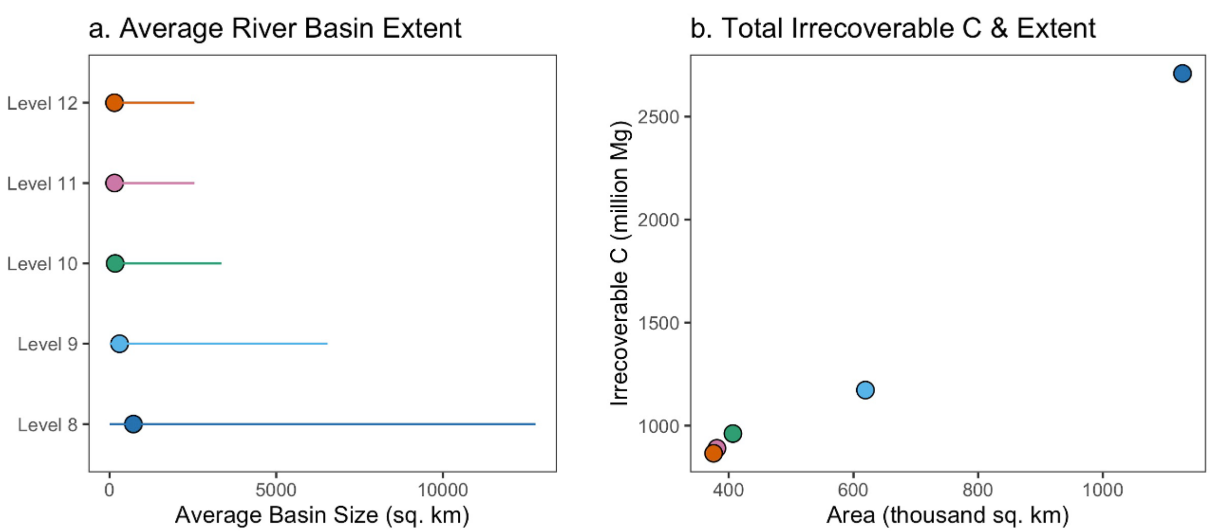

Figure 4 | Comparison of a) average river basin extent, and b) total irrecoverable carbon and total extent for five different "levels" of HydroSHEDS coastal river basins, or units of analysis taken in this study. In panel a), the bars correspond to the maximum and minimum river basin extents for each level. Total irrecoverable carbon and extent for "level 10" (for which results are presented in this study) differ little from "level 11" and "level 12", but increase substantially for "level 9" and "level 8".

A Case Study of Surf Protected Areas in Indonesia

To exemplify how surf breaks can potentially contribute to protection of coastal ecosystems, we describe Surf Protected Area Networks (SPANs), a surf conservation model pioneered by Conservation International, Save The Waves Coalition, and local partners around the world. Using surfing to create momentum for coastal conservation, SPANs operate within local contexts to strengthen policy and legal protection of surf ecosystems and sustainable community development. Across all contexts, SPANs engage local communities to first identify and map threats to surf ecosystems, and subsequently design interventions to mitigate these threats.

In Indonesia, for example, the Surf Conservation Partnership has facilitated establishment of a network of seventeen Surf Protected Areas using the Locally Managed Marine Area approach in collaboration with Indonesian environmental organizations, local government, and community-based partners. This approach supports community use of their legal authority to establish village regulations (in Bahasa Indonesia: *peraturan desa*) that protect their natural resources. Individually, these community-based conservation areas are small (~3,000 ha on average); however, they are purposefully established in contiguous networks that span substantial areas in aggregate (>43,000 ha). Additionally, this approach is designed to leverage strong motivation from communities with local surfers to protect their surf breaks and surrounding ecosystems. Locations with surf tourism are believed to have opportunities to establish conservation finance mechanisms that derive revenue from visiting surfers to support protected area implementation, mirroring models from SCUBA diving tourism and eco-tourism more generally.

The Indonesian SPAN has been established to support improved protection of coastal forests, mangroves, seagrass beds, coral reefs, beaches, and surf breaks on islands such as Supiori, Sumba, and Morotai (Figure 5). These areas overlap with key biodiversity areas with high levels of irrecoverable carbon, potentially contributing to both biodioversity conservation and climate mitigation goals.

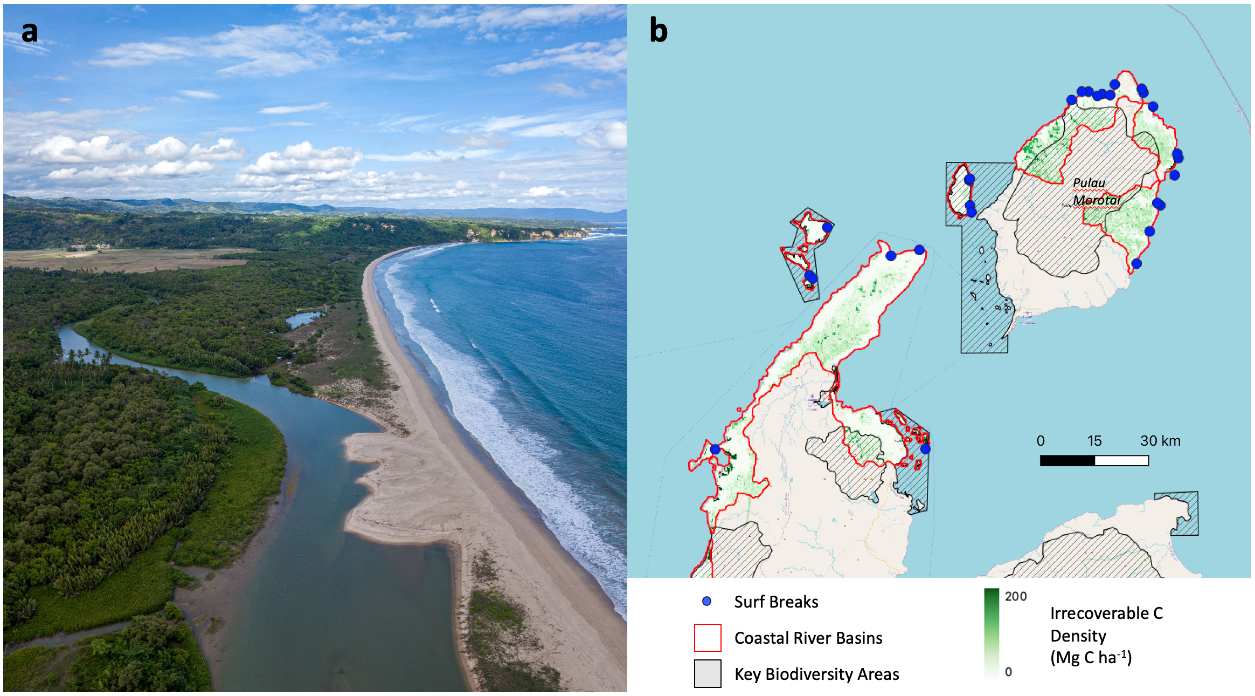

Figure 5 | Example of a) surf breaks and associated surf ecosystems of Sumba island (photo credit: Prastiano Septiawan), and b) overlay of key spatial layers (surf breaks, coastal river basins, Key Biodiversity Areas, and irrecoverable carbon) for Morotai Island. The basemap in b) is publicly available from OpenStreetMaps, whereas all other datasets are referenced in Table 1. Photo Credit: Prastiano Septiawan.

Discussion

Our results highlight surf ecosystems as conservation assets upon which improved protection of climate-critical ecosystems can potentially be built. Moreover, our case study exemplifies how existing surf conservation models are working to support local communities while investing in improved protection of coastal ecosystems. We identified a total of 961 million Mg C of irrecoverable carbon held in surf ecosystems, which equates to roughly 10% of energy related CO_2e emissions in 2022 [35]. Of this total, 223 million Mg C (~23%) is located within Key Biodiversity Areas without formal measures of protection. The spatial overlap of these carbon-rich and biodiverse ecosystems suggests opportunities for strengthening protection of coastal landscapes; however, the scale of this opportunity depends not only on total stocks, but also legitimate threats of loss of this carbon.

Carbon finance streams for surf ecosystem conservation can only be operationalized through mitigating legitimate threats of ecosystem conversion [36–38]. For these avoided conversion projects, strong evidence that the ecosystem is at risk of loss is required and is best-done with matched dynamic baselines, placebos, or other synthetic control methods for causal inference [39]. Identifying these opportunities requires additional local-scale analyses to identify surf ecosystem landscapes at risk of loss and where potential interventions can mitigate these risks, which we did not address in this scoping exercise. Our analysis includes a large number of ecosystems types that extend beyond forests (e.g., salt marshes), and we lack reliable maps of risk of conversion across this broader suite of ecosystem types at global scales. Further analyses at local to national scales are needed to better constrain risk of ecosystem loss. However, at conservative carbon market prices today (10$ per Mg CO_2), mitigable threats to just 1% of irrecoverable carbon in surf ecosystems could present conservation finance opportunities of roughly 350 million USD.

Any intervention to mitigate risks to surf ecosystems must be guided by and in support of local communities. While establishment of protected areas may work in some cases, recognition of areas as other effective area-based conservation measures (OECM) may be more appropriate in instances where communities do not want, or cannot create, protected areas [2]. OECMs encompass a wide array of existing conservation efforts such as traditional or Indigenous land management and are being promoted as ways to recognize existing successful efforts and make conservation more equitable [40,41]. In many cases, successful conservation efforts may already exist in surf ecosystems and the task thus becomes formal recognition and support of these systems through the OECM designation [42]. Importantly, OECMs provide a key opportunity for surf conservation practitioners to collaborate with local communities [2]. For example, Indonesia is both revising its conservation laws to incorporate coastal OECMs and incorporating surf breaks into its future marine protected area planning processes.

While protection of marine resources in proximity to surf breaks is easily understood, conservation of terrestrial ecosystems in support of surf conservation is more complex. Here, we used an ecologically informed unit of analysis, coastal river basins, as a way of linking terrestrial ecosystems to surf breaks. Not all land use activities within a river basin 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 [10,43], as well as management strategies in the face of climate change [7]. 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 irrecoverable carbon through surf ecosystem conservation, albeit with several limitations. First, we focused on irrecoverable carbon, which is only a fraction of the total carbon held in surf ecosystems. While irrecoverable carbon may be prioritized under resource and time constraints, any carbon lost due to ecosystem conversion will impact the climate. The scale of the potential climate benefits is therefore likely larger than what we present here. Second, we used the WDPA to locate existing protected areas, but these data do not reflect the *quality* of the protection that currently exists. Moreover, regulations such as national laws may provide additional protection for surf ecosystems not considered here. Accounting for these additional levels of protection was infeasible at a global scale but should be included in future analyses at local scales. Lastly, we do not consider the importance of a wave for a given community (i.e., measures of wave "quality"), which can influence the scale of opportunities for surf conservation. We encourage future research on these topics, which will help operationalize conservation of surf ecosystems.

Conclusions

Improved conservation of surf ecosystems is a potentially promising avenue for intersectional goals of supporting local communities, conserving biodiversity, and mitigating climate change. Surf ecosystem protections—such as OECMs or protected areas—can also help to achieve global conservation targets. Our study quantifies irrecoverable carbon within global surf ecosystems and, using a case study in Indonesia, exemplifies how surf conservation 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.

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Data

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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