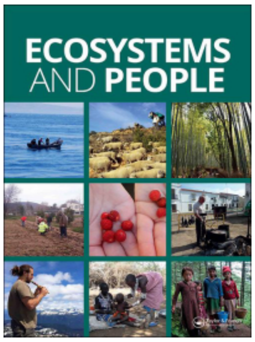

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PERSPECTIVE

Not just carbon: biodiversity credits for restoration of the marine animal forests

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ABSTRACT
The ecosystems known as Marine Animal Forests (MAFs), predominantly inhabited by sessile invertebrates, represent critical biodiversity hotspots under imminent threats from human activities and climate change. This perspective evaluates the concept of biodiversity for MAFs restoration by incentivizing MAF restoration projects, and harnessing the advantages of biodiversity credits under the notion of 'biodiversity-carbon credits' for the MAFs, further aligning with global biodiversity objectives. Beyond addressing a significant restoration gap, our approach harmonizes with international initiatives, encouraging additional classes of stakeholders to join restoration efforts. Illuminating these often-neglected ecosystems, our proposed approach seeks to implant proactive measures for the restoration and conservation of the global MAFs, contributing to a sustainable future in which ecosystem functioning is re-established. By elevating biodiversity and carbon immobilization, our approach not only augments ecological services but also fortifies the resilience of these vital marine habitats.

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Background

Human activities, particularly the release of greenhouse gases (GHG) and alternations in land use (for instance, the global decline of forests due to conversion for agriculture, urbanization, or mining), are primary drivers for climate change (Brierley and Kingsford 2009; Calvin et al. 2023), profoundly impacting biodiversity across terrestrial, aquatic, and marine ecosystems (Calvin et al. 2023). Specifically, within marine ecosystems, these human activities disrupt biodiversity by influencing species distribution and abundance, altering connectivity trajectories, functionality and impacting essential processes, leading to biodiversity decline (Blowes et al. 2019; Duarte et al. 2020). Additionally, biodiversity loss has a cascading effect, encompassing the degradation of ecosystem services, disrupting the balance equilibrium and functioning of ecosystems (Bindoff et al. 2019), thereby carrying far-reaching implications for ecosystems and the well-being of human societies (Worm et al. 2006).

Efforts to address climate change and human-induced impacts have predominantly focused on land-based ecosystems and mitigating carbon emissions (Roe et al. 2021; Droste et al. 2022). These approaches further encompass initiatives such as carbon credits (CC), biodiversity offsetting (BO) (BBOP 2013; World Economic Forum 2022), biodiversity credits (BCD) (Porras and Steele 2020; World Economic Forum 2022; Ducros and Steele 2022) and blue carbon credits (BLC) that primarily referred to marine photosynthesizing ecosystems like mangroves, kelps and sea grasses (Table 1). CCs operate on the well-defined principle that carbon emissions can be offset by supporting emission-reducing acts such as reforestation, where each CC unit corresponds to one ton of emitted CO_2 (Fawzy et al. 2020). In contrast, the concepts of BO and BCD are ambiguous (Vaissière et al. 2017; Maron et al. 2018; Simon and Dorothée Herr 2023). Both represent a quantified measure of biodiversity that can be traded in the market to address issues like biodiversity decline and habitat loss due to development projects and agriculture (BBOP 2012a). Yet, clear standards defining what constitutes a biodiversity unit are currently lacking (BBOP 2012b; Chiavacci and Pindilli 2018).

The Marine Animal Forests (MAFs) stand out as biodiversity-rich habitats, representing ecosystems that are profoundly impacted by anthropogenic activities and climate change (Rossi 2013; Rossi et al. 2022). The MAFs are marine ecosystems dominated by sessile invertebrates that form intricate 3-dimensional structures and are further classified as ecosystem engineers. These structures form a complex network of ecological niches, functioning as habitats, refuges, food suppliers and nursery-beds for a wide range of species (Jones et al. 1994; Rossi et al. 2017;

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Table 1. Definitions for the terms 'carbon' and 'biodiversity' used in this manuscript in conjunction with the concepts of 'mitigation', 'offset' and 'credit'.

Name	Definition	Source
Carbon immobilization	A short-term temporary retention of carbon in the biomass of an organism.	Barnes (2018)
Carbon sequestration	Immobilized carbon that remains in the organism's biomass or ecosystem a long period of time.	Lal (2004)
Carbon credit	A tradable permit that represents the right to emit a certain amount of carbon dioxide or other greenhouse gases. One credit is equal to 1 ton of CO_2.	Fawzy et al. (2020); Roe et al. (2021)
Carbon offsetting	Activities that reduce or remove GHG emissions from the atmosphere, like reforestation and carbon capture.	Galik and Jackson (2009)
Blue Carbon	Carbon stored in coastal and marine ecosystems such as mangroves, seagrasses, and tidal marshes, which play a significant role in capturing and storing CO_2 from the atmosphere	Macreadie et al. (2021)
Habitat	Specific area or environment where a particular species or community lives and is characterized by its physical or biological features (coral reef, for example)	Hall et al. (1997)
Ecosystem	A dynamic complex of plant, animal and microorganism communities that interact with the abiotic components as a functional unit	Allee et al. (2000); Loreau (2010)
Biodiversity offsetting	'A conservation approach designated to compensate for significant residual adverse biodiversity impacts arising from project development after appropriate prevention and mitigation measures have been taken'.	BBOP (2012)
No-net-loss/Net gain	A conservation strategy aims to balance or compensate for the ecological losses caused by development through equivalent (no net loss) or greater gains (net gain) in biodiversity elsewhere.	BBOP (2012); BBOP (2013)
Biodiversity credit	'Biodiversity credits are an economic instrument that can be used to finance actions that result in measurable positive outcomes for biodiversity through the creation and sale of biodiversity units'.	Porras and Steele (2020)
Co-crediting	'Biodiversity incorporated into carbon crediting schemes. Traditionally performed for terrestrial biomes'.	Tedersoo et al. (2023)
Stacking ecosystem service credits	"Refers to multiple credits generated from one piece of land being sold separately in the relevant markets. "	Torabi and Bekessy (2015)
Bundling credits	"Bundling credits refers to selling multiple ecosystem services from one piece of land as a combined ecosystem credit".	Torabi and Bekessy (2015)
Biodiversity-carbon credit	Biodiversity credits and carbon credits are integrated to one unified credit unit – designated for the Marine animal forests.	This manuscript

Orejas et al. 2022; Shmuel et al. 2022). The ecosystems that encompass MAFs are shaped by various ecological engineers, including sedentary sponges, ascidians, bryozoans, polychaetes, bivalves and cnidarians (Rossi et al. 2017; Orejas et al. 2022) (Figure 1). MAFs are geographically widespread, spanning from tropical to polar regions, covering warm, temperate and cold-water habitats, from shallow coastal areas to deep-sea zones (Rossi et al. 2017). Thus, the MAFs provide a range of ecological services crucial for the livelihoods of millions of people globally (Paoli et al. 2017; Bindoff et al. 2019). Not all MAFs offer identical ecological services or provide equal benefits, and numerous services remain challenging to quantify (Rinkevich 2015b; Paoli et al. 2017). Due to their rich species diversity, intricate structural complexity and canopy structures formed by engineering species, MAFs emerge as biodiversity hotspots. Further, they play a significant role in ecosystem support and regulation (Paoli et al. 2017; Orejas et al. 2022), as well as in carbon immobilization (Fodrie et al. 2017; Coppari et al. 2019; Rossi and Rizzo 2020), while some (such as the tropical coral reefs) are further considered as carbon sequestrating MAFs facilitated by their foundational species (Ware et al. 1991; Rinkevich 2024).

As outlined, MAFs hold substantial potential for biodiversity enhancement and carbon immobilization (that is not yet linked with any trading properties, such as credits), and in certain MAFs (such as the coral reefs), there is also potential for carbon sequestration (Ware et al. 1991; Rinkevich 2024) (the flux of carbon that is partially retained in the system; Table 1). Drawing inspiration from mitigating approaches applied in terrestrial ecosystems, we present here an alternative perspective for the conservation and restoration of marine environments to address global and local biodiversity loss while mitigating anthropogenic impacts. Our proposal advocates for the integration of biodiversity and carbon credit concepts and mechanisms to incentivize restoration projects focused on MAFs, harnessing the advantages of both approaches. This perspective article outlines how the potential use of biodiversity credits aligns with international goals, illustrating its capacity to strengthen MAF restoration approaches while addressing climate change impacts and promoting biodiversity recovery.

What are carbon, biodiversity, and offsetting credits?

In response to global climate concerns, the 1997 Kyoto Protocol has aimed to collectively tackle climate change caused by GHG emissions. The protocol

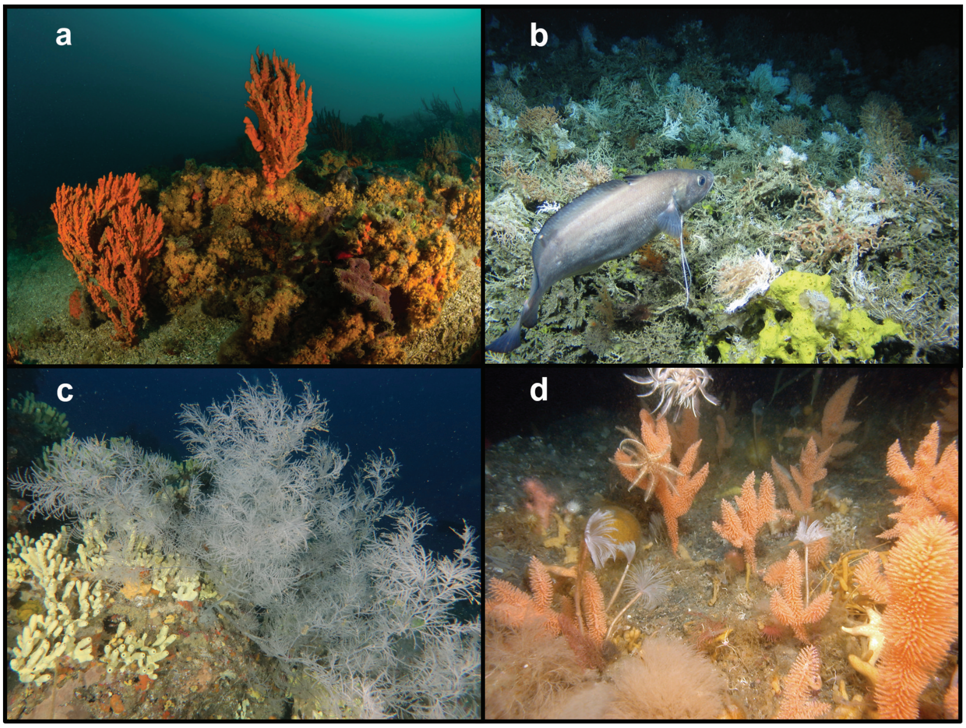

Figure 1. Different MAFs habitats. a: Poriferan and Cnidarian dominated MAFs; (credit: Thanos Dalianis). b: A greater forkbeard (*phycis blennoides)* in a cold-water coral reef Logachev coral carbonate mound province (rockall bank, NE Atlantic; credit: J Murray Roberts).c: The engineering MAF species is *Antipathella subpinnata* (black coral) in the Ligurian Sea (Mediterranean Sea) (credit: Lorenzo Bramanti). d: A gorgonian MAF in Antarctica (credit: Julian Gutt).

introduced tradable CCs as financial and regulatory instruments for reducing GHG emissions, allowing for international trading (Fawzy et al. 2020). Individuals, organizations, and companies have the option to purchase CCs as a means to offset their carbon footprint and support climate mitigation initiatives (Table 1). Subsequently, industries may offset or reduce a portion or the entirety of their carbon footprint by adopting greener technology, engaging in CCs trading with other companies or purchasing CCs from CO_2 sequestration initiatives projects such as reforestation (Fawzy et al. 2020; Roe et al. 2021). In the marine context, CCs deliverables are termed 'blue carbon' (BLC), referring to the carbon stored or absorbed in photosynthesizing marine organisms or sediments (Table 1), usually linked to salt marshes, mangroves and seagrasses (Macreadie et al. 2021).

Carbon-focused projects like land reforestation or BLC, might prioritize carbon sequestration by planting fast-growing monoculture species (Lee et al. 2019; Di Sacco et al. 2021), unintentionally neglecting biodiversity conservation. This narrow focus on carbon can lead not only to a dwindled genetic diversity in the restored area but also to reduced resilience against pests and diseases within these ecosystems, potentially resulting in an overall decline in ecosystem services (Liu et al. 2018). In the context of BLC projects, the synergistic effects of submerged coastal environments may also be lost in the pursuit of carbon sequestration objectives (Lee et al. 2019).

Although the concept of BO lacks precision (Vaissière et al. 2017; Maron et al. 2018), it remains a widely embraced conservation strategy. Similar to CC, it seeks to balance the negative impacts and adverse effects of development projects by generating biodiversity-related gains elsewhere. This approach involves quantifying and converting differences in biodiversity characteristics between impacted and offset sites into biodiversity credits that can be traded or regulated in markets (Table 1). Currently, these credits represent the only means for investors and banks to monetize offsets, though the practice has been shown to be controversial. These BO credits can express ratios or an absolute value of species count, ecological services quantification and qualification, area or abiotic parameters (such as terrain, streams, soil etc.) (Gonçalves et al. 2015) and may be referred to as conservation credits, ecosystem credits, species credits, or biodiversity credits, depending on the specific country or program (Chiavacci and Pindilli 2018). The primary objective of this approach is to achieve a state of 'no net loss', preferably a 'net gain' of biodiversity (Table 1) (Moilanen et al. 2009; Business and Biodiversity Offsets Programme BBOP 2012). Biodiversity equivalence has a pivotal role in this process, requiring that the ecological value of the offset site is comparable to that of the impacted site (BBOP 2012a). Biodiversity credits also function as a financial instrument for enhancing biodiversity, independently from environmental regulations, promoting biodiversity enhancement (Table 1) (Porras and Steele 2020; World Economic Forum 2022; Tedersoo et al. 2023). Each credit signifies a positive change in biodiversity attributes and represents either a unit of area, number of species, abundance or other biodiversity indices (separately or together) (Tedersoo et al. 2023). This mechanism acts as an incentive for landowners or non-governmental organizations (NGOs) to engage in actions promoting biodiversity through nature-based solutions such as habitat restoration or conservation (Birrer et al. 2014; World Economic Forum 2022; Ducros and Steele 2022; Simon and Dorothée Herr 2023). While biodiversity credits initiatives have garnered traction, particularly on terrestrial habitats, there is a noticeable lack of initiatives targeting the MAFs despite the ongoing loss of biodiversity due to human activities such as the fishing industry or deep sea mining, for example. This gap in attention to the MAFs within the biodiversity credits landscape highlights a critical oversight, warranting increased consideration and emphasis, especially in the context of biodiversity loss.

Despite its potential benefits, the term of BO faces several fundamental challenges. Firstly, the intricate and challenging nature of biodiversity assessment makes its quantification complex, introducing difficulties in ensuring complete equivalence or achieving a state of 'no-net-loss' between impacted and offset areas (BBOP 2013; Maron et al. 2016, 2018). Secondly, the matrices associated with biodiversity credits or biodiversity offsetting, whether addressing equivalency, ecological impact, or biodiversity gain, often lack transparency (BBOP 2012b; Maron et al. 2016; Lindenmayer et al. 2017). Thirdly, many biodiversity credit projects tend to focus on issues such as the loss of area, habitat quality in the loss area, ratios of assumed theoretical ecological services or the number of species and/or specimens that are lost, neglecting the organisms' functional roles in habitat maintenance (Gonçalves et al. 2015; Droste et al. 2022). As the above biodiversity issues are rarely considered together, the success of current offset projects depends on other inclusive elements such as comparable measures, access to reliable data, and effective monitoring and enforcement (BBOP 2012b; Gonçalves et al. 2015). Yet, none of the above approaches is universally agreed upon, and, particularly for ecosystem-engineered habitats in the oceans, it is often lacking, including the evaluation of the biodiversity of coral reefs, kelp forests and seagrasses.

Acknowledging the constraints of focusing solely on carbon sequestration and storage, there has been growing awareness in recent years of the crucial role that biodiversity plays in augmenting habitat maintenance, improving ecological functions, and in supporting ecosystem services (Tilman et al. 2014; Liu et al. 2018, 2018; Lee et al. 2019; Hua et al. 2022; Andres et al. 2023). The recognition that biodiversity contributes to the survival and functionality of organisms has led to the emerging concept that stakeholders can enhance their economic incentives beyond carbon credits by incorporating biodiversity considerations into their practices (Torabi and Bekessy 2015; Bryan et al. 2016; Tedersoo et al. 2023; Kangas and Ollikainen 2023). In forestation, this approach may increase the potential for carbon sequestration, even when utilizing species with lower carbon sequestration capabilities. Additionally, it can prolong the temporal effectiveness of carbon storage (and carbon immobilization) while providing supplementary ecological services through the maintenance of biodiversity (Poorter et al. 2015; Huang et al. 2018; Feng et al. 2022). Although the combination of carbon and biodiversity credits is gaining traction in domains like silviculture ('co-crediting', "stacking credits; Table 1) and blue carbon (Bryan et al. 2016; Tedersoo et al. 2023), this integrated approach is notably absent also in the context of MAFs. Given the profound global and local significance of MAFs for biodiversity, along with their impact on ecological functions that influence ecosystem services, we argue that the incorporation of biodiversity (and in some cases, carbon immobilization or sequestering) for the MAFs is imperative to create an incentive for effective restoration, ultimately facilitating climate change mitigation and decelerating the pace of biodiversity loss.

Intergovernmental marine biodiversity goals

Acknowledging the pressing global environmental and sustainability challenges, the United Nations (UN) has designated the third decade of the 21st century as the 'Decade on Ecosystem Restoration'. This initiative underscores a collective global effort to restore ecosystems, aiming for up to 30% of coastal and offshore areas (United Nations 2019). It underscores the central roles of ecosystem resilience and adaptation in addressing climate change by storing carbon and safeguarding biodiversity.

The declaration of the Decade on Ecosystem Restoration was subsequently complemented by the targets outlined in COP15 CBD UN (2022) and by the recent discussions in COP16 (Convention on Biological Diversity 2024a, 2024b). Noteworthy among these targets are those directed explicitly at marine restoration, including the objective to ensure that by the year 2030, at least 30% of degraded areas will undergo effective restoration (Target 2). This is in sharp contrast to the current state where only 8% of the ocean is under some form of protection, and less than 3% is fully or highly protected (Valença et al. 2024). Additionally, there is an emphasis on the necessity to mitigate the impacts of climate change on biodiversity by employing nature-based solutions, that include active restoration (Target 8). Furthermore, COP15 adopted the Kunming-Montreal Global Biodiversity Framework, which recognizes the need to augment international, public, and private funding for restoration (Target 19). It also emphasizes the importance of transparency and accountability in executing these actions (Section J; CBD UN 2022).

Coastal and marine conservation initiatives require substantial financial resources, which are often dictated by political decisions. These resources are frequently limited and overshadowed by competing priorities, as oceans typically rank low on the political agenda. In contrast to past situations, the UN and international bodies, such as the EU, have emphasized the importance of supporting marine biodiversity projects (United Nations 2019; European Commission 2020). They advocated for collaborations among governments, international organizations, and the private sector to finance and implement marine conservation and mitigation initiatives, acknowledging that it is impractical to depend solely on formal funding from governmental institutions. The UN biodiversity strategies for 2030 further highlight the critical role of funding marine biodiversity projects in achieving conservation and mitigating targets (United Nations 2015, 2019; European Commission 2020; Convention on Biological Diversity 2024c). To address funding challenges, the UN and the EU have also stressed the need for innovative financing mechanisms to support nature-based solutions for marine biodiversity projects. By leveraging public-private partnerships, these organizations, and others (BNP Paribas 2023; Convention on Biological Diversity 2024c), aim to mobilize additional resources and effectively overcome financial barriers, ultimately contributing to protecting and restoring marine biodiversity.

Biodiversity credits for the MAF

> Biodiversity is the variety of life and its processes. It includes the variety of living organisms, the genetic differences among them, the communities and ecosystem in which they occur, and the ecological and evolutionary processes that keep them functioning, yet ever changing and adapting. (Noss and Cooperrider 1994)

In the given context of the above provided definition, the biodiversity within MAFs plays a crucial role in their ability to endure and adapt to environmental changes, (Rossi 2013; Nash et al. 2016; Drury and Lirman 2017; Brandl et al. 2019; Topor et al. 2019; Benkwitt et al. 2020) and can potentially help mitigate the impacts of human activities and global changes. Analogous to terrestrial forests, species that act as ecosystem engineers within MAFs habitats contribute to the complexity of these ecosystems, creating a multitude of ecological niches that influence the behavior of other organisms and foster the establishment of habitats with a high level of species richness and functions (Jones et al. 1994; Graham and Nash 2013; Horoszowski-Fridman et al. 2015; Shmuel et al. 2022). In non-disturbed MAF ecosystems, interactions among MAF dwelling species, coupled with the interplay between biotic and abiotic parameters, intraspecific genetic diversity, successful reproduction and recruitment, weave a complex network of species interactions and trophic relationships within MAFs, enhancing habitat stability and resilience (Altieri et al. 2007; Rossi et al. 2017; Gribben et al. 2019; Benkwitt et al. 2020). This is highlighted at various biodiversity levels. High intraspecific diversity enhances resilience to disturbances by broadening the range of responses within populations under different environmental conditions (Hughes and Stachowicz 2004; Reusch et al. 2005; Meyer et al. 2009; Baums et al. 2013; Brown et al. 2022). Higher species diversity increases the likelihood that some species can compensate for the loss of others, helping maintain ecosystem functions and productivity (Nash et al. 2016; Noss 1990; Nyström 2006). Species-rich communities are often more resilient, more efficient in resource use, and better at recovering from disturbances due to genetic diversity and functional redundancy, which ensures ecosystem stability (Hooper et al. 2005; Nyström 2006; Emmett Duffy 2009). This biodiversity-driven resilience supports the MAFs' capacity to adapt to changes in environmental conditions, safeguarding these vital ecosystems and contributing to carbon immobilization and other ecological services (Worm et al. 2006; Tilman et al. 2014; Emmett Duffy et al. 2017; Huffmyer et al. 2023). Yet, this biodiversity-driven resilience is not absolute, as MAFs are increasingly subjected to intense direct human activities (e.g. bottom trawling, mining) and climate change, which can exceed their natural adaptive capacity. In terrestrial ecosystems, the hypothesis that high levels of carbon storage and sequestration are positively correlated with biodiversity (Schuldt et al. 2023) and that increased biodiversity, in turn, enhances carbon storage and sequestration (Poorter et al. 2015; Liu et al. 2018; Huang et al. 2018; Feng et al. 2022) remains a topic of ongoing discussions. Although the causal relationship is not fully understood, the link between carbon storage/sequestration and biodiversity is evident (Poorter et al. 2015). This relationship is even more intricate in the case of MAFs, since the two are deeply interconnected (Rossi et al. 2012, 2017). It is important to recognize that while MAFs as a whole ecosystem have the potential to contribute to carbon sequestration, their role remains uncertain, though they are considered relevant elements in broader blue carbon discussions (Ware et al. 1991; Shi et al. 2021; Rinkevich 2024; James et al. 2024).

Despite the crucial role MAFs play in global biodiversity and their extensive ecological services, restoration efforts of these ecosystems (apart from tropical coral reefs) remain noticeably insufficient. This deficiency is attributed to knowledge gaps regarding the ecology and biology of these habitats and their organisms, the lack of financial support, and inadequate public awareness (Duarte et al. 2008). The integration of biodiversity and carbon credits in MAFs restoration presents a potential solution to address this gap. Shifting the focus from carbon sequestering to the concept of MAF biodiversity (including, but not necessitating carbon immobilization) may create tradeable units that can be exchanged in a relevant market. Each such unit comprises essential values (Table 1; Figure 2):

(1) Biodiversity value: this quantifies the habitat quality within the context of biodiversity definition by Noss and Cooperrider (1994). It will be determined by biodiversity indices and matrices. This would also include the augmentation of the associated MAF biomass, such as fishes, echinoderms, mollusks, crustaceans, etc.
(2) Carbon immobilization potential gain: This assesses the habitat's capacity for carbon immobilization (in some MAFs, like the coral reefs, towards carbon sequestration, Perry et al. 2012; Coppari et al. 2019) akin to the calculations involved in carbon credits. It should also consider the carbon stored in the biomass of associated fauna, including both vertebrates and invertebrates, particularly in long-lived species.
(3) Fisheries value: This measures the increase in the edible MAF biomass (fish, echinoderms, mollusks, and crustaceans), which has economic value. The abundance of these species is linked to the complexity and longevity of the MAFs.

We also acknowledge that not all MAFs can generate blue carbon at the level of traditional blue carbon ecosystems (e.g. seagrasses) or that some MAFs may not qualify for carbon credits at all. Yet, this does not conflict with the integration of carbon and biodiversity credits in MAFs restoration acts, as it is not a zero-sum situation. If carbon is neither stored nor sequestered, carbon credits will not be created, and incentives will come solely from biodiversity credits.

The core idea behind using biodiversity-carbon credits in MAF restoration is grounded in the premise that restoration efforts (including introducing artificial structures to degraded or non-functional habitats) can have a significant impact on carbon immobilization and species biodiversity. Even the simple act of transplanting habitat-forming species (beyond tropical scleractinians or bivalves) can

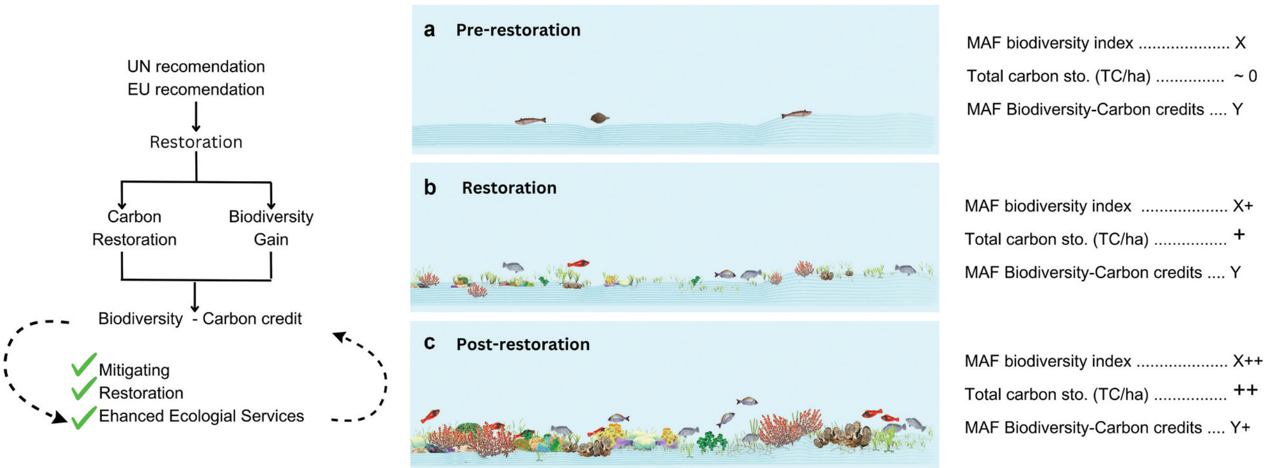

Figure 2. Illustration outlining the integrated Biodiversity-Carbon credits concept for the MAF. Left panel- International, national and domestic initiatives developed in accordance with the processes outlined in steps a-c within the middle panel. Aligned with the UN and EU recommendations for global change mitigation, enhanced biodiversity and augmented carbon sequestration are co-joined through habitat restoration (a and b in the middle panel), to create novel perpetuating financial instrument (c in the middle panel). The chosen MAF site for restoration activities (a in the middle panel) represents dwindling biodiversity values and neglected (almost zero) carbon stocks (right panel), hence, making it uncreditable. The letters for X and Y (right panel) are placeholders representing theoretical values for a 'MAF biodiversity index' and the 'MAF biodiversity-carbon credits', respectively. 'Total carbon sto. (Tc/ha)' represents the value of carbon stored per hectare. MAF biodiversity-carbon credits is the combination of the total carbon stored (Tc/ha) with MAF biodiversity index. The post-restoration site (c), sustained through augmented biodiversity, assists in mitigating human impacts, and offers additional ecological services. This, in turn, can lead to an increase in the issuance of biodiversity-carbon credits and economic benefits for a sustained habitat (including fishing and tourism activities). The plus signs (+) represent a theoretical value (of the respective index) that was added to the index due to restoration effort or post-restoration state.

initiate carbon immobilization in areas where it was previously lacking. This also enhances ecological niches, promoting the recruitment of diverse organisms with unique functions that would not have otherwise existed. With effective planning, monitoring, and the cascading benefits of habitat restoration, ecosystems can maintain resilience, leading to increased biodiversity and, in turn, elevated carbon immobilization and storage (Figure 2). Therefore, using biodiversity-carbon credits in MAFs restoration may add to the suggested priorities and strategies for these ecosystems, as suggested for coral reefs (Kleypas et al. 2021; Vardi et al. 2021). As an example, (Rinkevich 2024) proposed the use of the easily deployed floating reefs modules (each 10×10 m, holding up to 10^4 coral colonies), which grow more quickly due to favorable conditions. Scaling this approach to cover an area of 1 km^2 could enhance biodiversity, create opportunities for generating biodiversity credits, and also sequester carbon, enabling the generation of carbon credits.

The biodiversity-carbon connections are shaped by factors such as the complexity of the ecosystem engineers, their age and the ways they can allocate carbon in their structures (and for how long) (Rossi et al. 2012). Any emerged biodiversity-carbon credit system will be based on complex indices rather than being overly reliant on species richness alone. It should encompass ecological attributes such as intraspecific genetic diversity, functional diversity and relative abundance of species, so as their capacity to sequester and store carbon (Noss 1990). Assuming that the restored MAFs of the future will not fully replicate the richness and biodiversity of past MAFs sensu (Rinkevich 2015a), the biodiversity credits generated will not be compared to pristine statuses or historical conditions. It will quantify the biodiversity scores added to a restored MAF, along with the supply of essential ecological services.

Biodiversity credits for MAF restoration allow businesses and individuals to achieve a ‘net gain’ in ecosystem restoration. By merging carbon capture with biodiversity goals, this approach encourages NGOs, private land (sea) owners, and investors to engage in initiatives that offer mutual environmental benefits (Kangas and Ollikainen 2023).

Conclusions

MAFs serve as crucial biodiversity hotspots profoundly impacted by human activities and climate change. Despite their vital contribution to global ecological services, current conservation and restoration efforts predominantly focus on terrestrial ecosystems, often overlooking the importance of MAFs.

Our proposed integration of biodiversity and carbon credits, where carbon sequestration and carbon immobilization (where applicable) are effectively encompassed within the developing biodiversity index, offers a transformative approach to MAF restoration. This approach is not just a theoretical concept but a practical and urgent necessity as it seamlessly aligns with intergovernmental biodiversity goals, underscoring the importance of innovative financing mechanisms facilitated through public-private partnerships. It further responds to the urgent call for effective strategies to restore and protect marine ecosystems. This concept, which emphasizes both biodiversity and carbon immobilization, captures the manifold benefits that the MAFs offer (Figure 2). It is also highly flexible, accommodating the different types of MAFs. In MAFs where carbon is neither stored nor sequestered, carbon credits will not be generated, and the incentives will rely entirely on biodiversity credits. The implementation of the biodiversity-carbon credits reflects a comprehensive approach to carbon immobilization and biodiversity enhancement within the MAFs, contributing to broader conservation and restoration efforts and enhancing the overall ecological well-being of these unique marine environments. This concept, which emphasizes both biodiversity and carbon immobilization, further encourages a broad spectrum of stakeholders to engage in comprehensive restoration efforts, effectively addressing the challenges faced by MAFs and contributing to a more sustainable future.

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Author contributions

Dor Shefy Conceptualization, Writing – original draft, Writing – review & editing, Visualization.
Sergio Rossib Conceptualization, Writing – review & editing, Supervision, Project Administration, Funding Acquisition.
Baruch Rinkevicha Conceptualization, Writing – review & editing, Supervision, Funding Acquisition.

Disclosure statement

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