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Blue carbon in an eastern boundary upwelling zone – A case study in Namibia

Simon H. Elwen [a,b,1,*], Usman Khan [c], Anja Kreiner [d], Anja K. Van der Plas [d], Margit R. Wilhelm [e], David Barnes [f], Kerry Howell [g], Tara Pelembe [a]

[a] The South Atlantic Environmental Research Institute (SAERI), Stanley Cottage North, Falkland Islands, Stanley, FIQQ 1ZZ, UK
[b] Department Botany and Zoology, Stellenbosch University, Stellenbosch, South Africa
[c] Namibia Nature Foundation, Namibia
[d] National Marine Information and Research Centre, Ministry of Fisheries and Marine Resources, Swakopmund, Namibia
[e] Department of Fisheries and Ocean Sciences, University of Namibia, Henties Bay, Namibia
[f] British Antarctic Survey, Natural Environment Research Council, Madingley Road, Cambridge, CB3 0ET, UK
[g] School of Biological and Marine Sciences, University of Plymouth, Plymouth, PL4 8AA, UK

A R T I C L E I N F O

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A B S T R A C T

Blue Carbon (BC) refers to Nature-Based Solutions in marine environments that aim to reduce greenhouse gases through carbon sequestration using natural processes. Much of the BC focus to date has been on tropical coastal habitats, especially salt marshes, mangroves, and seagrass beds, while research in temperate marine environments has lagged. In this paper, we investigate the BC potential in a cold-temperate eastern-boundary upwelling ecosystem, the northern Benguela off Namibia. We identified four areas, where the BC concept can be applied, identify data gaps and areas for future research. 1) Macroalgae play a large role in carbon sequestration globally, although many of the values and specifics remain debated. We recommend research to investigate the ultimate flows, fate and permanence of carbon in Namibian kelp forests, and the development of a high-quality national map of kelp biomass distribution. 2) The northern Benguela has a high abundance of gelatinous plankton, possibly associated with the collapse of the small pelagic fish stocks. Gelatinous plankton play an important role in the global carbon cycle and research into their role in carbon flow and sequestration in the northern Benguela is recommended. 3) Commercial fisheries are amongst the highest producers of carbon globally. We strongly support policies that promote the restoration of Namibian fish stocks, especially sardine and recommend undertaking analyses of the carbon-footprint of Namibian fisheries and their supply chains to identify areas where carbon production could be reduced through improved efficiency, reduced impact on the seabed and optimised transport solutions. 4) Namibia hosts some of the world's most carbon-rich marine sediments along its continental shelf. We recommend conducting a BC natural capital assessment of the environmental and financial value of these sediments and any impacts thereon. These actions could open new markets for Namibian products that prioritise low-carbon foodstuffs. Combined, a more thorough assessment of Namibia's BC ecosystems could contribute substantially to Namibia's nationally determined contributions.

1. Introduction

Anthropogenic greenhouse gas (GHG) emissions are driving rapid global climate change (IPCC, 2007, 2014, 2023) with unprecedented rates of change in atmospheric and ocean carbon dioxide (CO_2) levels (Feely et al., 2008), ocean acidity (Doney et al., 2012), sea temperature (Perry et al., 2005; Bindoff et al., 2007), air temperature (Sithole and Murewi, 2009) and salinity (Roessig et al., 2004) amongst others (see review in Moloney et al., 2013). The biota of the world's marine ecosystems have also shown changes in species assemblages and distribution patterns across trophic levels from viruses (Doney et al., 2012), seagrasses (Short and Neckles, 1999) and jellyfish (Miller et al., 2020;

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* Corresponding author.
E-mail address: Simon.Elwen@gmail.com (S.H. Elwen).

[1] Research Associate, Dept Botany and Zoology, Stellenbosch University

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Attrill et al., 2007) to estuarine and marine fish (Roessig et al., 2004; Perry et al., 2005) and marine mammals (McLeod, 2009; Kaschner et al., 2011). These changes in both physical and biological systems are further compounded by other human mediated impacts including habitat destruction, overfishing, pollution and the introduction of invasive species. Mitigating further impacts of climate change and halting loss of nature have become global priorities (Pörtner et al., 2023) and even small contributions to reducing atmospheric carbon and other greenhouse gasses are considered worthwhile.

Multiple initiatives and projects are underway globally to attempt to reduce further release of GHG into the atmosphere, and to actively remove carbon that is already there. This proactive approach to carbon capture from the atmosphere and locking it away long-term is also called carbon sequestration and it falls under two broad methods: technological or human made approaches, and nature-based solutions (Baurov, 2021). Technological approaches include actively filtering CO_2 from the air and converting to stable compounds for long-term storage and/or pumping gasses into underground rock formations (Baurov, 2021). Nature-based solutions (NBS) recognise the fundamental role of some natural processes to hold and actively sequester atmospheric carbon over long-term (century scale) periods in sediments, biomass and/or water and include projects with various levels of human involvement and technical management.

The term 'Blue Carbon' is relatively new, only appearing with any regularity since ~2010 (Google ngram viewer, Macreadie et al., 2019). 'Blue Carbon' (hereafter BC) refers to all biologically-driven *carbon fluxes* and storage in marine systems that are amenable to management (IPCC, 2019). Carbon from the atmosphere is fixed by primary consumers and stored within the bodies of marine organisms (from plants and plankton, to coral skeletons and whales) or marine sediments over the period of years to centuries. A small proportion of this (not respired or recycled by the microbial loop on death) is buried in sediment. When older than centuries this carbon is considered sequestered (e.g. below the oxygenated lay of muds, silts and clays). The term 'Blue Carbon' is used to refer to both existing stocks of carbon (e.g. bodies of marine organisms or their remains in benthic sediments) and more broadly to the projects that are actively trying to quantify, map, protect or even increase carbon storage through managing natural resources such as mangrove and kelp forests, or protect existing stocks from future disturbance (Barnes et al., 2021; Bax et al., 2022). Much of the Blue Carbon focus to date has been on coastal habitats, especially salt marshes, mangroves, and seagrass beds, but in more recent years there has be a recognition of the potential of other sources, such as macroalgae (i.e kelp; Krause-Jensen and Duarte, 2016) and farther from shore, in the huge amounts of carbon stored in fauna such as cold water coral associated communities (Barnes et al., 2021), gelatinous plankton (Lebrato et al., 2013), fish (Sala et al., 2021), large whales (Pearson et al., 2023), habitats such as fjords (Zwerschke et al., 2022) and ultimately the benthic sediments of the open ocean (Atwood et al., 2020). These are resources in which the carbon can be protected and managed with carbon sequestration in mind.

In addition to the role in reducing the impacts of climate change, sequestered carbon can also be considered an asset with financial value that can leverage finance through market-based and non-market approaches and be sold or traded on international carbon markets. These types of financial investments can offer an important source of income in developing countries with smaller economies (Bennett et al., 2024). Countries which are Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to submit reports on their "Nationally Determined Contributions" (NDC) of carbon to the global atmosphere, which include goals of how their carbon emissions targets will be met. Countries which are non-Annex 1 countries (mostly developing countries including Namibia and South Africa) submit national communications every four years with biennial updates. Despite the clear conservation and financial value of Blue Carbon resources, and recognition of the value of BC by the UNFCCC, oceanic and coastal sources (and sinks) of carbon are largely overlooked in the NDC evaluations of many countries (Bennett et al., 2024). For example, Blue Carbon sources/sinks receive very little mention in recent NDC reports for either South Africa (DFFE, 2021) or Namibia (MEFT, 2021, 2023), despite extensive investment in marine research, and the recognised importance of fisheries and ocean-based resources (the "Blue Economy") to the economies of both these countries (Loureiro et al., 2022; MFMR, 2022). Bennett et al. (2024) provide a review of the Blue Carbon potential in the island state of the Seychelles in the tropical south west Indian Ocean, highlighting the potential importance and challenges of BC resources to NDC calculations and financial investments. Another example is the island and surrounding seamounts of Tristan da Cunha in the mid-South Atlantic that have been recognised to have substantial stocks of blue carbon of considerable potential financial value, which are now being safeguarded from fishery damage through recent implementation of a large marine protected area (Barnes et al., 2021). It is thus valuable to have a good understanding of the Blue Carbon resources of coastal countries, in terms of identifying, quantifying and working to fill these data gaps. In Namibia, some relevant data on carbon resources do exist (e.g. (Siddiqui et al., 2023) and ocean acidification monitoring started in November 2021 (AvdP, pers. obs.) and are reviewed in this paper.

As a relatively new term and concept, the boundaries of what constitutes BC and the relative importance of different components of the marine environment in contributing to meaningful carbon sequestration are still the focus of ongoing research and debate. For example, the importance (and associated monetary value) of macroalgae (Krause-Jensen and Duarte, 2016; Eger et al., 2022; Gallagher et al., 2022) and global fishing (Sala et al., 2021: Hiddink et al., 2023) in exporting and sequestering, vs releasing carbon are both subject to intensive and high profile debate. Some of the results of early studies showing great promise in the global scale of BC, may have been overly reliant on extrapolation of values from relatively few studies, or flawed in their calculations. In addition, serious flaws have been identified with several carbon credit schemes, questioning their long-term effectiveness, with reviews and adjustments to these credit schemes currently underway (Greenfield, 2023). These challenges, and many others to the field of BC research are widely recognised and there is extensive global research in the field (Macreadie et al., 2019). However, in general, protection of nature benefits the global climate (Shin et al., 2022) and this is rarely likely to be better maximized than in blue carbon habitats. As (blue) carbon sequestration and the monetization of NBS trading gain attention in the global media and scientific literature, it is essential that local data are collected to ensure a correct and honest assessment of BC values to accurately inform governments, NDC calculations, and the budding carbon credit industry.

In this paper we identify Blue Carbon (re)sources and potential within Namibia's EEZ, a country that is home to one of the environmentally richest sectors of the global ocean, the Benguela Upwelling Ecosystem, and has started a marine spatial planning process (MFMR, 2021). The country has many human activities which impact the marine environment including extensive industrial fisheries, and existing and potential marine mining for diamonds, hydrocarbons and phosphate creating potential conflicts requiring careful management. The combination of these factors may create opportunities to reduce carbon emissions and/or increase storage with strong potential of sequestration within Namibia under the blue carbon umbrella through managing human impacts on the marine environment, protecting existing stocks and promoting the recovery of damaged ecosystem areas.

2. An overview of Namibia and its marine environment, including the Benguela upwelling ecosystem

Namibia is a country with a low human population and density, and a predominantly dry or desert landscape (Fig. 1). The ~1570 km of coastline and adjacent EEZ falls within the Northern Benguela

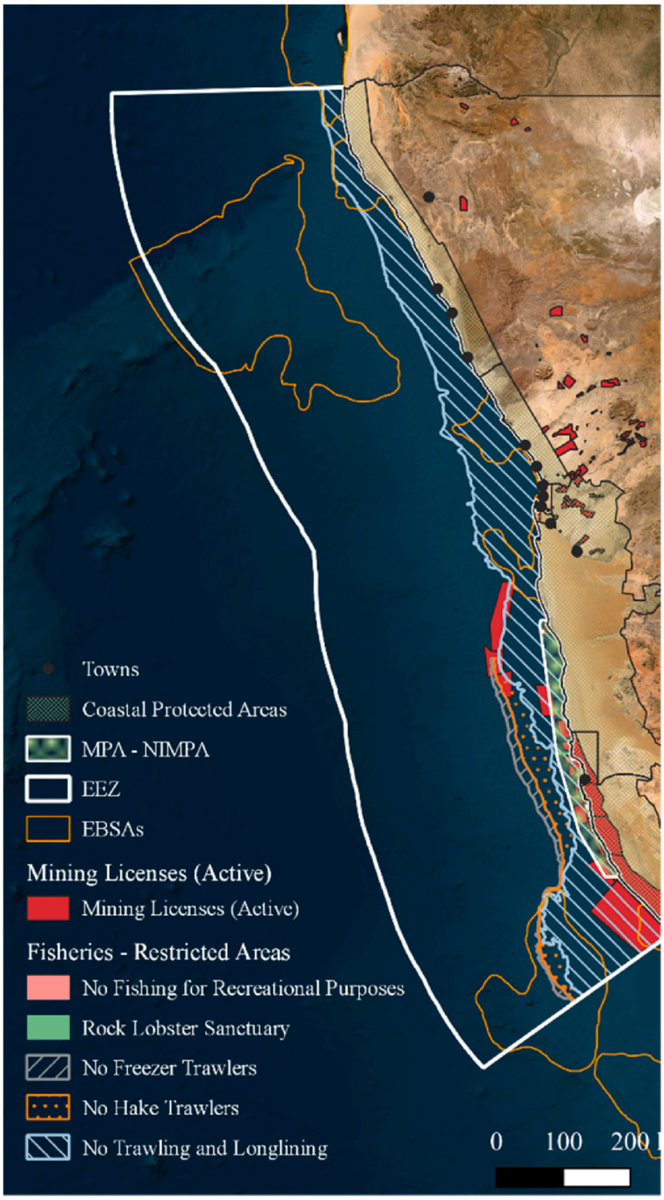

Fig. 1. Map showing the Namibian coastal environment with the Exclusive Economic Zone (EEZ), coastal and marine protected areas, defined EBSAs (Ecologically or Biologically Significant Areas, NMU ESBA portal), major fisheries compliance zones, and active mining license areas (Namibian Geological Survey, 2022).

Ecosystem making Namibia's coastline and adjacent ocean relatively unusual in the global blue carbon context. Firstly, eastern boundary upwelling ecosystems such as the Benguela, Humboldt and California currents, are characterised by wind-driven upwelling bringing cold, nutrient rich waters to the surface where they are the base of some of the most productive areas of the marine ecosystem globally (Shannon and O'Toole, 2003). The cold waters prohibit the growth of seagrasses and mangrove forests, where much blue carbon work to date has focused. However, the Benguela is highly productive in terms of nutrients, phytoplankton, kelp forests, gelatinous plankton (jellyfish) and at least historically, small pelagic fish (Shannon and O'Toole, 2003). Carbon transfer within upwelling ecosystems is complex and the ecosystems can act both as a sink (upwelled nutrients stimulate phytoplankton productivity) or a source of carbon (upwelled waters are rich in dissolved inorganic carbon). The unique characteristics of these upwelling systems mean that they are sometimes excluded entirely from global studies on blue carbon (e.g. Mariani et al., 2020). Further, the Benguela is known to be unusual amongst upwelling systems in having extraordinarily high organic carbon accumulation [up to 23% dry weight in benthic sediments (Currie et al., 2018; Inthorn et al., 2006; Mollenhauer et al., 2007)] as well as high levels of H_2S (Hydrogen Sulphide). H_2S is produced by the large beds of sulphide oxidizing bacterial mats on the seabed, which result in anoxic 'sulphur blooms' occurring over large areas and further complicate calculations of carbon flow in the ecosystem (Weeks et al., 2004; Currie et al., 2018; Emeis et al., 2018).

Additionally, the Namibian coastline lacks perennial rivers except at the northern (Kunene River) and southern borders (Orange River) which are important in a carbon context as rivers can contribute significant amounts of sedimentary carbon into coastal ecosystems (e.g. Bax et al., 2022). Finally, human settlements and density are incredibly low along the coastline with only 4 towns and two relatively small harbours along the ~1570 km of coastline, with access to much of the coastline restricted on the terrestrial side due to the presence of conservation areas or mining concessions. Most human access to the coastline (including recreational activities and coastal development) is limited to the central ~200 km between Walvis Bay and the southern part of the Skeleton Coast National Park.

Namibia's ocean space is relatively industrialised in terms of large-scale commercial fisheries and the country has recently undergone a Marine Spatial Planning process (MFMR, 2021) and developed its first MSP for the central region. This process has identified EBSAs (Ecologically or Biologically Significant Areas) but not gone as far as to develop these further into Marine Protected Areas (Finke et al., 2020). Namibia hosts a significant commercial fishing industry which contributes substantially to the country's GDP (roughly 2–3 % annually, NSA, 2022). The mineral resources of Namibia are relatively well described, and Namibia has a well-developed terrestrial and marine mining industry. Marine and coastal mining for diamonds has been taking place for over 100 years, through marine dredging and strip mining of beaches (Schneider, 2020). There has been extensive surveying for hydrocarbons, especially in the 21st century, and some exploratory drilling is currently taking place with expectations of high yields. Additionally, marine phosphate mining (using dredging) has been proposed but has been held up by objections from the community. If it goes ahead it could dredge 34 km^2 of phosphate rich sediments with an average depth of 2.3 m over an initial 20-year license period (Baufeldt et al., 2022).

3. Blue carbon potential in Namibia

We have identified four broad sectors within Namibia where the Blue Carbon concept and knowledge of carbon values and carbon flow could be beneficial to help reduce Namibia's carbon emissions at an industry and country level. These are macroalgae, gelatinous plankton, fisheries and benthic sediments. Reduction in carbon emissions and sequestration of carbon using nature-based solutions could open opportunities for the potential monetization of carbon through carbon credit programmes, or potentially open new international markets for Namibian products. Below we provide a brief overview of each of these sectors, their role in a blue carbon framework, and how these transfer to the Namibian context.

3.1. Macroalgae

Macroalgae are one of the most productive marine primary producers on a global scale with benefits for human society well beyond just carbon sequestration. Macroalgae produce oxygen, reduce marine nutrient pollution, provide key ingredients to food and cleaning products, and act as natural barriers reducing wave energy, helping to protect coastlines from erosion, while their complex three-dimensional structure provides a range of unique habitats and refuges for many species, thereby supporting high densities and richness of biodiversity (Eger et al., 2023). Through photosynthesis – they convert carbon held in the water column into algal biomass. As these algae grow, they shed fragments and leak dissolved organic carbon during storms. Larger pieces of kelp may drift for many kilometres ultimately sinking to the sea floor where most is recycled by microbial action but 1–11% of the carbon contained therein can be buried and may be locked away from atmospheric exchange. Additionally, macroalgae may export roughly 82% of their primary production to adjacent communities as detritus (Krumhansl and Scheibling, 2012), particulate organic carbon (POC – tiny pieces of kelp in the *μm* scale), and dissolved organic carbon (DOC). Many species grow on rocks as 'holdfasts', but those species which grow on sandy sediments may also transfer some of the carbon (~0.4%) into the sediments (Krause Jensen and Duarte, 2016). In environments where kelp are relatively close to deep water environments, the movement of 'drift kelp' detritus from the kelp beds out to deep water areas such as canyons can result in a substantial export of carbon from coastal ecosystems and burial into benthic sediments (Quieros et al., 2019; Smale et al., 2022). Once this is genuinely removed from the carbon cycle (i.e. buried beyond exposure to recycling through bioturbation or bioirrigation) it has BC value in becoming technically sequestered. Thus, societal activities that safeguard already sequestered carbon or enhance current capture and storage (leading to such sequestration) can and should be valued.

A recent evaluation of the global value of kelps across the six major genera included the key ecosystem services of fisheries production, nutrient cycling and carbon removal – calculated potential values of between US$ 64,400 and US$ 147,000 per hectare per year (Eger et al., 2023). Looking at only the values from carbon and nutrient cycling *Ecklonia* spp. (the dominant genus in southern Namibia) was valued at US$ 36,109 and *Laminaria* spp. (the dominant genus in central Namibia) at US$113 681 per hectare, and $72,020 for *Macrocystis* (the non-native species being farmed commercially within Namibia). The bulk of the calculated $ value was in the removal of nitrogen and phosphorous, with carbon making a much smaller contribution – the authors provide only averages across all species for removal per hectare per year: for Nitrogen: mean = $73,831, 620 kg per year, Phosphorus: mean = $4,075, 59 kg, and Carbon capture: mean = $163, 720 kg). Carbon sequestration varies considerably across kelp genera with *Ecklonia* from the South Atlantic having the lowest global value with an average of 31g per m^2 per year and 109 g/m^2/year for *Laminaria/Saccharina.*

There are three main ways in which macroalgae fit into the Blue Carbon framework and which could potentially be applied within Namibia.

1) Commercial aquaculture of kelp and other seaweeds is one of the fastest growing forms of aquaculture globally (Hu et al., 2023). Seaweeds need little in the way of fertilizer or pesticides and can be grown in many locations globally from protected bays to the open ocean. Seaweeds can provide a sustainable source of food for humans, feed for livestock, bioactive compounds for human use and even as a feedstock for the production of bioenergy and biofuels through anaerobic digestion or fermentation, as kelp biomass can be converted into biogas, bioethanol, or other forms of renewable energy. Carbon credits can potentially be claimed for i) bioenergy produced using fuels developed from macroalgae, ii) reducing GHG emissions in livestock and iii) carbon directly exported to potential sequestration routes by farmed kelp in situ or as pieces break off and drift away, among others (Claes et al., 2022). From a Blue Carbon perspective – seaweed aquaculture is the most developed and closest to widespread acceptance and accreditation. As the farms are constrained in size, actively managed and there is already considerable baseline information and investment to build from, it is much easier to generate the data needed for carbon accreditation. Within Namibia, there is already one seaweed aquaculture project operating in Lüderitz, southern Namibia. This operation is using a faster growing, non-native species giant kelp (*Macrocystis pyrifera*). The company are already investigating a wide range of the metrics needed to work towards carbon accreditation, including analyses of sediment baselines, kelp growth rates and distribution patterns, developing biomarkers to identify kelp in the broader ecosystem, etc. If successful and shown to have no impacts on local ecosystems, there should be scope for expansion of this industry.
2) Active collection and burial or sinking of kelps. The floating kelp *Sargassum* grows in the Tropical Atlantic and has also undergone extensive range/abundance expansion since around 2011 (Wang et al., 2019), with mass bloom events (~8000 km long belts of weed) causing significant challenges for shipping, and wash outs on beaches resulting in high removal costs. There is a rapidly growing business of promoting the capture and sinking of rafts of *Sargassum* at sea (before it can land on beaches) with the goal of claiming carbon credits therefrom. However, there is concern from the scientific community that this industry may be 'working ahead of the science and ethics' due to the large number of unknowns in this sector, highlighting the conflicts (and ethical issues) that can that occur when carbon sequestration is monetized (Ricart et al., 2022). Sargassum or similar free-floating seaweeds do not occur in Namibia, however native kelps like *Ecklonia* and *Laminaria* species do break free and drift widely, including ashore. Collection of drifting kelp at sea or from beaches is certainly possible and in Namibia at least three licenses have been issued for the collection of kelp on beaches in the Lüderitz/Sperregebiet area (K. Grobler, MFMR, pers. comm.) with kelp mainly dried and used for fertilizer and animal feed. The potential of commercial seaweed harvesting within Namibia was highlight as long ago as 1987 (Rotmann, 1987; Molloy, 1990; Critchley et al., 1991), with mentions of *Gracilaria vurrucosa*, *Laminaria schinzii* and *Ecklonia maxima* as the main species of interest. The industry is small and labour intensive with variable employment, as beach cast events were unpredictable. Adding carbon sequestration values to kelp buried or removed from beaches could add further value to these businesses if correctly balanced against the likely high fuel costs associated with collection and burial, and the important role kelp has in providing nutrients and habitat structure to the beach ecosystem (Hyndes et al., 2022).
3) The protection of existing resources or restoration of degraded habitats can be done through an increase in protected areas, removal of direct predatory impacts like sea urchins and active seeding of kelp forests in degraded areas, among others. Maintaining near intact, species- and carbon rich habitats (including blue carbon) is a first priority before restoration or habitat creation, in that mature carbon pathways are most efficient (Shin et al., 2022; Pörtner et al., 2023). Kelp forest ecosystems are naturally highly variable, and the science of kelp forest restoration is regarded as still very much a developing field, with no single method being applicable across all systems (Layton et al., 2020; Eger et al., 2022). Efforts to restore sea forests lag far behind those of other major ecosystem types (Filbee-Dexter et al., 2022). A global review of restoration projects by Eger et al. (2022) identified over 250 restoration project attempts over ~50 years, with most done for short periods and in small areas. Notably none of these were within the Benguela Ecosystem. Identified projects included both restoration of degraded habitat and 'afforestation' (creating new kelp forests in potentially suitable areas). Projects were most successful when conducted near existing healthy kelp forests providing important insight into an additional role of existing healthy forests (Eger et al., 2022). Within Namibia, direct threats to existing kelp forests such as active removal/habitat destruction, are relatively low outside of diamond mining areas (see Pulfrich and Penney, 2006). The majority of natural kelp ecosystems lie to the south of the country and within the Namibian Islands Marine Projected Area, while the central coast is almost all directly offshore of the extensive dune seas of the Namib-Naukluft National Park with effectively no shore-based or nearshore human impacts or development. Coastal development is focused around the three main coastal towns (Lüderitz, Walvis Bay, Swakopmund). Coastal mining for diamonds is likely to be the most direct threat as small-scale

diamond divers cut kelp and move sediments during diamond dredging, although this practise is quite limited to the Lüderitz area. Additionally, a focused study revealed that recovery of benthic communities and functional similarity occurred within 8–12 months of impact (Pulfrich, 2007). Given the rapid recovery of kelp cut for diamond diving and the distribution of kelp beds within or adjacent to existing protected areas, there are likely not many additional legislative tools that can be applied to meaningfully improve the protection or restoration of these habitats. However, to protect existing stocks of the resource, and accurately assess future changes - it is strongly recommended that accurate estimates are made of the distribution extent and density of current kelp species. Quantitative assessment of their carbon storage, export and sequestration efficiency are needed as well as the broader environmental services and societal benefits of kelp forests (e.g. Eger et al., 2022). These values can then be included explicitly in economic evaluations of the protected areas, as well holistic Environmental Impact Assessments, and will be important in tracking changes in distribution and abundance in the face of global climate change.

3.1.1. *Macroalgae – cautions and risks*

Although highlighted as potentially an important resource of considerable magnitude for carbon sequestration at a global scale (Krause-Jensen and Duarte, 2016), the investment into the Blue Carbon potential of macroalgae is not without risks and criticisms (Gallagher, 2022). Many high-profile global studies are based on very broad scale spatial analyses and rely heavily on extrapolation from a limited number of studies, or may be based on theoretical or modelled ranges, and so the ranges and values calculated therefrom may involve considerable error (i.e. be overestimated). Where a species *can live* is very different to where it *does live* or could potentially be farmed given other logistical, spatial and legal constraints. Caution must be applied when interpreting these values within more localised areas (countries, ecosystems). In Fig, 2 we highlight a clear example of this from Namibia: a comparison of the data layer of modelled global kelp distribution (Jayathilake and Costello, 2020) with the in situ aerial data (Pulfrich and Penney, 2006) for the same area suggests that the global data layer of theoretical kelp habitat overestimates the real kelp habitat by a factor of two orders of magnitude (UNEP modelled area = 4365 km^2, calculation from aerial survey: 4.53 km^2). Although it is likely that kelp could grow within this modelled distribution area if suitable substrate were available – it does not, and there is no realistic situation in which it would, so any (financial) calculations using this modelled range are potentially quite misleading.

3.1.2. *Ecological uncertainty and complexity*

For carbon to be considered ‘sequestered’ and play a role in reducing global climate change, it must be removed from the carbon cycle for a time period of centuries. Kelp ecosystems are notoriously variable between and within regions (Morris and Blamey, 2018; Layton et al., 2020; Smale et al., 2022) and research (and associated debate) on the role of kelp in carbon sequestration is very much on-going. As much of the calculated carbon sequestration is through loss of drifting kelp detritus to deep sea ecosystems, it is essential to be able to quantity the fate for each study site as it may vary significantly with water depth, currents, the presence of upwelling, etc., so real carbon sequestration values could vary considerably even within ecosystems (e.g. Morris and Blamey, 2018). In addition, the fate of organic matter like kelp once it reaches the deep sea is poorly studied. It is arguable whether it is actually even ‘sequestered’. More broadly, Gallagher et al. (2022) conducted a global review of relevant studies and have concluded that previous work on carbon sequestration by kelp forests is largely wrong and kelp forests may often be carbon sources rather than carbon sinks. They argue that as kelp forests are so important for biodiversity, they attract vast quantities of plankton and other organic material from adjacent open waters, providing extra food for filter feeders which may ultimately produce more CO_2 than the kelp consumes. Whole ecosystem approaches are required to quantitatively assess local food web capture, storage, export and sequestration pathways and fates of carbon (Barnes et al., 2021; Bax et al., 2021), rather than just one component such as macro-algae.

Additionally, kelp ecosystems are very vulnerable to both natural and human pressures - marine heatwaves can decimate large areas of kelp forest for extensive periods and with current global climate trends, heatwaves are likely to increase in both strength and rate (Miller et al., 2020). Marine heatwaves have caused extensive deforestation in the NE Pacific, changes in top predator abundance (disease, hunting, etc.) can have significant knock on effects into kelp forests (Harvell et al., 2019). Changes can result in ecosystems shifting to new stable states that are low or lacking in kelp entirely. If investing in kelp forests for the Blue Carbon potential – these large-scale risks and the long-term stability of sequestered carbon are essential to quantify and account for. An additional major pressure on many kelp forests and their restoration globally is sea urchin predation (Layton et al., 2020) and removal of sea urchins from forests is the focus of several restoration projects. However, the impacts of sea urchins and their removal can vary, and this is likely not a useful area of project development in southern Africa. For example, removal of urchins may benefit kelp but have knock on effects for other species in the ecosystem reliant on those for prey (Blamey et al., 2012) and the responses of kelp forests to urchin predation may vary considerably even within ecosystems (Morris and Blamey, 2018), again highlighting the essential need for whole community data. Removal of sea urchins and any interference with natural food webs should only be considered after careful and wider consideration. Increasingly there has been emphasis on considering biodiversity as well as, and simultaneously with, climate mitigation solutions as synergistically they tend to be more successful at addressing both crises (Shin et al., 2022; Pörtner et al., 2023).

Combined, these factors highlight some of both the value and complexities of macroalgae ecosystems and their role in the Blue Carbon sector. To date there are no finalised standards available for developing the methodology of carbon accreditation from seaweed or kelp farms from the global carbon standard organisations of VERRA or Goldstandard. However they are in the concept note stage (e.g. at VERRA as M0172, July 2023) while the Kelp Forest Foundation (Namibia) have submitted a concept note to GoldStandard in late 2022 (S. Deane, KFF, pers. comm.). In summary, although there has been extensive interest over the potential role of macroalgae in sequestering carbon at a meaningful global scale, it cannot be regarded as a silver bullet and there is considerable local and species variation which must be thoroughly investigated.

3.2. *Gelatinous plankton*

Jellyfish, or gelatinous zooplankton include the cnidarian jellyfish, ctenophores, pelagic ascidians and other taxa. Jellyfish appear to be increasing in numerous locations around the globe, often with dramatic consequences for ecosystems and human activities, blocking fishing nets, pipe inlets and reshaping ecosystems (Gibbons et al., 2016). Jellyfish biomass and ‘blooms’ are likely to increase in response to climate change as they have a higher capacity to cope with ocean acidification (Hall-Spencer and Allen, 2015) than many fish species. Despite being mainly constituted of water, jellyfish contain substantial amounts of carbon, and the carbon component of the global biomass of gelatinous zooplankton in the upper 200 m of the ocean has been estimated at 0.038 Pg C (Lucas et al., 2014; Lebrato et al., 2019). Due to the short life span of most gelatinous zooplankton, which is typically from weeks up to 12 months, biomass-production rates above 0.038 Pg C y^{-1}, have been estimated (Ceh et al., 2015; Raskoff et al., 2003). Luo et al. (2020) estimate even higher values, with their estimated total global export of POC by gelatinous plankton in the region of 1.6–5.2 Pg C y^{-1} representing 32–40% of global POC export, and that excludes components such as jelly-falls, which may further increase calculated values. However, once 'fallen' into the benthic zone, gelatinous plankton are rapidly scavenged and become an important part of the deep-sea food web (Sweetman et al., 2014), so there is certainly not a simplistic case of sinking jellyfish equate to sequestered carbon. All studies which extrapolate across the globe are vulnerable to excessive simplification. However, it is clear that gelatinous plankton play a very important and relatively recently recognised role in the global carbon cycle. Currently, the global perspective of the role of gelatinous plankton in a Blue Carbon framework mainly focuses around their importance as a reservoir of carbon and their role in carbon transfer from pelagic to benthic environments (Lebrato et al., 2013, 2019).

In Namibia, the marine environment (the Northern Benguela ecosystem) underwent an ecological regime shift during the 1960s and 1970s - substantial, irreversible changes in the structure and function of the ecosystem (Cury and Shannon, 2004). Overfishing caused the collapse of sardine which was coincident with large subsequent increases in gelatinous plankton and other fish species, notably the bearded or pelagic goby (*Sufflogobius bibarbatus*) (Roux et al., 2013). Significant quantities of jellyfishes in the region were first noted by researchers in the early 1970s and by the 1980s they had reached a very high biomass, estimated at more than 40 Mt (Fearon et al., 1992). Modelling studies suggest a reasonably direct inverse relationship between gelatinous zooplankton biomass and small pelagic fish stocks (mainly sardine), in that when one collapses the other causally increases (Shannon et al., 2009; Roux et al., 2013), although caution must be applied as model parameterization of jellyfishes is typically surrounded by considerable uncertainty (Pauly et al., 2009).

Studies on jellyfish within Namibia have increased since the 2000s with some information available on distribution, trophic interactions, environmental predictors, predation, blooms and their role in the ecosystem shift among others (Brierley et al., 2001, 2004; Lynam et al., 2006; Utne-Palm et al., 2010; Flynn et al., 2012; Roux et al., 2013; Ziegler and Gibbons, 2018; Ras et al., 2020). Thus, much of the data needed for studies into their role in the carbon cycle and sequestration already exists. Systematic data collection on jellyfish during fisheries research surveys in Namibia only started in the early 2000s and it is hence very difficult to find quantitative proof for an increase in biomass of jellyfish. Flynn et al. (2012) collated all available sources of information on jellyfish abundance up to 2006 and compared it with the presence of pelagic fish catches and fish larvae over time and space at multiple scales. Although they could not conclusively prove an increase in jellyfish abundance (mainly due to lack of data prior to fisheries overexploitation), they did find anecdotal evidence of an increase, as well as a degree of spatial predictability linked to oceanographic convergence zones and evidence of higher jellyfish abundance in areas of lower fish larvae abundance, suggesting a predatory relationship. They conclude that the recovery of commercial pelagic fish (notably shallow water hake, sardine and anchovy) is hampered in the long term due to predation of their larvae by various jellyfish species and support the existence of regime shift in the ecosystem (Cury and Shannon, 2004; Flynn et al., 2012; Roux et al., 2013).

To the best of our knowledge there are no active or planned publications or projects investigating gelatinous plankton within a blue carbon or carbon-credit framework within Namibia. Fishing for jellyfish has been suggested as a method to control populations during bloom events which can negatively affect human activities and other species. Theoretically – an active fishing approach could be used as a form of carbon capture, or carbon could be included as a financial benefit in addition to other uses of the jellyfish, although Gibbons et al. (2016) recommend a very cautionary approach to any form of active management of jellyfish through fishing. It is clear from the above that gelatinous zooplankton must be considered in any calculations of standing carbon stocks and in any discussions or models of carbon flux and carbon sequestration, including those involving recovering fish stocks or ecosystem scale models.

3.3. Commercial fisheries

Overfishing has long been recognised as a leading environmental and socio-economic problem in the marine realm which has reduced global biodiversity and impacted the functioning of ecosystems. Although in the last few decades there have been significant recoveries of at least some stocks (Worm et al., 2009), the general pattern of deterioration continues (FAO, 2022). Fisheries in Namibia reflect these global trends with a history of excessive overfishing, ultimately resulting in the collapse of the sardine stock and near collapse of the hake fishery, but with signs of recovery in some sectors. For example, the hake trawl and long-line sectors are now conditionally MSC certified, although overall stock size remains below maximum sustainable yield level and by 2014, there had been a general decrease in trawl effort to half what it was in 2000 (Kathena et al., 2018).

Total catches of all commercial fish stocks in Namibia peaked at just over 2 million tons of fish and crustaceans in 1968. Simplistically, and assuming the average composition of 12% C per kg of wet mass of body weight – this represents approximately 240, 000 tons of carbon removed from the Benguela and potentially released into the atmosphere in that year alone. Current catches of all species are much lower: hake for example, peaked at 800,000 t in 1972 but the TAC in 2022 was only 154,000 tons (Wilhelm et al., 2015, MFMR reports), which at 12% carbon theoretically represents 18,840 t of carbon directly extracted from the Namibian ocean before considering other ecosystem impacts.

Reducing fishing is likely to help rebuild stocks, associated biodiversity and carbon pathways to burial. Combined with reduced fuel use resulting from lower fishing effort, impacts on the seabed and generally increased ecosystem health, reduced fishing can lead to considerable increases in carbon sequestration (Czamanski et al., 2011; Mariani et al., 2020). Large amounts of forage fish also help rebuild the stocks of meso- and top predators with similar positive results for population recovery, biodiversity gain and potentially carbon sequestration (Doughty et al., 2016; Sherley et al., 2020; Erasmus et al., 2021). The hake fishery in Namibia is well operated and regarded as sustainable, but it is a good example of a fishery where an understanding of impacts and tweaks in operation could result in significant decreases in carbon released especially if considered across the entire supply chain.

An evaluation of the 'carbon footprint' of the entire hake supply chain in Spain (including fish from Namibia representing 30% of total imports) revealed that: total greenhouse gas emissions from the hake production and value chain in 2017 were 681 kt CO_2e, with an emission intensity of 4.42 kg CO_2e per kg of whole fish, where fishing operations represent 67% (456 kt CO_2e) of emissions and the remaining 33% (225 kt CO_2e) was associated with transport to market (maritime, air or road) (Aragao et al., 2022). If including the value of 4.42 kg CO_{2e} per kg of whole fish for the entire value chain (from Aragao et al., 2022), the total Namibian hake TAC in 2022 would have a carbon footprint in the region of 680 tons of CO_2e (for those going to Spain at least). For these exported fish, the method of travel out of Namibia forms a significant component of the carbon footprint - 33% in the case of hake entering Spain (Aragao et al., 2022). Maritime and road transport of fish had the lowest emission intensities at 0.50 kg $CO_2e.kg^{-1}$ and 0.42 kg $CO_2e.kg^{-1}$ respectively, compared to air transport at 7.70 kg $CO_2e.kg^{-1}$. Air transported hake was thus responsible for 73% of emissions despite being only 14% of the total transported volume. These results clearly show that the method of transport for foodstuffs should be very carefully considered at a global level, and that due to the differences in the carbon/kg emissions of air and maritime transport it is sometimes more carbon efficient to import frozen food a long way than fly fresh food a short distance.

Industrial fishing is a very energy intensive industry and fuel use remains one of the largest contributors to carbon emissions per kg of fish produced (Kirchner, 2014; Muñoz et al., 2023). The global fishing fleet was estimated to use 41 billion litres of fuel in 2011 alone (Parker et al., 2018). Fuel use varies considerably with fishing method, with trawlers and dredgers being especially fuel intensive. Although, due to the larger amounts of biomass typically caught with trawlers, that industry can have a relatively low carbon footprint per kilogram of fish when considering only fuel consumption (Tan and Culaba, 2009; Bastardie et al., 2022). Within the Namibian hake industry, Kirchner (2014), showed that fuel costs represented about 20% of the costs of the 'wet-fish' (fresh fish) component of the industry, but as much as 35–40% of the operating costs for freezer trawlers which use additional fuel to run the onboard processing plants. On short trips, a larger proportion of time (and thus fuel) is spent travelling to and from the fishing grounds so there is a trade-off with the value of the fish (which also increases in value with size, with larger fish typically farther from shore). Additionally, vessel and instrument age play an important role in fishing efficiency, as well as vessel size with larger vessels typically catching more fish per unit effort (Kirchner, 2014; Kirchner and Leiman, 2014). Kathena et al. (2018) used commercial catch data from the Namibian hake industry to investigate population size and distribution and found that their model fit was significantly improved by inclusion of individual 'vessel ID', which they regarded as a 'fuzzy proxy' capturing factors such as crew experience, vessel noise and the quality and maintenance level of the vessel and equipment. This highlights another important factor that is hard to capture in studies at a global or regional scale: the importance of differences in fuel consumption per kg of fish caught at the level of ships and crew experience (see Fig. 2).

Another way in which fishing results in significant carbon release is the impact of dredge and trawl fisheries on benthic sediments. Bottom trawling such as in the Namibian hake industry, disrupts natural carbon flows in seabed ecosystems, changing sediment mixing, resuspension and impacting the benthic community. The true nature and scale of this impact is not well understood, especially in Namibia, and varies across ecosystems, trawling methods, bottom types and target species (e.g. Hilborn et al., 2023). Some papers in this field suggested the global trawl industry was potentially responsible for more carbon release than the global airline industry as calculations showed the industry trawled 1.3% of the global ocean (4.9 million km^2 annually), resulting in the release of 1.47 Pg of aqueous CO_2 emissions, owing to the higher carbon metabolism which occurs in sediments within a year of trawling (Sala et al., 2021). However, these values have been questioned and may be substantially overestimated due to miscalculations in some of the carbon transfer rates (Hiddink et al., 2023; Hilborn et al., 2023). The carbon component of benthic marine sediments in Namibia is very high but calculating transfer rates is complicated by high levels of anoxic water on the seabed, so we discuss these in more detail below. Adjusting fishing areas to avoid areas of benthic sediments with the highest carbon density is one simple route to significantly reducing the impacts of the trawl industry. However, the current fishing rules already limit hake trawling to water deeper than 200 m in the north and central area, and deeper than 300 m in the south, thereby already missing the carbon rich sediments of the continental shelf plain west of Walvis Bay, so potential gains may be relatively minor (Figs. 3 and 4).

Additionally, many extrinsic factors also shape the nature, efficiency and productivity of fisheries operations including weather patterns, financial exchange rates, global demand and fuel prices (Kirchner, 2014), creating the opportunity for small adjustments to make potentially big differences in operational and carbon efficiency. As carbon footprints and biodiversity impacts of food become increasingly important to international markets, a clear understanding of the carbon (and biodiversity) impacts of Namibian fisheries will be a powerful first step in helping to identify areas of concern and improvement. Although there are clearly many factors beyond the control of the fishing industry (exchange rates, foreign markets, etc), a Blue Carbon lens may help in applying some of these 'levers' to improve both the fishing and carbon efficiency of the industry. An energy and carbon audit of the hake industry would reveal many of these opportunities (Kirchner, 2014; Bastardie et al., 2022; Anggawangsa et al., 2023; Muñoz et al., 2023). Through a modelling exercise, the industry and regulatory authorities could investigate options which balance fishing on larger, higher-value fish, away from high carbon sediments (see below), optimise trip duration to reduce fuel use and reward more fuel efficient and catch

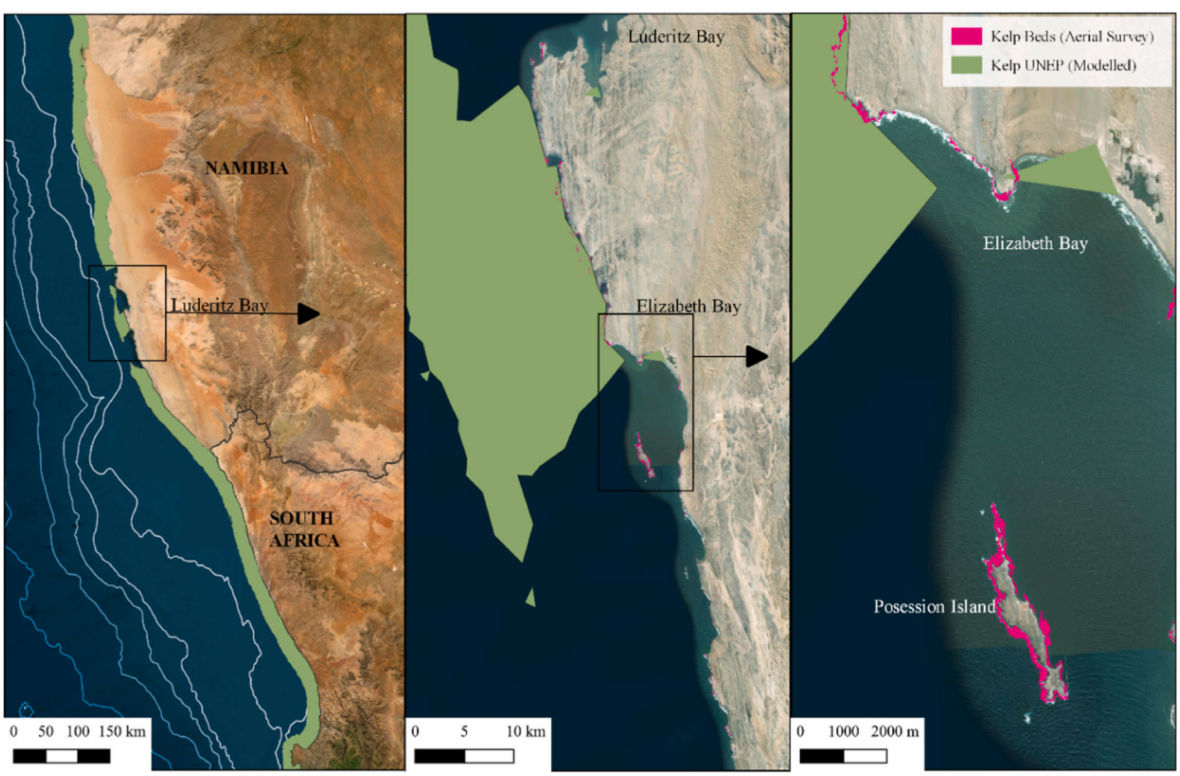

Fig. 2. Comparison of two datasets on the distribution of kelp species in southern Namibia, one a global modelled dataset of potential distributions (green polygon, Jayathilake and Costello, 2020) and the second the actual distribution (pink polygons) of kelp species from aerial surveys (Pulfrich and Penney, 2006).

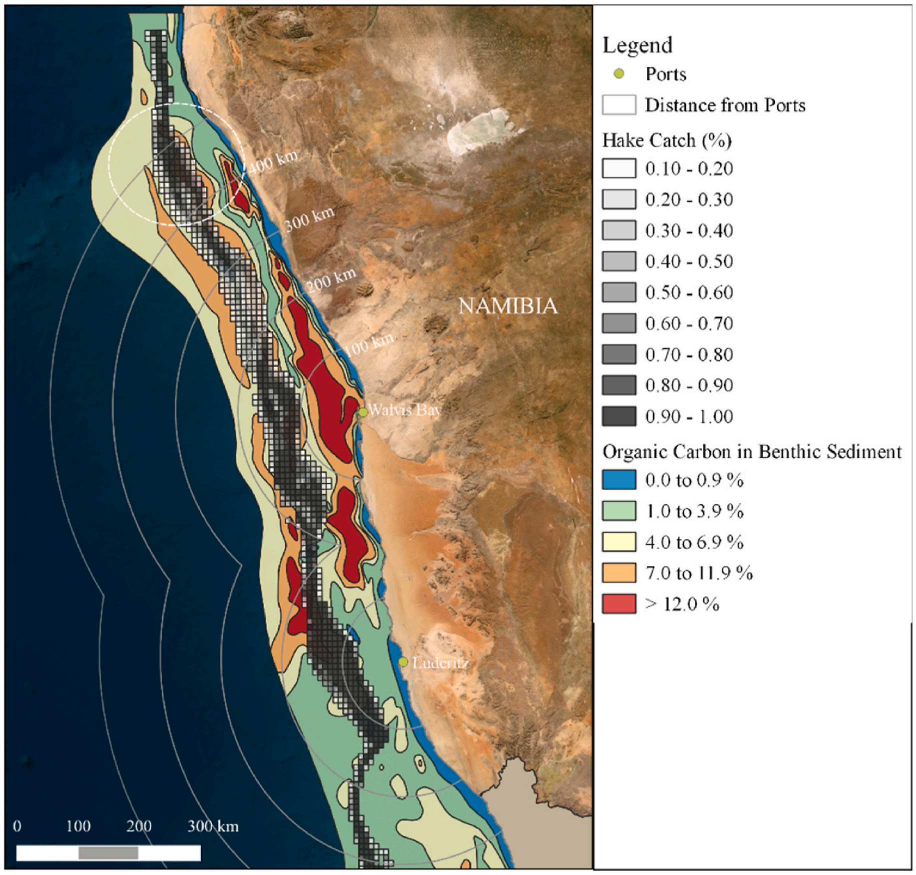

Fig. 3. Map of the Namibia coastline and Northern Benguela Ecosystem, to highlight some relevant data layers which could be used to reduce the carbon footprint of marine fisheries. Here we show the overlap of bottom trawling effort for hake (*Merluccius* spp, grey grid) with organic carbon marine sediments (coloured polygons) as well as a set of 'distance from harbour' rings representing a key aspect of vessel fuel use by the fishing industry. A recommendation of this manuscript is a detailed analysis of the carbon 'footprint' of the fisheries supply chains in Namibia, and an analysis to optimise the balance between carbon release, fishing effort, and environmental and economic needs.

effective vessels and crews. Some of the costs and savings for such changes could potentially be offset through carbon or fisheries credits (Squires et al., 2021; Krabbe et al., 2022) or reduction in harmful fisheries subsidies (Skerritt and Sumaila, 2021).

Although there are currently no carbon credits specifically for fisheries or stock recovery, other more holistic forms of fisheries credits have been investigated for some time (Van Riel et al., 2015) and there have been suggestions to refocus how fisheries are managed to prioritise Maximum Carbon Sequestration (MCS) over Maximum Sustainable Yield (MSY) (Krabbe et al., 2022). This could have substantial benefits within Namibia's relatively small but high value fisheries.

3.4. Benthic and oceanic carbon

Benthic carbon stocks include both biotic (habitats, species) and abiotic (e.g. sediments) components of the seabed and play an important role in the global carbon cycle. Benthic sediments are the ultimate repository of much of the carbon sequestered by oceanic processes as atmospheric carbon is fixed by organisms which then sink after dying. In addition, deep water biota such as molluscs, corals, bryozoans and other biomass-rich taxa also fix carbon as calcium carbonate, their skeletons may persist for millennia and can represent a significant amount of sequestered carbon themselves (Barnes et al., 2019, 2021). Calculation of contributions to carbon flow in this is complex as the process of calcification involves both emission of CO_2, change in pH and likely changes in the fate of some organic carbon, but ultimately builds vast banks of carbon rich seabed substrate which may persist for many thousands of years. The carbon in benthic sediments can easily be disturbed by seabed mining and trawling, and the disruption of this sequestered carbon can result in it being mixed back into the water column (aqueous CO_2), and ultimately the atmosphere. Calculating carbon stocks and flow in open ocean habitats is challenging due to the vast spatial and temporal scales, and the oceanographic linkages involved, with studies varying in scales making comparison difficult (Mollenhauer et al., 2007; Emeis et al., 2018; Barnes et al., 2021; Zwerschke et al., 2022; Bridges et al., 2023; Siddiqui et al., 2023; Rixen et al., 2024).

The benthic environment of Namibia is relatively well described with available information on benthic sediments, their distribution, make up and nutrient flows (e.g. Mollenhauer et al., 2007; Currie et al., 2018; Emeis et al., 2018; Siddiqui et al., 2023). Spatial data on carbon density is available through both local data sources (MFMR, 2021) and global data layers (Atwood et al., 2020), which compare well as they appear to use largely the same underlying data (Fig. 4). The benthic environment off the Northern Benguela is unusual due to the presence of large amounts of anoxic or low oxygen water and sulphur producing bacteria, especially in the central belt between ~19°S and 27°S. The high density of phytoplankton, zooplankton, pelagic fish, etc. within the Benguela means that these carbon rich life forms sink towards the ocean floor when they die resulting in a near-constant supply of organic material, which adds to the diatomaceous, sulphuric mud belt along the inner Namibian shelf (Currie et al., 2018). This mud belt extends for more than 700 km in waters less than 200 m deep (Bremner, 1983; Emeis et al., 2004). This results in very high organic carbon accumulation [up to 23% dry weight (Bremner, 1978; Inthorn et al., 2006; Mollenhauer et al., 2007)] which promotes bacterial production of hydrogen sulphide (H_2S)

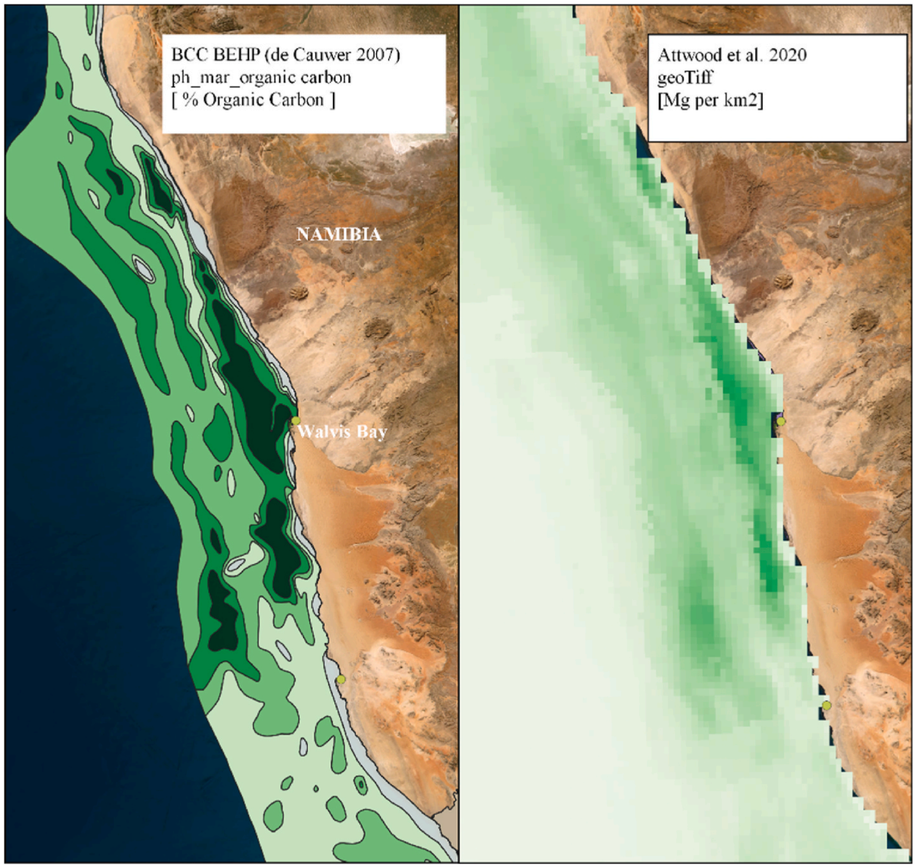

Fig. 4. Map of two different open-source data sets showing relative presence of organic carbon in benthic sediments off Namibia and their high degree of general agreement (in contrast to the kelp maps in Fig, 2). The left panel shows the polygon data layer produced as part of De Cauwer's (2007) development of GIS data layers of the Benguela Current Commission. The right panel shows the same area from a global gridded data layer produced by Atwood et al. (2020). See links in reference list. Both maps rely on multiple point samples of sediments from multiple oceanographic sampling trips.

and the associated sulphide-oxidizing bacteria. Strong lateral transport of organic matter in sediments and near-bottom sea water results in a net movement of organic matter (and carbon) off the shelf and into the deep ocean where it can be considered sequestered in the long term (Inthorn et al., 2006). At a broader scale, the high biological productivity and carbon sequestration of the Benguela even goes some way towards counteracting the net release of CO_2 into the atmosphere which occurs in the adjacent biologically productive Southern Ocean (Siddiqui et al., 2023). The question of spatial and temporal scale is important in studies of this nature, but the role of the high biological productivity of the Benguela in converting, transporting and ultimately burying carbon into marine sediments is well recognised.

At a high level it appears that there is currently sufficient data on carbon stocks in benthic sediments and life forms in Namibia to undertake a Blue Carbon assessment of the Namibian protected areas, shelf or even the EEZ, similar to that of Barnes et al. (2019) for the Ascension Island EEZ. The largest vulnerability to this system at all levels is changes in the upwelling regime due to shifts in global climate. There are already well known shifts in the oceanography (Lamont et al., 2018) and biota (Shannon et al., 2020) of the Benguela Ecosystem with increases in sea surface temperature of 0.1–0.4 °C per decade the last 40 years (Sweijd and Smit, 2020) as well as decreases in upwelling in the northern Benguela, linked with a poleward shift of the atmospheric South Atlantic High pressure system (Jarre et al., 2015). However, both observations and model projections indicate that the reduction in upwelling favourable winds applies to the northern part of the northern Benguela whereas south of ~20°S the southerly winds, and thus the upwelling, are predicted to increase (Doney et al., 2012; Rykaczewski et al., 2015; Wang et al., 2015; Lamont et al., 2018; Yang et al., 2020; Brandt et al., 2024).

Further changes to the Benguela Ecosystem could ultimately result in the collapse or significant reductions in the upwelling nature of parts of the ecosystem with global scale impacts (Bakun et al., 2010).

4. Recommendations for research

In Table 1 we summarise the core recommendations for future research for each of the sectors discussed above.

5. Conclusions

Reducing anthropogenic carbon production and capturing existing atmospheric carbon from the atmosphere is a goal of global importance (IPCC, 2023). The oceans, and so-called Blue Carbon resources and projects offer a powerful way to help achieve these goals. In this paper, we summarised areas of Blue Carbon potential within Namibia, and the cold temperate waters of the northern Benguela ecosystem. We have identified four areas where the Blue Carbon concept can be applied within Namibia and be used to focus future research.

While the concept of Blue Carbon is relatively new and what exactly falls under the umbrella thereof remains debated (e.g. should it refer only to systems or species with truly long-term sequestration such as sediments and the shells or skeletons of invertebrates, and not short lived biota like fish and gelatinous plankton?), the biomass of marine life and their movements while both alive and dead mean that they play an integral role in the global carbon cycle and need to be considered in such calculations and are an important part of discussions at a broader level. Blue carbon ecosystems are clearly important at a global scale and

Table 1
Recommendations for research to help quantify and promote carbon sequestration and development of Blue Carbon strategies and financing within the northern Benguela Ecosystem off Namibia.

Sector	Recommendation
Macroalgae	Develop an accurate map of current macroalgae presence and density within Namibia to aid calculations Blue Carbon ad ecosystem services calculations and develop a baseline against which change can be assessed.
Gelatinous plankton	We recommend further research into their role in carbon flow and sequestration in the northern Benguela and inclusion of gelatinous plankton in any discussions or models of carbon flux/sequestration in the region.
Commercial fisheries	Undertaking a detailed analysis of the carbon-footprint of Namibian fisheries and their supply chains to identify areas where carbon production could be reduced through improved fishing efficiency, reduced impact on the seabed and optimised transport solutions. Further, we recommend avoiding trawling areas of high benthic carbon density (already in place to some extent through the 200–300 m depth restrictions). We strongly support policies that promote the further restoration of Namibian fish stocks, especially the collapsed sardine.
Benthic sediments	We recommend conducting a blue carbon assessment of the potential environmental and financial value of these sediments, and any impacts thereon by fisheries, mining, climate change etc
Policy	Blue carbon projects and resources in Namibia clearly contribute significantly to the production and sequestration of carbon. We recommend that these blue carbon sources are included in future calculations towards Namibia's Nationally Determined Contribution report to the UNFCCC.

ultimately, should be reflected in Namibia and other countries' NDCs to the UNFCCC, where they can be used to guide the development of the necessary policies and actions to implement them. (Hamilton et al., 2023).

CRediT authorship contribution statement

Simon H. Elwen: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Usman Khan:** Writing – review & editing, Conceptualization. **Anja Kreiner:** Writing – review & editing, Validation, Methodology, Data curation. **Anja K. Van der Plas:** Writing – review & editing, Validation, Methodology, Data curation. **Margit R. Wilhelm:** Writing – review & editing, Validation, Data curation. **David Barnes:** Writing – review & editing, Validation, Methodology, Conceptualization. **Kerry Howell:** Writing – review & editing, Validation. **Tara Pelembe:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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