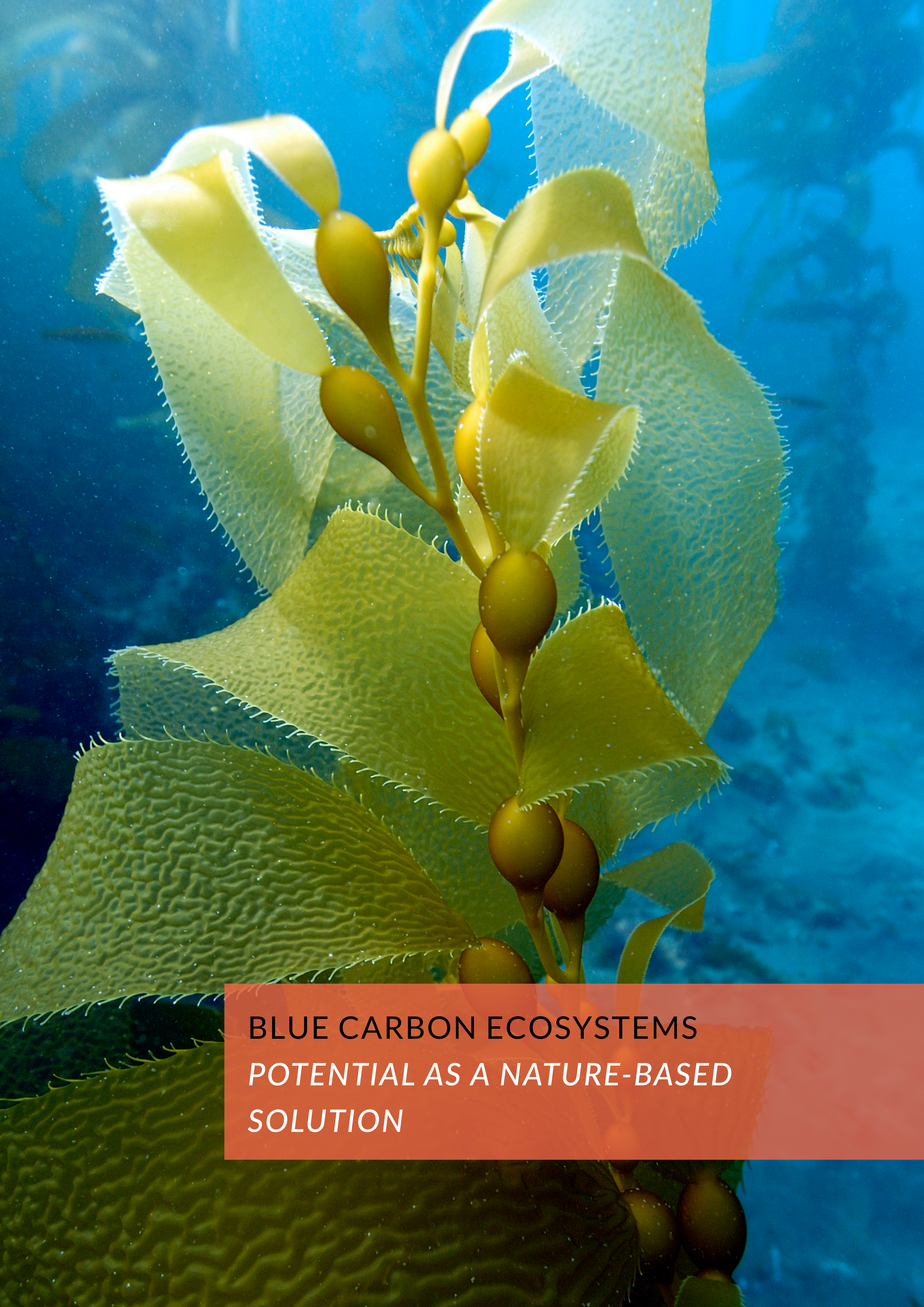

BLUE CARBON ECOSYSTEMS

POTENTIAL AS A NATURE-BASED SOLUTION

BLUE CARBON ECOSYSTEMS:
POTENTIAL AS A NATURE-BASED SOLUTION

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EXECUTIVE SUMMARY

1. Blue carbon refers to the carbon that is stored in coastal and marine ecosystems.

2. The protection and enhancement of blue carbon ecosystems give opportunities to mitigate climate change while also providing a wide range of other non-carbon benefits, such as coastal protection, biodiversity, and fisheries enhancement.

3. Some blue carbon habitats, such as mangroves, are well understood and there are often cheap and scalable management solutions that will improve carbon storage. Other proposed habitats, such as kelp forests, involve much greater scientific and management uncertainties.

4. Blue carbon can be released when these ecosystems are degraded or lost, thereby accelerating climate change; some of this carbon is ancient and essentially irreplaceable, hence the priority should be to protect existing blue carbon ecosystems.

5. Protection and restoration of blue carbon habitats around the world, including mangroves, seagrass and saltmarsh, could contribute mitigation equivalent to 3% of current anthropogenic emissions; the potential contribution to national targets varies widely between countries. Hence blue carbon management has an important role in tackling the climate crisis but must not be used to delay emissions reductions.

DEFINITIONS AND DISTINCTIONS

The term ‘blue carbon’ has no single scientific definition and different authors use it variously. It always refers to carbon that is stored in coastal and marine systems. However, there are three sources of contention in this meaning:

What is ‘carbon’?

Carbon occurs in organic and inorganic forms. Organic carbon is typically found in complex molecules, such as sugars, that contain long chains of carbon and hydrogen atoms. It is usually formed by organisms. Inorganic carbon is found in other molecular forms, including in ores and with metals and is often not of biological origin. However, some inorganic carbon, such as calcium carbonate (which makes shells) is biological in origin. Most of the carbon found in the ocean is CO_2 dissolved in water; this is inorganic and is not usually considered a carbon store, since it is not inert and makes the ocean more acidic.

What is a ‘store’?

Most carbon in living things cycles from their bodies back into the atmosphere (as they respire or die and decompose) within days to a few years. Hence, even large organisms like whales are not considered a carbon store since they hold carbon only temporarily. Some types of organic carbon, such as wood, resists decay and may keep carbon from the atmosphere for much longer. Organic carbon that is buried away from oxygen can become stored for millennia. There must be capacity for storage, away from the atmosphere, for decades to centuries at least before most authors would use the term ‘carbon store’.

What is the origin of the carbon?

Blue carbon ecosystems may store carbon that is captured by the organisms living there (for example by photosynthesis in a mangrove forest; this is called autochthonous carbon) or that is transported from elsewhere and then buried (for example organic carbon carried down a river and then deposited in a seagrass meadow). If the blue carbon habitat is removed, this external (or allochthonous) carbon may degrade and return to the atmosphere or may simply be buried and stored elsewhere. Which of these fates is likely is often uncertain or unknown for any particular ecosystem.

In this briefing, we do not distinguish between autochthonous and allochthonous carbon, since in most cases the complexities involved would render management interventions prohibitively expensive. We consider a carbon store to be of at least decades to centuries longevity. We distinguish where possible between organic and inorganic carbon and indicate where original authors have been ambiguous. Inorganic carbon, such as calcium carbonate, is generally not vulnerable to re-oxidation. There is ongoing scientific debate about the extent to which calcification (for example the production of shells and coral) should be regarded as contributing to carbon stores, since the process releases carbon dioxide into the water (as well as capturing carbon in calcium carbonate), with the extent of this carbon release depending on local chemical conditions. Hence in general, we recommend a policy focus on organic carbon, which is often manageable by policy interventions, may be vulnerable to loss, and is less scientifically uncertain than inorganic forms.

1.0 INTRODUCTION

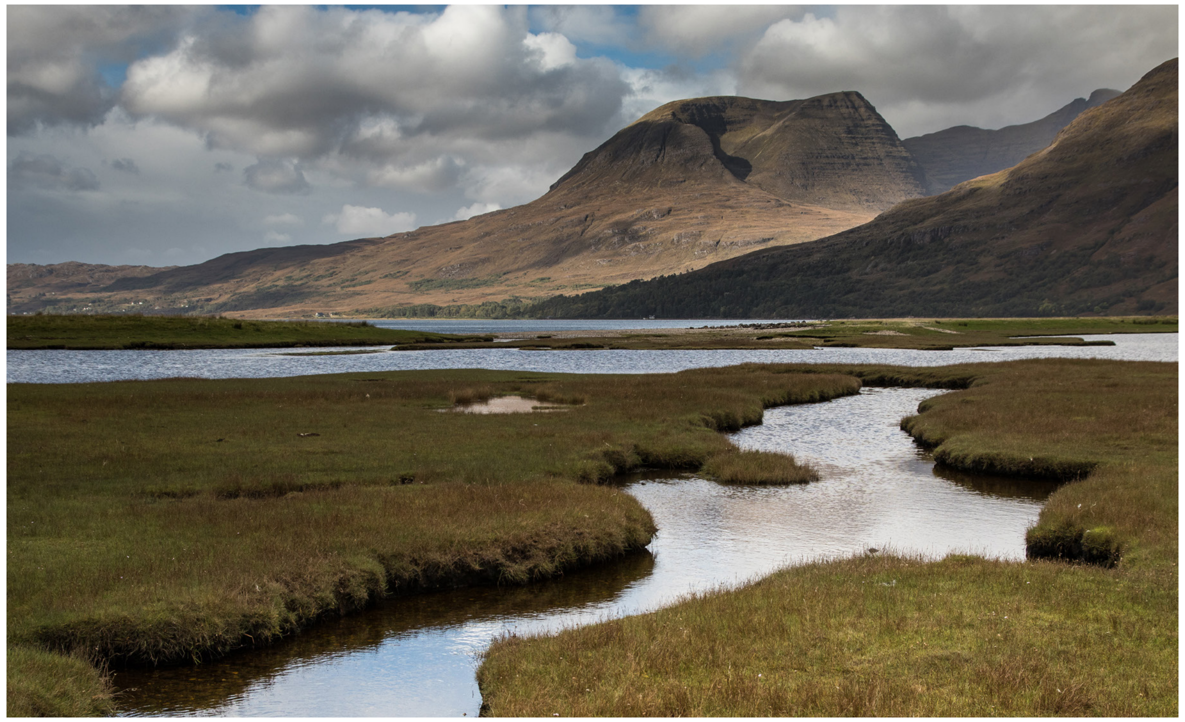
The Paris Agreement commits signatories to endeavour to limit anthropogenic global warming to 1.5°C above pre-industrial levels. Achieving this requires both rapid reductions in greenhouse gas emissions and protection and expansion of natural carbon sinks[1]. Many governments are enshrining relevant targets in national law. For example, the Scottish Government has committed to achieving net-zero greenhouse gas (GHG) emissions by 2045, with an interim target of a 75% reduction in GHG emissions relative to 1990 levels by 2030[2]. In common with global targets, meeting this national aspiration will require enhancing the removal of atmospheric CO2 into a store - known as carbon sequestration[3]. Blue carbon refers to the organic carbon which is stored in marine and coastal ecosystems (herein referred to as blue carbon ecosystems). For countries with extensive coastlines, blue carbon ecosystems can provide a nature-based contribution to climate change mitigation. For example, blue carbon ecosystems in Scotland contain an estimated total organic carbon stock that is comparable to that of Scotland's terrestrial ecosystems - 9.6 and 9.5 billion tonnes of carbon dioxide equivalent (CO2e) respectively[4-8].

Vegetated coastal ecosystems (i.e., saltmarshes, seagrasses, and mangroves) may store exceptionally high densities (tonnes per ha) of carbon. They capture carbon through photosynthesis but also by trapping carbon rich particles and sediments. Because their sediments are waterlogged and anoxic, which inhibits microbial breakdown, carbon buried below-ground in these ecosystems may remain stored for centuries to millennia[9]. Healthy blue carbon ecosystems do not become saturated with carbon because sediments accrete vertically in response to sea-level rise, and so their capacity to sequester carbon may remain high over time, even once they are mature or fully grown, in contrast with other ecosystems such as terrestrial forests[10,11]. Saltmarshes, seagrasses, and mangroves collectively store an estimated 121 billion tonnes of CO2e globally[12].

These blue carbon ecosystems have the highest natural carbon sequestration rates on a per unit area basis[13]. However, when they are disturbed or degraded, their capacity to sequester carbon is reduced and their substantial carbon stores can be released as CO2 into the atmosphere. For instance, the protection of blue carbon ecosystems could avoid 304 million tonnes of CO2e per year from loss and degradation. In addition, restoration could sequester a further 841 million tonnes of CO2e per year by 2030, which together equates to 3% of annual anthropogenic global emissions[12]. These ecosystems also provide many other services, such as coastal protection, natural purification of water and fisheries enhancement, which can assist with adaptation to climate change[14].

The Intergovernmental Panel on Climate Change (IPCC) have provided guidelines for incorporating saltmarshes, seagrasses, and mangroves into National Greenhouse Gas (GHG) Inventories[15]. Despite this, blue carbon ecosystems are not currently included in the UK's GHG Inventory[16]. The United Nations Climate Change Secretariat has published the 2022 GHG Inventory submissions of all Annex 1 Parties included in Annex 1 of the UN Framework Conservation on Climate Change (UNFCCC)[17]. Further blue carbon stocks may exist in other coastal and marine systems, including kelp forests, coastal sediments, and marine fauna[18]. However, there is scientific uncertainty about the contribution of these systems to long-term carbon sequestration, and they are currently ineligible for inclusion in UNFCCC climate financing mechanisms and for accreditation by most carbon standards servicing the voluntary carbon market[13].

This briefing presents an overview of current knowledge about blue carbon ecosystems. It explores the current and potential contribution towards climate change mitigation of those blue carbon ecosystems that are already widely recognised and discusses other candidate blue carbon ecosystems. It also outlines the threats to blue carbon ecosystems, their restoration potential, and the associated non-carbon co-benefits of blue carbon protection and restoration. Its aim is to present concise information to policy makers and others considering blue carbon in the wider context of responses to climate change, hence blue carbon storage and sequestration capacities are compared with more familiar terrestrial ecosystems. Whilst it is global in scope, and aimed at a diverse audience, it is rooted in a Scottish context and the concluding policy recommendations are directed particularly to a Scottish and UK audience.


"Beinn Alligin", by Simaron, licensed under CC BY-SA 2.0.

2.0 ESTABLISHED BLUE CARBON ECOSYSTEMS

2.1 Saltmarhses

Saltmarshes are coastal ecosystems that are periodically flooded at high tide and support a characteristic community of salt-tolerant plants[19]. They are globally distributed, although predominantly occur at temperate and high latitudes. Saltmarshes form where there is an accumulation of fine-grained carbon rich sediments, sometimes extending one or more metres in depth, in low-energy environments such as sheltered bays and estuaries[20]. Estimates of carbon sequestration rates vary substantially at local and regional scales, ranging between 235 and 804 tCO2e/km2/year (tonnes of carbon dioxide equivalent per square kilometre per year; ambiguity on form of carbon but likely to be all or mostly organic)[21]. This may be partially offset by methane emissions from saltmarshes in low-salinity estuaries, although these non-CO2 GHG emissions are poorly quantified[22,23]. Saltmarshes provide multiple co-benefits in addition to carbon sequestration, such as coastal protection against flooding and erosion, improved water quality, and biodiversity[24-26].

In Scotland, the extent of saltmarshes has been estimated at 58.4 km2[27]. Scottish saltmarshes hold an estimated total organic carbon stock ranging between 974,788 - 1,725,509 tonnes of CO2e (organic carbon) in the top 10cm of sediments and sequester approximately 16,093 tonnes of CO2e (organic carbon) per year[28,29]. The geographic extent of saltmarshes is not well resolved, but global estimates suggest that between 25-50% of historical saltmarsh coverage has been lost through coastal development and conversion to agriculture[30]. Sea level rise threatens remaining saltmarshes through a process called coastal squeeze, wherein artificial coastal defences prevent saltmarshes from migrating landwards in response to rising sea levels[31]. The methods of saltmarsh restoration for small-scale projects are relatively well understood. They commonly involve 'managed realignment' of the coastline, in which land is deliberately flooded to create saltmarsh by breaching coastal defence structures[19]. There are at least 41 managed realignment sites in the UK; however, only four have been established in Scotland to date[27,32]. An average carbon sequestration rate of 340 tCO2e/km2/year has been estimated for saltmarshes restored through managed realignment in eastern England, with carbon stocks comparable in size to those of natural saltmarshes after 100 years (27,158 tCO2e/km2 and 25,323 tCO2e/km2 respectively)[19,33]. However, there are still some uncertainties in the rate of carbon sequestration by restored saltmarshes. Estimated costs of managed realignment in the UK range from £1,200,000-£2,000,000 per km2 including land purchase[34,35].

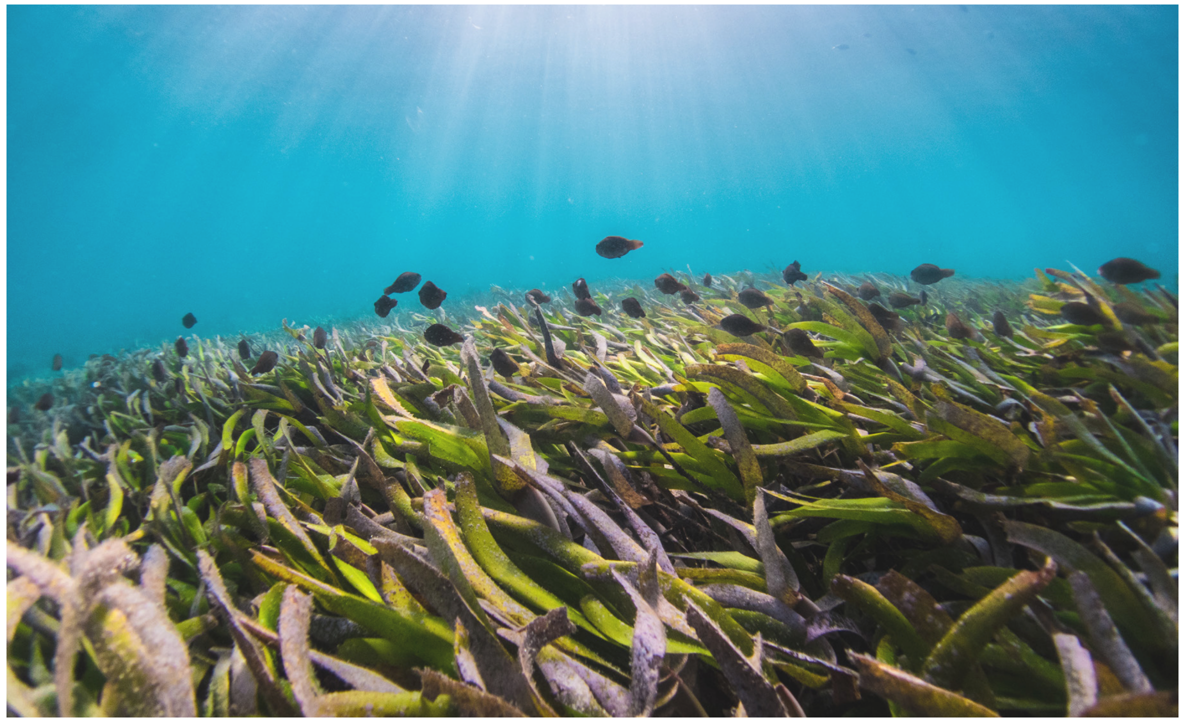
"Remnant Salt Marsh", by Andrew is licensed under CC BY 2.0.

"Thrift covered saltmarsh at Northton, Isle of Harris, Wetern Isles Area" by Lorne Gill, licensed by NatureScot.

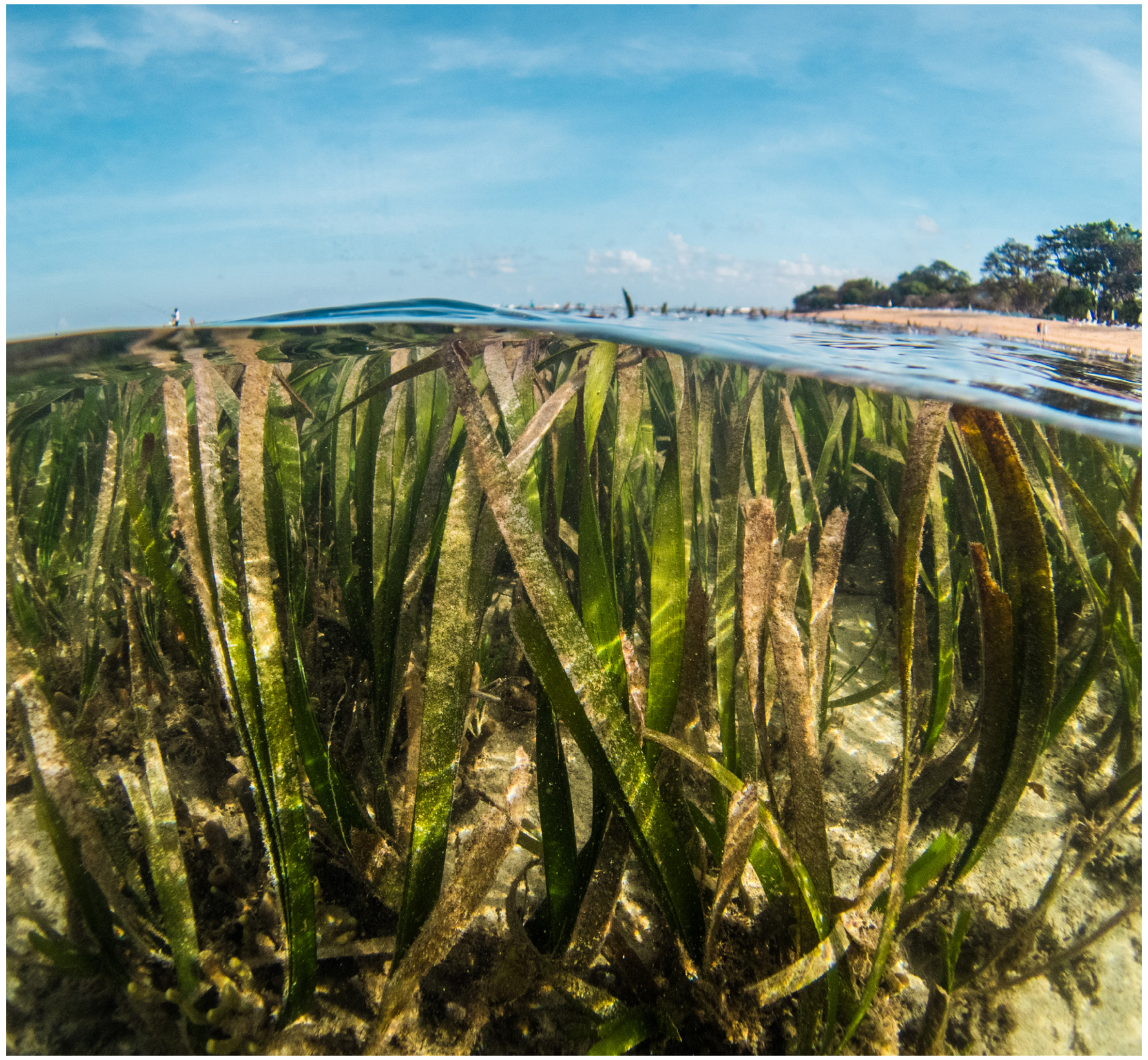
2.2 Seagrasses

Seagrasses are flowering plants that form dense underwater meadows in shallow coastal areas on sheltered fine-grained sediments. They are distributed around the world, occurring in temperate and tropical regions. The slow decomposition and turnover rate of organic carbon stored in seagrass biomass and, in particular, their capacity to trap and accumulate carbon-rich sediment may result in high carbon densities[36]. Rates of sequestration in Mediterranean seagrass meadows are estimated at 154 tCO2e/km2/year, although there may be significant regional variation due to differences in species, depth, and sediment characteristics[15,37]. As with saltmarshes, seagrass meadows have co-benefits beyond carbon sequestration including coastal protection against flooding and erosion, improved water quality, and biodiversity, including habitat provision for iconic fauna such as turtles and dugongs[38]. In Scotland the extent of seagrasses has been estimated at 21 km2[39]. Scottish seagrass meadows hold an estimated carbon stock 146,279-692,166 tonnes of CO2e in the top 50cm of sediment (organic carbon) and sequester approximately 5,000 tonnes of CO2e (likely organic and inorganic carbon) per year[40,41].

The geographic extent of seagrass meadows is poorly mapped; an estimated 29% of global seagrass coverage has been lost in the last half century due to coastal pollution and physical damage from dredging and trawling[42,43]. The increasing frequency and intensity of marine heatwaves and storms, driven by climate change, may result in large-scale seagrass losses and the oxidation of their sediment organic carbon stocks[44]. Established methods for seagrass restoration implemented in small-scale projects involve the dispersal or planting of seagrass seeds, as undertaken in a pilot project by Project Seagrass, Swansea University and the Pembrokeshire Coastal Forum in 2020, and transplanting laboratory or nursery grown seedlings[45,46]. Alternative approaches include modifying site sediment and/or hydrology to re-establish suitable conditions for natural seagrass regeneration[47]. However, the restoration of seagrass meadows is a slow process, often taking years to decades, and there are difficulties associated with quantifying carbon sequestration rates resulting from seagrass restoration[48,49,50]. There is a lack of large-scale seagrass restoration projects in the UK and so cost estimates are not well established. However, estimated costs of seagrass restoration in the United States have ranged from $120,000-$400,000 per km2[36].



"Thalassodendron ciliatum, parrotfish sillloute, Zanzibar, Tanzania", by Project Seagrass.



"Enhalus Acoroides, Bali, Indoneisa", by Project Seagrass.

2.2 Mangroves

Mangroves are salt-tolerant coastal forests found along sheltered bays, estuaries, and inlets in tropical and subtropical regions worldwide. They cover an estimated 138,000 km2 which represents only around 50% of their pre-industrial extent; although rates of loss have declined recently these forests are still being removed and lost in many countries[51,52]. They may have very high carbon densities because of deep, carbon rich sediments, sometimes extending five or more metres in depth. Total ecosystem carbon stocks, including this soil carbon, averages 324,500 tCO2e/km2 but often exceeds 367,000 tCO2e/km2 where there are deep soils (which are typically not sampled to full depth, with total stocks therefore underestimated)[53]. This carbon is at risk of oxidation if the forests are degraded or destroyed[54]. In mature forests, without annual increases in total biomass of trees, sequestration continues at around 640 tCO2e/km2/year because of sediment accretion; rates may be much higher in recovering or rapidly growing forests[55]. In addition to carbon capture and storage, mangroves provide a wide range of other benefits, such as coastal protection and timber provision. Because the communities of people living in or adjacent to them are often poor and heavily dependent on local natural resources, their importance for livelihoods and culture may not be fully captured by economic analyses[56].

Approaches to carbon measurement and management developed for terrestrial forests, with long accepted and understood protocols, can be more readily applied to mangroves than to other blue carbon systems. Hence their inclusion in national inventories and voluntary carbon trading schemes is more advanced than for other blue carbon systems. However very considerable opportunities remain for further conservation and expansion. Existing forests are still being lost and degraded, whilst at least 8000 km2 globally are biophysically suitable for mangrove restoration[57]. Global financial interest in mangroves, and blue carbon in general, as nature-based solutions potentially exceeds $10 billion[58].

“Mangrove Forest Philippines” by Alex Traveler / Mangrove Action Project.

“Mikoko Pamoja, Kenya, Gazi Bay” by ACES.

3.0 POTENTIAL BLUE CARBON ECOSYSTEMS

3.1 Kelp

Kelp are large brown macroalgae (seaweeds) that form dense underwater forests along temperate, sub-polar, and polar coastlines. Kelp forests primarily grow on hard substrates, so the local burial of organic carbon is usually impossible[59]. However, a small fraction of kelp-derived carbon could contribute to long-term carbon sequestration through the transport and burial of detritus in sea floor sediments[60]. Globally, kelp forests sequester an estimated 635 million tonnes of CO2e per year (organic carbon) in the deep-sea[61,62]. Yet, the location, rates of carbon sequestration, and permanence of carbon stocks are uncertain and there may be considerable regional variation[63,64]. Kelp forests provide numerous co-benefits in addition to carbon sequestration: They support commercially important fish and shellfish, improve water quality, and may also provide coastal defence against erosion[65,66]. Furthermore, the cultivation and harvest of kelp can be used to produce a variety of products such as biofuels, which have the potential to reduce GHG emissions[67].

In Scotland, kelp forests are extensive around the West Coast, the Outer Hebrides, Orkney, and Shetland. They are estimated to cover 3747 km2 of Scotland's inshore coastal waters and store 1.2 million tonnes of CO2e in their living biomass (organic carbon)[40,68]. Furthermore, the burial of kelp detritus into Scotland's coastal sediments is thought to sequester 6.3 million tonnes of CO2e per year (organic carbon)[40]. Globally, kelp forests are being lost at their southern distribution limit due to ocean warming and the increasing frequency of storm events and marine heatwaves[69]. Whilst there are areas in the world where kelp is expanding, possibly due to regional cooling, on average kelp ecosystems are declining, largely due to local drivers such as disturbance from bottom trawling, pollution and eutrophication, and coastal development[70]. Other drivers of loss include disturbance from bottom trawling, pollution and eutrophication, and coastal development[71]. Kelp forest restoration is at an early stage in the UK: cost estimates are presently unknown and restoration methods are still experimental[72]. These approaches include reducing trawling, as implemented by the Sussex Inshore Fisheries and Conservation Authority in 2021, and transplanting nursery or laboratory grown kelp[73-74]. However, the impacts of kelp restoration on carbon sequestration in coastal sediments are uncertain and this is the subject of ongoing research[62].

"Tang", by Magnus Hagdorn is licensed under CC BY-SA 2.0.

3.2 Coastal sediments

Rather than sequestering atmospheric carbon directly, marine sediments accumulate carbon originating from both marine and terrestrial sources[75,76]. They are a large and globally significant carbon sink, which may store nearly twice the amount of carbon in the top 1m of depth than terrestrial soils – with total organic and inorganic carbon stocks of 8521 and 4863 billion tonnes of CO2e respectively[77,78]. Despite their vast area, the sequestration rate of carbon in marine sediments is low, estimated at 573 million tonnes of CO2e (organic carbon) year globally[79]. However, there is considerable uncertainty associated with the stocks and accumulation rates of marine sediment carbon, as these can vary depending on location and sediment type[80]. For example, organic carbon content is higher in sea loch sediments, which are largely composed of fine-grained mud, compared to coarse-grained sandy sediments such as those found in shallow coastal bays[81-82].

The primary threat to organic carbon stocks in marine sediments is sea floor disturbance, most commonly from bottom trawling[83]. Globally, the release of carbon from sediments into the water column caused by bottom trawling have been estimated at 1.47 billion tonnes of CO2 per year, although there are significant uncertainties as to the proportion of this disturbed sediment carbon which reaches the ocean surface and potentially the atmosphere[84]. Nonetheless, bottom trawling is often concentrated in organic-rich sediments with high organic carbon densities, such as sea lochs, coastal muds and burrowed muds, which are at increased risk from disturbance[85].

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The top 10cm of seafloor sediments within Scotland's exclusive economic zone (457,926km2) contain an estimated carbon stock between 1.4-1.5 billion tonnes of CO2e (organic carbon), with the highest density of sediment organic carbon located in the inshore waters off Scotland's west coast[79]. Management interventions such as a reduction in trawling or the implementation of Marine Protected Areas (MPAs) could prevent the release of carbon stored in marine sediments and provide co-benefits such as the protection of habitat and species diversity, although such measures may have socio-economic impacts on fishing communities[83,86].

3.3 Marine Fauna

Marine fauna contain carbon in their biomass, which may be later exported to deeper waters through respiration and defecation[10]. A small proportion of this organic carbon may sink and become sequestered long-term in sea floor sediments, although most faeces are rapidly consumed by bacteria and benthic organisms[87,88,89]. As such, there are large uncertainties about the contribution of marine fauna to long-term ocean carbon sequestration in the deep-sea[90]. Furthermore, there are governance issues surrounding the management of marine fauna as sources of blue carbon because populations often live in areas beyond national jurisdiction, such as open waters. As a result, actions designed to assist the recovery of fish and other marine fauna populations are unlikely to contribute significantly to national climate mitigation policies, unless this is through indirect benefits for associated blue carbon habitats such as seagrass or marine sediment[10]. Nonetheless, marine fauna are widely threatened by overfishing, coastal development, human disturbance, and ocean warming[91]. Many countries have included the sustainable management of coastal and marine fisheries as adaptation actions within their Nationally Determined Contributions (NDCs) because of improved livelihoods and food security, with enhanced protection for these fauna intended to build resilience in the face of new pressures on their populations from climate change[92].

"Female grey seal at Ullapool harbour", by George P. is licensed under CC BY 2.0.

Table 1. Carbon stocks and sequestration rates in blue carbon and comparator ecosystems

Ecosystem	Carbon sequestration rates ($tCO_2e/km^2/year$)	Global carbon stocks ($Mt\ C_{org}$)
Saltmarshes	*235 - 804** [21]	*400 – 6500* [93]
Seagrasses	*367 – 646** [93,94]	*4260 – 8520* [10,95]
Mangroves	*640*** [55]	*9400 – 10,400* [93]
Kelp	*N/A*	*9 – 20* [96]
Coastal sediments	*62** [76]	*44,000 - 130,000 in the upper 5cm* [96}
Marine fauna	*N/A*	*N/A*
Terrestrial forests	*0 – 4,070*** [98]	*795,000 – 927,000* [99]
Peatlands	*66-103*** [100,101]	*265,000 – 565,000* [102]

** the original sources are ambiguous as to which forms of carbon these values include*
*** the original sources refer to organic carbon sequestration*

"Humpback whales, Mo'orea, French Polynesia", by Toby Matthews / Ocean Image Bank.

Table 2. A summary of blue carbon policy options

Habitat / system	Global extent (Km2)	Scientific Certainty	Global Potential	Climate Justice	Management Tractability	Accreditation Potential
Mangrove Forests	138,000 - 152,000[10,51]	✓✓✓	✓✓	✓✓✓	✓✓✓	✓✓✓
Seagrass	177,000 - 600,000 [94]	✓✓	✓✓✓	✓✓✓	✓✓	✓✓
Saltmarsh	22,000 - 400,000 [93,94]	✓✓	✓✓	✓	✓✓✓	✓✓
Coastal Sediments	Up to 27,000,000 [103]	✓	✓✓✓	✓	✓	✓
Kelp	1,430,000 - 1,790,000 [104]	✓	✓✓	✓	✓	✓
Mega-fauna	N/A	✓	✓	✓	✓	✓

Table 2. Key

	✓✓✓	✓✓	✓
Scientific Certainty	Stocks, fluxes, extent, and impacts of interventions are all well understood	Significant uncertainty about some key parameters, such as sources and fate	Plausible scientific arguments exist but are yet to be confirmed
Global Potential	Major potential contribution to total BC stocks	Moderate potential contribution to total BC stocks	Minor potential contribution to total BC stocks
Climate Justice	Changes in management could make major contributions to livelihoods or welfare of people most affected by the climate emergency	Some potential for changes in management to contribute to climate justice	Little likelihood of widespread impacts on climate justice
Management Tractability	Options for improved management are well known, feasible at many sites and have been widely demonstrated	Options for improved management are known but may be difficult or expensive, or restricted to relatively few sites	Options for improved management are speculative, or very expensive or difficult to implement
Accreditation Potential	Already accredited under at least one voluntary carbon standard with history of generating credits	Accredited or on the verge of accreditation with at least one standard with credits emerging on market	Accreditation unlikely in the next five years

4.0 POLICY RECOMMENDATIONS

1. The established blue carbon ecosystems – mangroves, salt marshes and seagrass beds – provide a wide range of valuable services in addition to carbon sequestration. These include contributions to climate change adaptation, such as reducing the impacts of rising sea levels. Existing ecosystems should be conserved.

2. Mangroves are the best understood blue carbon habitat. Conservation of existing forests, and restoration of degraded and destroyed ones, are low risk policy priorities bringing climate benefits along with a wide range of other ecosystem services. Countries with mangroves should incorporate them into GHG inventories and national conservation plans. Countries without mangroves should support their conservation and expansion with additional financing and through international law.

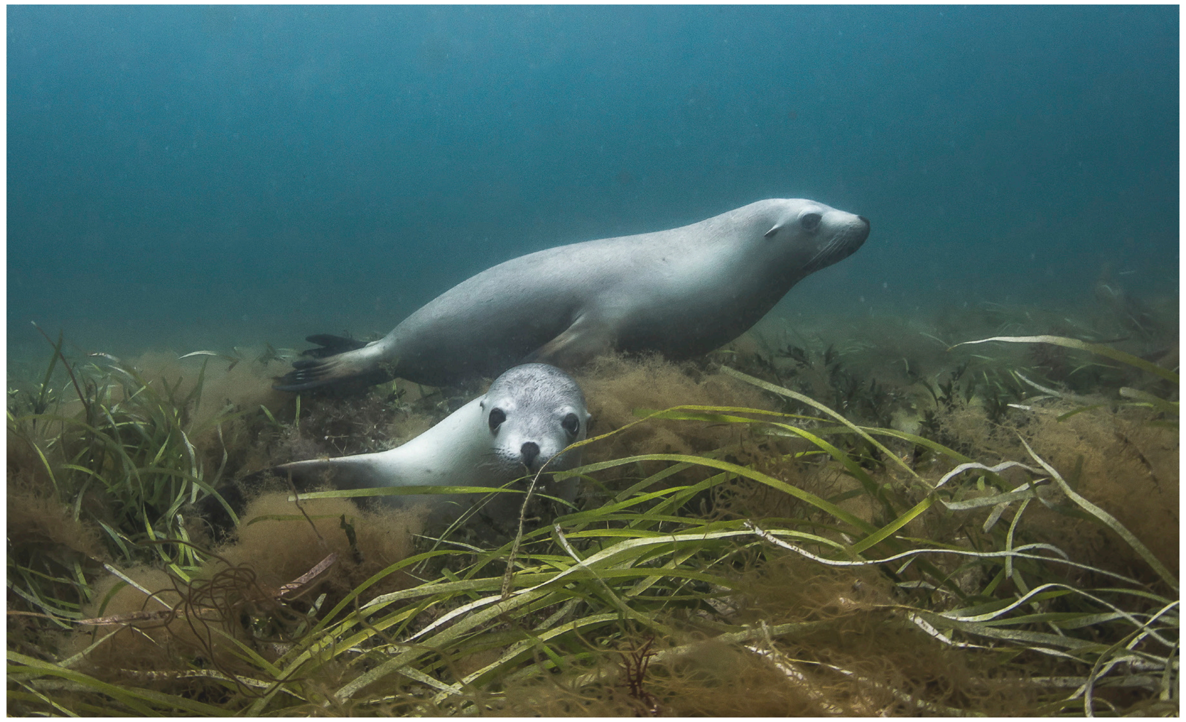
3. Knowledge of saltmarsh and seagrass extent and health is patchy to poor over much of the world; more information is needed to inform national conservation and mitigation plans.

4. Restoration or creation of seagrass and saltmarsh, through for example seeding the seabed and managed realignment, can bring multiple benefits but is usually too expensive to be funded by carbon finance alone. Policy needs to encourage restoration by combining sources of funding.

5. More research, including large scale experiments, is needed on the potential for other blue carbon habitats, such as marine sediments and kelp, to contribute to mitigation (e.g. through trawling exclusion areas). A precautionary approach should be considered in relation to proposals that will disturb existing potential blue carbon stores in these habitats.

6. Well-understood blue carbon habitats may have exceptional carbon densities but, because of limited global extent, have much smaller total stocks than other ecosystems such as peatlands. Hence a global emphasis on these systems that distracted from the need to protect other natural sinks, or from the urgency of emissions reductions, would be a mistake. Policy needs to include blue carbon management in a suite of approaches to address the climate emergency.

"Mangroves and Seagrass, Florida" by David Gross / Ocean Image Bank.



"Sea Lions in Seagrass", by Jeff Hester / Ocean Image Bank.

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ACES

MANGROVE ACTION PROJECT MAP

PROJECT SEAGRASS

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