BLUE CARBON

IN THE UNITED KINGDOM

UNDERSTANDING AND DEVELOPING THE OPPORTUNITY

BLUE MARINE FOUNDATION

UNIVERSITY OF EXETER

CONTENTS

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FOREWORD

We are at a pivotal point in human history, where immediate action is required to combat the human-made climate crisis. Atmospheric carbon dioxide (CO_2) levels today are higher than at any point in the past 800,000 years [2,3]. As a result of global warming caused by greenhouse gas emissions, many countries have seen record extreme temperatures, more frequent wildfires, and destructive floods. This has resulted in devastating impacts upon people and nature. The ocean is experiencing increased temperatures, acidification, and oxygen depletion. Marine ecosystems have experienced significant, and increasing, disruption as the impacts of climate change, multiplied by other human impacts – notably industrial fishing – have applied huge pressure on life below water.

Increasingly, there is the recognition that the ocean plays a key role in maintaining a stable climate. A global movement to protect at least 30 per cent of the ocean by 2030 is gaining momentum. However, it has also become clear that the role of the ocean as a climate change solution has been overlooked, with a huge amount of evidence and policy development required to protect blue carbon habitats, most of which are in catastrophic decline. This must happen quickly and one route to rapidly and properly valuing these habitats and the climate services that they provide may be the evolution of a voluntary market. There are many ways that this could develop, BLUE is concerned that it develops in a way that benefits marine life.

According to the latest assessment by the International Panel on Climate Change (IPCC) [4], climate change is now unavoidable and some of its effects are irreversible on meaningful human timescales. The IPCC, however, states that if the urgently needed actions are taken then we will be spared some of the worse impacts to come. Two fundamental solutions to this emergency are dramatic reduction of greenhouse gas emissions and the removal of emitted carbon dioxide from the atmosphere [4], preferably through nature-based solutions.

Scientific evidence is clear that governments and companies must act immediately if we are to achieve commitments of net-zero greenhouse gas emissions in the next few decades [4]. Emissions that governments and companies cannot prevent can be offset by natural and technological systems that absorb carbon from the atmosphere. It is here that nature-based solutions can play an important role in carbon sequestration. Most of the attention to date has been on the role land-based ecosystems, such as forests, peat bogs, and tundra, can play as carbon stores and in carbon removal. The ocean has been neglected, but that is changing and marine habitats could play a key part in closing the $700bn nature based solutions funding gap identified by Sir Partha Dasgupta.

In the last year, BLUE has conducted extensive due diligence to develop a portfolio of blue carbon conservation and restoration projects. In this process we have learned what constitutes a good project, one that also leads to the recovery of biodiversity and the just and socially equitable involvement of local communities (many of whom are on the front lines of climate change). We see substantial demand that currently exceeds supply and have identified barriers that are preventing blue carbon projects from developing. What constitutes rights and wrongs when it comes to carbon finance is of paramount importance, but it can only be properly discussed once the opportunity is understood.

This report authored by Blue Marine Foundation and the University of Exeter therefore provides a clear introduction to blue carbon, a marine nature-based solution with multiple benefits for our climate, biodiversity and coastal communities. It explores blue carbon habitats, their associated carbon capture rates and carbon stocks and the threats they face. It has been written to build the case that blue carbon is an important component of climate change mitigation and needs to urgently be included in climate policy and in an emerging global voluntary blue carbon market.

Dan Crockett
Blue Marine Foundation

Image credit: Alex Tattersall

EXECUTIVE

To coincide with COP26, Blue Marine Foundation (BLUE) and the University of Exeter have published a report that calls for evidence, trust, and transparency in the emerging field of blue carbon.
All views and findings of the report are held by BLUE, not necessarily by the sponsor.

SUMMARY

Blue carbon, the term given to marine habitats that sequester and store carbon dioxide, represents an incredibly exciting opportunity for marine conservation and restoration.

Each of the major blue carbon habitats (the definition is currently limited by the United Nations Framework Committee on Climate Change to mangroves, seagrass, saltmarsh) provide nurseries for marine life and extraordinary benefits to the communities that live alongside them. Each habitat is also, sadly, in severe decline. Meanwhile, global carbon dioxide emissions continue to rise and nature-based solutions for sequestering carbon are in short supply. Blue carbon is a concept that governments can include in their national greenhouse gas inventories, and that companies may be able to invest in at a scale that dwarfs philanthropic donations to marine conservation. However, the science of blue carbon is in its infancy, with gaps in evidence and quantification. The techniques to develop, verify and monitor blue carbon projects and their impact on biodiversity globally are still emerging.

This report aims to explore the global scale and opportunity for blue carbon habitats to act as a climate change solution, the benefits that this will provide and the consequences of degradation. It points out the fact that often blue carbon habitats sequester carbon very rapidly, as compared with terrestrial forests, and store it for long timeframes. It considers the opportunities represented by the better acknowledged and understood blue carbon habitats in the United Kingdom (mangroves are present in the United Kingdom Overseas Territories). It also looks at more innovative forms of blue carbon such as macroalgae and sediment, both of which are research priorities that have been overlooked by science until recently. The report examines the potential for blue carbon projects within UK waters. Finally, the authors explore the emerging blue carbon market and the potential for this to develop in the United Kingdom, before highlighting some potential projects.

Saltmarsh, of which the United Kingdom has some 44,000 hectares and could have much more with successful management realignment, represents a huge opportunity that a coalition of scientists are currently researching. Verification by a saltmarsh carbon code could unlock billions in future investments. Saltmarshes provide nursery habitat for juvenile fish among numerous other co-benefits. UK seagrass, between 7,000 and 9,000 hectares of it, may be one of the largest seagrass carbon stocks in Europe outside the Mediterranean with its extraordinary Posidonia species. The quantity and restoration potential of kelp (between 400 and 800,000 ha) is far greater than either of these, although complexity in the way kelp stores carbon makes verification complicated. See the later section on blue carbon in the United Kingdom for more detail on these figures.

At an even greater level still, UK sea shelf sediment protects a store of 205 million tonnes of carbon and could sequester hundreds of thousands of tonnes each year. In fact, an Office for National Statistics report this year concluded that using conservative estimates seagrass, muds, sands and saltmarsh could capture 10.5 million tonnes of carbon dioxide equivalent each year, with a value of £57.5 billion. The authors admitted that this could be six times less than the real figure due to a lack of available data [3]. The awareness of this value is growing. BLUE has been approached by businesses across numerous sectors in the last year seeking offsets, as have other NGOs. BLUE holds the view that any progress towards developing a market that services this demand (for blue carbon offsets) must be based on evidence, trust, and transparency. It also must reflect and value the fact that blue carbon habitats boast extraordinary co-benefits.


Image credit: James Bowden

The report authors conclude that the United Kingdom has a powerful opportunity to show leadership in creating a scalable voluntary carbon market that actively incorporates blue carbon. As voluntary carbon markets become regulated and the ambition for net zero commitments accelerates, it is imperative that the market develops in an equitable and transparent way. BLUE also recognises the opportunity for a form of credit that may not provide an offset in a conventional sense but builds in the incredible biodiversity benefits of conserving and restoring blue carbon habitats. When and if this could develop to include the additional carbon sequestered and stored by protecting whole seascapes remains an important question and a research priority. The report recommends that research institutions, the corporate sector, government, and NGOs collaborate to:

1. Develop evidence on the role of coastal and marine habitats in the UK to mitigate and adapt to climate change.
2. Move swiftly to protect UK blue carbon habitats.
3. Create an enabling environment to allow investment in the conservation and restoration of blue carbon habitats.
4. Build the necessary framework to include habitats within the UK Greenhouse Gas (GHG) Inventory.
5. Work together to build a transparent blue carbon market that creates high quality, high integrity credits verified by trusted, independent methodologies.
6. Ensure that the value of co-benefits provided by blue carbon habitats are properly recognised, quantified, and valued by an emerging voluntary market.
7. Stimulate greater investment from the corporate sector by ensuring that risk is properly understood and presented transparently.
8. Ensure that local communities involved in the management and protection of the habitat are valued and involved stakeholders.

There is an opportunity for nature-based solutions in the sea to be permanently associated with genuinely additional carbon sequestration, the recovery of biodiversity and a range of other valuable co-benefits. However, both the incorporation of the ocean in UK climate change policy (and representation of climate change mitigation and adaptation in existing policy mechanisms) and the establishment of a voluntary market will require multiple stakeholders to collaborate in a transparent way.

Image credit: James Bowden

Definitions

Carbon sequestration

Carbon sequestration is the removal of carbon dioxide (CO_2) from the atmosphere by natural or artificial processes and its long-term storage in the form of carbon. This process occurs naturally when atmospheric CO_2 is taken up by terrestrial and marine trees, grasses, plants and algae through photosynthesis and is stored as carbon in biomass (trunks, branches, foliage, and roots) and soils.

Blue carbon

Blue carbon ecosystems are some of the world's most efficient absorbers of CO_2 and long-term carbon sinks. The carbon sequestered by the world's oceans and coastal wetlands is termed 'blue carbon'. These ecosystems are some of the world's most efficient absorbers of CO_2 and largest long-term carbon sinks [6]. To date, research has focused on the blue carbon capacity of three coastal wetland habitats: mangroves, seagrasses and tidal marshes. These habitats are currently the only marine habitats that the Intergovernmental Panel on Climate Change (IPCC) provides guidance to countries for inclusion in their national greenhouse gas inventories [7].

Other **emerging blue carbon** components of interest include seaweed, especially kelp and Sargassum, phytoplankton, shellfish beds, seabed sediments and marine vertebrates, like sharks, whales and deepwater 'mesopelagic' fish. For want of detailed research, these are yet to be included in international climate policies or carbon financing mechanisms [8], but are known to be important components of carbon sequestration to seabed sediments and the deep ocean.

Why is blue carbon important?

Rapid CO_2 capture

Blue carbon ecosystems have such high carbon sequestration rates that they capture more carbon per unit area per year than most terrestrial forests [6] (Figure 1). In fact, they are such hotspots for carbon uptake that they bury a comparable amount of carbon as terrestrial forests annually, despite occupying less than 3 per cent of global forest area [9]. This is due in part to their high primary productivity (the speed at which a plant turns solar energy into organic substance), but mainly because the roots of blue carbon habitats efficiently trap sediments and organic matter from both within and outside the ecosystem boundaries, thereby increasing sediment accretion while raising the seafloor [9]. Coastal wetlands occupy less than 0.2 per cent of ocean area (~ 58 million hectares[i] [6,10–15]; Table 2) but account for nearly 50 per cent of carbon buried annually in marine sediments [16]. This means that protection of a small amount of coastal area returns very impressive natural carbon sinks and leads to climate adaptation benefits, such as resilience to extreme weather events.

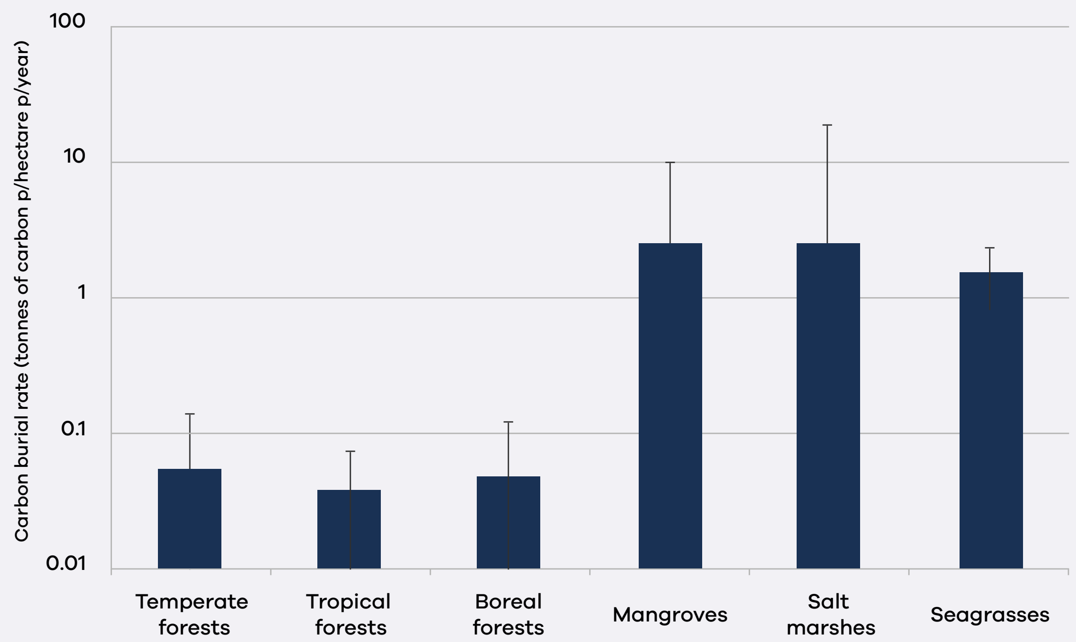


Figure 1. Carbon burial rate and storage potential of Blue Carbon Ecosystems. Comparison of mean long-term rates of carbon sequestration (tonnes of carbon per hectare per year) in soils of terrestrial forests and sediments of blue carbon vegetated coastal ecosystems. Error bars indicate maximum rates of accumulation. Note the wide range of values (logarithmic scale) of the y axis. Sources: Mcleod et al., 2011 [6].

Long-term storage

About 50 to 90 per cent of coastal wetland carbon is stored in below ground soils and sediment where saltwater and oxygen deprived conditions slow decomposition of organic matter, leading to accumulation of extensive soil carbon stocks [17]. Carbon incorporated into plant biomass, such as branches and tree trunks, is stored for decades or centuries at most [6,18], whereas carbon in the soil can accumulate over hundreds or thousands of years and be locked away for millennia [16,19,20]. For example, a seagrass (*Posidonia oceanica*) meadow in Spain is over 6000 years old with accumulated carbon deposits over 11 m thick [19]. Furthermore, 'green' terrestrial forests store most of their carbon above ground and are more vulnerable to fire, whereas blue carbon habitats are secure carbon stocks if protected from degradation.

Additional benefits of blue carbon

One of the most valuable aspects of blue carbon habitats are the extensive 'co-benefits' they provide. As well as climate regulation, the protection and restoration of coastal wetlands provide exceptional benefits for biodiversity, fisheries and local communities. Blue carbon projects have the capacity to fulfil ambitions of multiple United Nations Sustainable Development Goals simultaneously. They enhance biodiversity, fisheries, food security and eco-tourism revenues. For example, **despite covering less than two per cent of the Mediterranean Sea, seagrass supports at least a third of the total value of commercial species landed within the region [21].** They also offer coastline protection from natural disasters, extreme weather events and erosion, provide raw materials, and enhance pollution mitigation and water purification [22]. These ecosystem services are being severely impacted by human activities. Supporting blue carbon projects and including them within appropriate policy frameworks can ensure they are effectively managed [23].

Nature-based solutions to the climate crisis

The importance and contribution of the ocean to the planetary carbon cycle and climate change mitigation is immense but currently undervalued. The ocean has absorbed one-third of human-related CO_2 emissions [29,30] and while the sea is threatened by climate change, it also provides many solutions to the climate crisis [17]. Blue carbon is one of these solutions. The protection and restoration of blue carbon ecosystems, including seaweed farming, could offset about 0.6 billion tonnes of carbon dioxide equivalent (CO_2e) a year by 2030 and about 1 billion tonnes of CO_2e annually by 2050 [17]. To put that into context, annual global emissions reached a record high of about 59.1 billion tonnes of CO_2e in 2019 [31] and we need to halve worldwide emissions by 2030 and reach net zero CO_2 emissions by 2050 in order to hold temperature rise close to 1.5 degrees [4]. In 2019, emissions in the UK reached over 550 $MtCO_2e$. It is estimated that terrestrial and marine ecosystems in the UK sequester 39 $MtCO_2e$ annually, which is about 7 per cent of national annual emissions [135]. Thus, conservation and restoration play a fundamental role in maintaining and increasing the potential of nature-based solutions in the UK.

Blue carbon ecosystems have such high carbon sequestration rates that they may capture ten to fifty times more carbon per unit area per year than terrestrial forests [6].

[i] For each coastal wetland habitat we have used the following central estimates: mangroves 14.5 million hectares, tidal marshes 5.5 million hectares and seagrasses 38 million hectares.

Blue carbon habitats need immediate protection

Degradation

Ecosystems that were once net sinks of carbon can become significant sources of CO_2. Destruction of blue carbon ecosystems results in a huge release of CO_2 back to the atmosphere from the disturbance of historical carbon deposits. Furthermore, the destruction of these habitats can result in the production of other potent greenhouse gases, namely methane and nitrous oxide, which have 25 times and 298 times, respectively, more global warming potential than CO_2 over 100 years [11, 32-34]. **Over the last 50 to 100 years over a third of global blue carbon ecosystems have been degraded or destroyed [6,35],** with estimated on-going losses of 0.1 to 3 per cent annually, depending on the ecosystem [15,17] (Table 1). It is estimated that more than 500 million tonnes of CO_2 emissions could be released annually from the destruction of coastal wetlands [11,36], more than the United Kingdom's total CO_2 emissions in 2018 [37]. The prevention of future coastal wetland loss is a clear priority. **Protection and restoration of these ecosystems is a very effective climate mitigation strategy.**

Table 1. Global rates of loss of blue carbon ecosystems and average emission rates from deforestation per year.

Ecosystem	Estimated total losses to date (per cent)	Recent rates of loss (per cent/year)	Average emission rates from deforestation (million tonnes of CO_2 emissions per year)
Mangroves	20 – 35 (Since 1960s)	0.11	7
Tidal marshes	25 – 50 (Since 1800s)	1 - 2	60
Seagrasses	29 (Since 1879 – 2009)	2 - 7	150

Sources: [5, 38-40] (mangrove loss); [41] (mangrove emissions); [42-44] (salt marsh loss); [11] (salt marsh and seagrass emissions); [45] (seagrass loss).

When coastal wetlands are damaged or degraded they capture less carbon and release significant amounts of greenhouse gases – carbon dioxide, methane and nitrous oxide that might have been stored for thousands of years.


Image credit: Benjamin L Jones

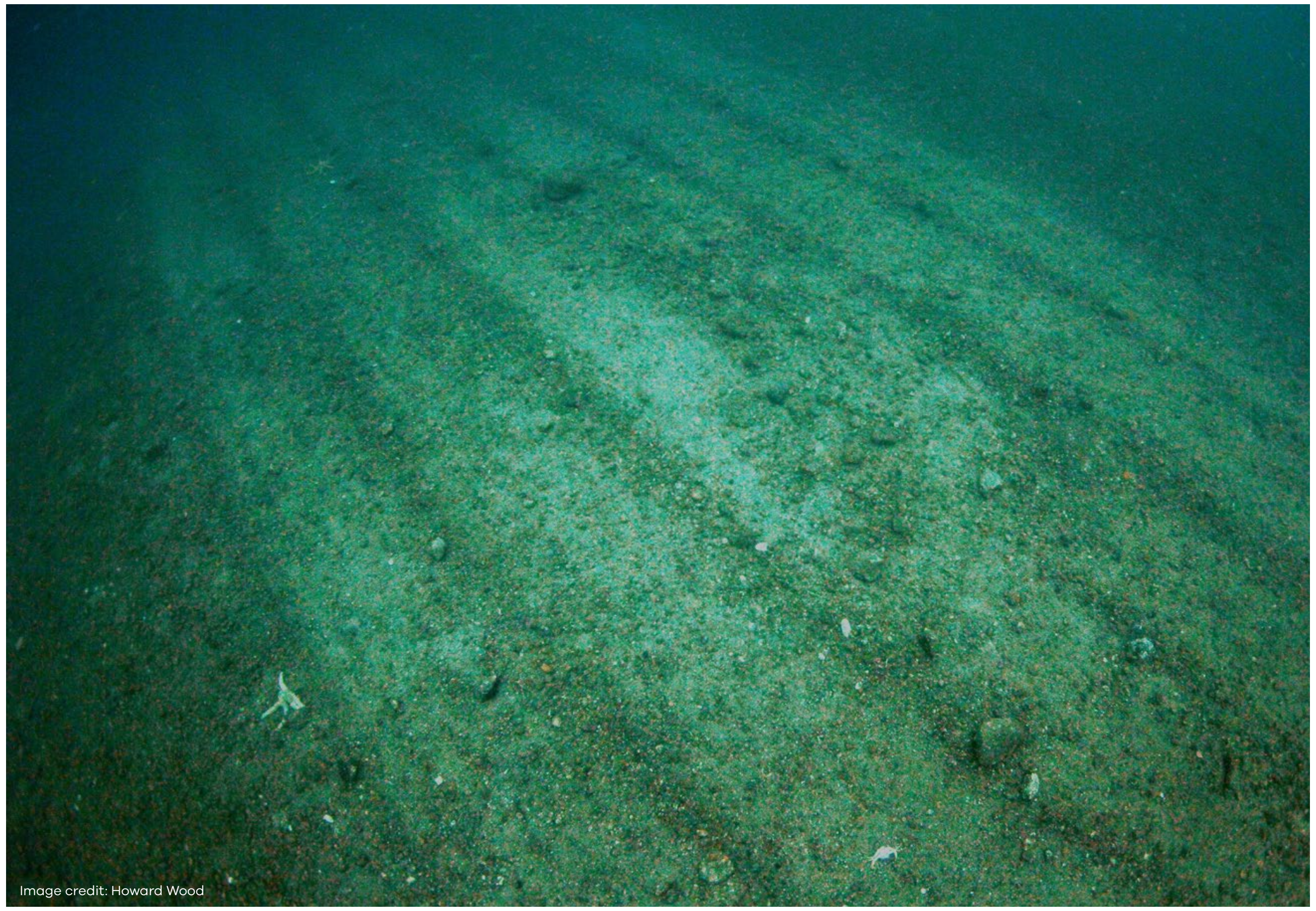


Image credit: Howard Wood

BLUE CARBON HABITATS

Image credit: Lewis Jefferies

Table 2. Global area, range and mean values of carbon storage potential for coastal and marine ecosystems.
Examples of how carbon is distributed amongst different ecosystems and the variation within each ecosystem.

Ecosystem	Global area (million hectares) Range and central estimate	Global carbon stock (billion tonnes of carbon)	Global carbon burial rate (million tonnes of carbon per year)	Average carbon burial rate (tonnes of carbon p/hectare p/year)	Average carbon stock to 1m depth (tonnes of carbon p/hectare)
Mangroves	13.8 - 15.2 (14.5)	2.6 - 10.4	31.1 - 34.4	1.65	386
Tidal marshes	2.2 - 40 (5.5)	0.57 - 10.36	4.8 - 87.2	0.9	255
Seagrasses	16 - 60 (38)	4.2 - 8.4	48 - 112	0.45	108
Macroalgae	354	NA	173	NA	NA
Seabed sediment	35,000	2322	156	0.004	66.34

Sources: Mangroves: Atwood et al., 2017[25]; Duarte et al., 2013[9]; Jardine and Siikamäki, 2014[46]; Tidal Marshes: Macreadie et al., 2013[47]; Mcowen et al., 2017[12]; Seagrasses: Fourqurean et al., 2012[48]; Kennedy et al., 2010[49]; McKenzie et al., 2020[10]; Macroalgae: Krause-Jensen and Duarte, 2016[50]; Seabed sediment: Atwood et al., 2020[55]; Berner et al., 1982[52]; Hedges and Keil, 1995[53]; Smith et al., 2015[53]. Mangroves, tidal marshes, seagrasses: Howard et al., 2014[54]; Howard et al., 2017[36]; IPCC, 2014[7]; Mcleod et al., 2011[6]; Pendleton et al., 2012[11]. NA = not applicable.

MANGROVES

Quick key facts:

- Mangrove forests are highly productive and sequester more carbon per unit area than any other tropical ecosystem, land or sea [55].
- Mangroves protect a global carbon stock of 2.6 – 10.4 billion tonnes [9,46], of which 80per cent is stored in the soil [55].
- Globally, mangroves sequester up to 34 million tonnes of carbon per annum [36], equivalent to one year's CO_2 emissions from 31 coal fired power plants [56].
- More than 30 per cent of the world's mangroves have been destroyed since 1960 and losses continue at a rate of 0.11 per cent per year [11,15,38,57], releasing greenhouse gases that account for up to 10 per cent of deforestation emissions globally.
- Healthy mangroves are important defences against storms and sea level rise and sustain coastal fisheries through their nursery function to fish and shellfish.

Mangroves are salt-tolerant forests that grow at the interface between land and sea in tropical and sub-tropical latitudes across over 118 countries [58]. In 2012, global mangrove cover was estimated at 14.5 million hectares [11], nearly the same size as Bangladesh, most of which was in Asia (42 per cent) [58].

Carbon value

Mangroves have the highest total global carbon standing stock of all coastal vegetated ecosystems [9,46]. The rate of carbon capture per unit area is about four times higher than tropical forests and rainforests on land [55]. On average, mangrove soils store 386 tonnes of carbon per hectare [7], but this can reach 1023 tonnes of carbon per hectare in organic-rich mangroves [55].

Habitat loss

Mangrove deforestation and disturbance of organic-rich soils can release more CO_2 per hectare than deforestation of any other forest type [59]. Due to a multitude of human threats more than one-third of the world's mangroves have been lost over the last 60 years [39]. In recent decades 80 per cent of human-driven mangrove loss occurred within six Southeast Asian nations, mainly from conversion to aquaculture ponds for export to support economic development [57].

Restoration

Over the last two decades, human-driven mangrove loss has decreased [57]. Recent global initiatives such as the United Nations programme on Reducing Emissions from Deforestation and Degradation (REDD+), Payment for Ecosystem Services (PES), carbon offset schemes and the Global Mangrove Alliance target to increase mangrove area by 20 per cent by 2030, has inspired and funded restoration and rehabilitation projects worldwide [61]. Of blue carbon habitats, mangrove restoration projects have gained most momentum, with projects attempted in many areas and at a range of scales – from local community efforts of a few hectares to large-scale 350,000-hectare restoration and protection projects. To date, projects have met with varied levels of success and failure and future projects should learn from shared best practice guidelines.

Best practice principles include robust site selection, accurate matching of mangrove species to sites and community-led mangrove management. Recent conservation policies in some countries have also succeeded in reducing human-driven mangrove loss. In the previously exploited Eastern Tropical Pacific, policies such as the establishment of protected areas have been effective at reducing deforestation, with an average loss rate of only 0.02 per cent per year [60]. Mangrove restoration and protection can be a powerful tool, enhancing biodiversity and supporting and protecting local communities. Avoidance of further deforestation is a priority, as once soil carbon is disturbed and oxidised it will take a long time to rebuild [62].

Co-benefits

Globally mangroves cover over 8 million hectares [38]. In addition to sequestering and storing carbon, they support biodiversity and local communities, providing about US $9.8 billion per year in ecosystem services worldwide [11]. These values include coastal protection from storms and tsunamis, sources of fuel, and regulation of sediment and water quality, which supports healthier neighbouring coral reefs and seagrass meadows [63,64]. Mangroves are also important for national tourism industries and community recreation [65]. On tourism alone, the Sundarban mangroves in Bangladesh contribute more than $50 million to the national economy [66]. Mangroves provide habitat for birds, rare species like proboscis monkeys and Bengal tigers [67], shellfish and nurseries for fish, with **about 75 per cent of all tropical commercial fish species spending part of their lifecycle in mangroves [63].**

TIDAL MARSHES

Quick key facts:

- Protect a global standing stock of about 1.4 billion tonnes of carbon[ii]. However, worldwide mapping of tidal marshes is far from complete [12], meaning the global standing stock ranges between 0.6 to 10.4 billion tonnes of carbon [36].
- Global carbon burial ranges from 4.2 to 87.2 million tonnes per year [47].
- Carbon is accumulated at a rate of about 0.9 tonnes per hectare per year [7].
- Between 25 – 50 per cent of global tidal marsh habitat has been lost since 1800 [35,42,43].
- Alongside their blue carbon value, tidal marshes provide natural flood protection, filtration of waterborne pollutants and habitat for commercial fish species and birds.

Tidal or salt marshes have high rates of primary production and grow in wave-protected tidal zones mostly above mean sea level. Tidal marshes are found in all regions, but most commonly in temperate areas [11], and are most productive at lower latitudes [68]. Despite their importance, global mapping of their extent and occurrence is not complete. A recent study estimates that tidal marshes cover 5.5 million hectares [12], but this is at the low end of previous best estimates which range from 2.2 to 40 million hectares [6,16]. Tidal marshes are known to occur in many countries and continents where spatial data is currently unknown, including Canada, Northern Russia, South America and Africa, making it difficult to quantify the global extent and carbon storage of tidal marshes. There is an urgent need for further research to increase certainty of these figures.

Carbon value

Tidal marshes are estimated to sequester carbon several times faster than tropical rainforests and they have an estimated global carbon burial rate between 4.8 to 87.2 million tonnes per year [47]. This is particularly impressive given that salt marshes only occupy 0.1 to 2 per cent of the total land area of tropical rainforests [6] and they can store carbon for millennia [47]. The majority of sequestered carbon is in the soil, which can be several metres deep.

Habitat loss

Easily accessible by land and water, tidal marshes have been susceptible to human exploitation for centuries [68]. There has been rapid global loss of tidal marshes since the 1800s of 25 – 50 per cent [35,42,43] and current tidal marsh decline is estimated at one to two per cent per year, generating around 0.02 to 0.24 billion tonnes of CO_2 emissions per year [11,17]. Current human activities can place multiple stressors on marsh ecosystems, including altered hydrology, waterborne pollution, marsh disturbance such as drainage for agriculture or lost to development, over-fishing of predatory species that help regulate species in the ecosystem [70], and climatic changes such as increasing air and sea surface temperatures and increasing CO_2 concentrations [68]. Rising sea levels threaten tidal marsh sustainability and permanence of their carbon sinks [71]. Nitrogen pollution (eutrophication) is also a major driver of change in tidal marsh ecosystems. Increased nitrogen inputs, via agricultural run-off and wastewater reduces tidal marsh root production [72], which reduces the plant's ability to accumulate soil. Eutrophication can also enhance the release of nitrous oxide from tidal marshes [73].

Restoration

Tidal marshes and their carbon sinks may survive rising seas if there is available space for them to migrate inland [71]. Salt marsh stability and future recovery is largely dependent on improving coastal watershed management to reduce nutrient loading [72], implement sustainable fishing practices and prevent salt marsh conversion to other uses. The ecosystem services provided by restored wetlands are often worth more in net economic benefits to people than if the site were developed for private use such as agriculture [71]. Hesketh Out Marsh for example, is one of the largest salt marsh restoration projects in the north of England, and has an estimated worth of $2000 per hectare and a total value of $644,000 over 322 hectares [75]. The area attracts 10,000 visitors per year and provides educational resources, flood defence for 140 properties, as well as biodiversity and species richness.

Co-benefits

For decades tidal marshes have been recognized as natural sea barriers, offering coastal areas protection from waves and floods [71]. Increasingly, they are being used as 'soft engineering' elements in coastal protection schemes, offering the advantage over hard defences like seawalls and dykes of being self-repairing [76,77]. Marshes benefit estuaries by filtering pollutants, and act as a sink for nutrient runoff, thereby reducing nitrogen input to estuaries and the risk of toxic algal blooms and marine dead zones [71]. They are essential refuges for young fish and crustaceans of fishery value [78], in turn supplying food and economic security for millions of people. They are valuable habitat for plants, birds and other animals [71], including vital stopovers for migrating birds [79]. Recent research also suggests that healthy salt marshes and coastal ecosystems could also play a role in reducing stress and anxiety, especially among communities that have experienced natural disasters [80].

[ii] Using an areal central estimate of 5.5 million hectares.

SEAGRASS

Quick key facts:

- Seagrass ecosystems protect a global carbon store between 4.2 to 8.4 billion tonnes of carbon, with some estimates up to 19.9 billion tonnes of carbon [48], the equivalent to greenhouse gas emissions from nearly 16 million cars driven for one year [56].
- About 29 per cent of monitored seagrass habitat worldwide has been lost since 1879 [45].
- Seagrasses hold less carbon per hectare than mangroves and salt marshes, but due to their large global extent and current rates of loss and degradation they could release between 0.05 to 0.33 billion tonnes of carbon dioxide emissions per year [11].
- Seagrasses support high biodiversity and contribute to the productivity of 20 per cent of the world's largest fisheries [81].

Seagrasses are highly productive submerged flowering plants that grow in meadows in shallow marine and estuarine waters. Seagrasses occur along shorelines of every continent except Antarctica and are estimated to cover about 0.1 - 0.2 per cent of the global ocean [82]. Estimates of areal cover range from 16 to 60 million hectares [11], but lack of seagrass mapping, particularly in Africa, Indian Ocean, Indo-Pacific region and the western coast of South America makes it difficult to accurately account for seagrass distribution and total carbon stores. A recent estimate based on modelling software suggested that global seagrass extent could be up to 165 million hectares [83], but this is at the high end of previous best estimates. Though we understand how important seagrasses are, we now need to know much more about their distribution to best protect remaining meadows and identify favourable areas to focus restoration efforts.

Carbon value

Even though seagrasses occupy under 0.2 per cent of the world's oceans, they sequester about 20 per cent of the carbon buried in ocean sediment annually [49]. Per hectare, seagrasses can store up to twice as much carbon as terrestrial forests [6] (Fig. 1) and globally, it is likely that seagrasses capture and store 48 to 112 million tonnes of carbon per year [49]. Seagrass sediment carbon stores can reach up to several metres in height, and store carbon for millennia [19].

An estimated 50 per cent of carbon stored in seagrass soils can be of external origin (allochthonous) and as such, seagrass meadows act as carbon sinks for larger areas [49]. Furthermore, an estimated 50 to 70 per cent of seagrass production is exported and buried elsewhere [49], meaning the assessment of seagrass sediment carbon pools alone might underestimate the role of seagrass in the carbon cycle [49,84]. Some seagrass species hold larger organic carbon stores in living biomass than others [48]. *Posidonia oceanica* meadows in the Mediterranean have been identified as a seagrass species that accumulate the largest stores of organic carbon per hectare in living biomass (~7.29 tonnes), about three times more than average global estimates of other seagrass species [48]. However, many geographic regions and seagrass species may be underrepresented given the lack of data [48].

Habitat loss

Seagrasses are among the world's most threatened ecosystems with approximately 29 per cent of the world's seagrass habitat lost since the 1800s [45]. **They have been described as 'coastal canaries', biological sentinels of human-induced change in our coastal ecosystems [85]**. Major threats to seagrass habitat include sewage waste and agricultural run-off, aquaculture, coastal development, climate change and mechanical damage such as dredging, anchoring and fishing [82,86,87]. The rate of seagrass decline has increased from 0.9 per cent per year before 1940 to 7 per cent per year since 1990 [45]. In the United Kingdom more than 44 per cent of seagrass habitat has been lost since 1936, likely due


Image credit: Dimitris Poursanidis

to centuries of dramatic land-use transformation and contamination of coastal and estuarine waters [86]. Excessive nutrient run-off from the land increases algal growth, 'eutrophication', reducing light for seagrasses [85]. Seagrasses are especially vulnerable to reduced water clarity, because they require some of the highest levels of light compared to other plant groups [88]. As they grow in shallow, protected areas, often in the path of watershed runoff, they are more exposed to environmental changes [85]. Furthermore, increased frequency of extreme temperatures, storms and rising sea levels associated with climate change are expected to increase mortality of seagrasses [87,89]. Historical losses and recent global mapping of seagrasses are poorly recorded and represent one of the major challenges in seagrass conservation [81].

Restoration

Several examples of successful seagrass restoration projects exist, achieved via removal of environmental stressors, such as water pollution [90], large-scale seeding programs [91] and the introduction of marine protected areas and legislation [92]. For example, a very successful project in Virginia, USA, restored 3,612 hectares of eelgrass (*Zostera marina*) in two decades, dispersing 70 million seeds in an area where eelgrass was eradicated 70 years prior to a slime mould disease [91]. However, major knowledge gaps remain in seagrass restoration [93]. Rehabilitation efforts can be very expensive and can be a slow process, sometimes taking decades for meadows to recover [94]. Future projects could benefit from a seascape approach that incorporates feedback from neighbouring ecosystems and positive interactions between species [95]. Seagrasses are less affected by eutrophication when mangroves and tidal marshes are present because they trap and bury nutrients, thereby improving water clarity [96]. Similarly, filter-feeding mussels in the vicinity of seagrasses transfer nutrients from the water to the sediment which increases seagrass growth [97]. Furthermore, the presence of seagrasses also increases survival rates of the mussels [97]. Harnessing positive interactions between species can facilitate rehabilitation with little additional investment. Moreover, further understanding of historical cover of seagrass, as well as mapping, will help to support future seagrass protection and restoration efforts.

Co-benefits

Like mangroves and tidal marshes, seagrasses have significant ecological and economic value [98]. Seagrass meadows filter sediment and nutrients from the water and protect shorelines from erosion and flooding [99]. Water purification by seagrasses can reduce contamination of pathogens in seafood, reduce coral disease [100] and improve water clarity, to the extent that there can be a visible difference between vegetated and non-vegetated sites [35]. Seagrass meadows help mitigate ocean acidification locally by taking up CO_2 and thereby raising seawater pH levels by about 30 per cent [101]. Seagrasses support biodiversity, including manatees, turtles, dugongs and invertebrates, and contribute to the productivity of 20 per cent of the world's largest fisheries [81].

Image credit: James Bowden

MACROALGAE

Quick key facts:

- Kelps attain some of the highest rates of primary production of any natural ecosystem [102].
- Global annual carbon burial rate of macroalgae is estimated at 173 million tonnes of carbon [50].
- Seaweed farming is the fastest growing sector of aquaculture in the world, 8 per cent per year [103].
- Global decline of kelp forests has been around 2 per cent per year over the past 50 years [102]. Kelps provide undersea forest habitat, food and shelter for many marine species, which support commercial fisheries. They offer coastal protection from waves and help to locally mitigate ocean acidification [104].

Kelp (brown algae) and other seaweeds (green and red algae) are called macroalgae, and are the most extensive and productive coastal vegetated habitat around the world, growing along approximately one-quarter of the world's coastlines. Some kelp species reach tens of metres in height and submerged kelp forests provide a three-dimensional element to the seafloor [102,105].

Carbon value

Recent estimates suggest that wild macroalgae could sequester 173 million tonnes of carbon per year globally, of which about 80 per cent is sequestered to the deep sea [106]. Macroalgae mainly grow attached to rocks and as a result they lack root structures that would gradually sequester and trap soil carbon like wetland habitats. Therefore, the climate mitigation value of macroalgae is predominantly through the export of carbon in plant biomass to sinks located in shelf sediments and in the deep ocean (> 1000 m), where it can be sequestered from the atmosphere for centennial timescales [50]. Seaweed aquaculture (farming) has been highlighted as a viable emissions mitigator as well as a way to produce sustainable food [17] and could be poised to enter the blue carbon offset market. It is the fastest growing component of global food production, with a growth rate of 8 per cent per year [103], and can provide alternative food, feed and fuel products to replace land-based options that have a higher CO_2 footprint [107]. First-order estimates suggest that seaweed farming could prevent 0.05 - 0.29 billion tonnes of CO_2 emissions per year by 2050 [17], equivalent to the greenhouse gas emissions avoided by 60,000 wind turbines running for one year [56].

Habitat loss

The global rate of loss of wild seaweed habitats varies considerably between regions. Globally it is estimated that one-third of kelp forests have been in decline over the past 50 years [105]. Threats to macroalgal habitats include overfishing, destructive fishing gears, over-harvesting, nutrient run-off, and ocean warming [108]. Macroalgae is not currently recognised as an official blue carbon ecosystem by The United Nations Framework Convention on Climate Change (UNFCCC) policies due to scientific knowledge gaps around the rates of carbon assimilation, the fate of exported macroalgae [109] and uncertainty around the long-term fixed storage of carbon [8,36]. However, research is increasingly catching up with ambition to integrate this habitat into blue carbon policy.

Restoration

Restoration of natural kelp forests is increasingly viewed as necessary to safeguard the numerous ecosystem services provided by kelp into the future [110]. In Sussex, UK, a wild kelp restoration and protection project is underway to restore 16,700 hectares of historical kelp forest within a larger area covering 30,000 hectares (304 km²) protected from trawling in 2021. Approaches to natural restoration include fishing restrictions, establishing protected areas, sea urchin removals by commercial harvest, the creation of artificial forests by adding boulders to sandy bottoms, seeding techniques such as 'green gravel', as well as identifying and planting species more resistant to ocean warming [111]. In terms of seaweed aquaculture, expansion is limited by the availability of suitable areas. Integrating seaweed farming with other forms of aquaculture, such as fish and bivalve farms could improve water quality and reduce waste nitrogen, whist providing space for seaweed farms [112]. Another approach to spatial management could be large-scale seaweed farms within offshore wind farms, as being trialled in a wind farm on the North Sea. However, while small-scale seaweed cultivation is considered low-risk, large-scale expansion of the industry will require greater understanding of environmental impacts [113].

Co-benefits

Kelp forests are ecosystem engineers and provide structural habitat, food and shelter for many marine species [36]. Kelp forests buffer waves, help to reduce coastal erosion and are highly productive and biodiverse habitats which support fisheries and attract tourists. Macroalgae acts as a carbon conveyor belt and the exchange of detritus is an important form of connectivity between coastal habitats, such as supporting neighbouring or distant food webs with exported detritus, in which local primary production is usually very low [109]. Seaweed can also elevate pH levels and supply oxygen to the water, thereby reducing local effects of ocean acidification and de-oxygenation [107].

Recent estimates suggest that wild macroalgae could sequester 173 million tonnes of carbon per year globally, of which about 80 per cent is sequestered to the deep sea [106].

Innovative blue carbon

Blue carbon accreditation methodologies exist for mangroves, tidal marshes and seagrasses. Now, researchers are seeking to develop new methodologies for other blue carbon storing habitats and marine animals. These include seaweed (including kelps) and seabed sediments, and even conceptual studies on bivalves and marine vertebrates, like sharks and whales.

Due to knowledge and evidence gaps in novel blue carbon science, the Intergovernmental Panel on Climate Change (IPCC) currently only provides guidance to countries to help them account for mangroves, tidal marshes and seagrasses within their national greenhouse gas inventories. However, the inclusion of novel blue carbon into the IPCC framework could lead to a holistic or seascape management of the marine environment, while also helping countries to meet targets laid out in the Paris Climate Agreement.

A seascape approach, where a multitude of habitats and species are protected in a given area, could result in significant benefits for climate change mitigation, food provision and biodiversity [114]. Within the highly dynamic ocean seascape there is an inherent connectivity between marine populations and habitats, and every component has a function within the global carbon cycle. Neighbouring blue carbon habitats can create favourable conditions for another, such as protection from waves and protection from excess nutrients and sediment [84]. Connectivity of habitats also supports healthy fish populations and trophic cascades, which may reduce over-grazing and disturbance of blue carbon plants [84]. Blue carbon projects that take a seascape approach could benefit from positive interactions between species and feedback from neighbouring ecosystems [64,95]. Furthermore, there is a clear need to prioritise innovative blue carbon research to clarify the carbon potential, sequestration rates and roles of these new blue carbon habitats.

Seabed sediments

Research is increasingly focusing on seabed sediments because the size of the seabed makes marine sediments on the ocean floor the largest pool of carbon storage in the world, covering 35,000 million hectares [51]. Globally, marine sediments are estimated to hold over 2,000 billion tonnes of carbon in the top 1 metre [51], and annually, a further 156 million tonnes of carbon could be accumulated and buried on the seabed [51,53,115] (Table 2). If left undisturbed, seabed sediment can be a crucial reservoir, storing carbon for millennia [114]. Disturbance of these carbon stores, such as by bottom-trawling, dredging and offshore construction, can re-mineralise sedimentary carbon to CO_2, though quantification and analysis of whether the carbon is released into the atmosphere or stays in the water column are still being carried out.

Recent first order estimates suggested that demersal fishing vessels release as much carbon dioxide as the entire aviation industry per year, and that reduced CO_2 emissions from reducing trawling effort could generate carbon credits [114]. Highly protected areas that prevent the disturbance of the seafloor can provide protection of seabed carbon stocks, but at present only about 2 per cent of global sediment carbon stocks have such protection [51]. Coastal shelves, shallow seas, productive upwelling areas, fjords, estuaries and areas where muddy sediments accumulate have been identified as potential 'hotspots' of carbon rich sediments, and could help identify priority areas for seabed carbon protection [51,114–116].

Shellfish

Blue carbon research has recently extended to the role of non-photosynthetic and calcifying ecosystems, such as oysters and clams, in capturing carbon. Shellfish or bivalves, like all living animals are sources of CO_2. They respire and the process of shell formation (calcification) leads to both the release and storage of carbon [117], and some studies have suggested that these ecosystems are likely to be net CO_2 sources rather than sinks [118]. However, bivalves may also be carbon sinks. Bivalves such as oysters and mussels are filter feeders that take particles from the water, ingest them and deposit them as faeces and pseudo-faeces (non-food particles, such as grit) – both of which contain carbon [119]. As an oyster reef grows these particles and the associated carbon can become trapped, and furthermore, the 3D complex structure of the reef can also trap particles from the water column [119]. Through sediment accumulation, shellfish reefs may contain significant pools of carbon [120]. In addition, recent research suggests that shellfish reefs may increase carbon sequestration and storage capacity in other habitats, thus providing an indirect mitigation potential [121]. Salt marsh fringing oyster reefs have been shown to preserve carbon-rich marsh sediment from eroding and facilitated seaward migration of salt marshes [121].

Fish carbon

Marine animals can sequester carbon through a range of natural processes that include accumulating and storing carbon in their bodies by eating phytoplankton and other marine species, excreting carbon-rich waste products that either sink to the deep sea or are consumed by other species, and fertilizing or protecting marine plants (Fig. 2). Scientists are beginning to recognize that healthy populations of fish and marine mammals have the potential to help lock carbon away from the atmosphere, whereas overfishing of stocks can remove large amounts of blue carbon from the ocean [122]. Research has suggested that marine vertebrates could represent an oceanic blue carbon stock of 0.7 billion tonnes of carbon [123], but fish carbon has received little attention from climate change mitigation schemes [122] given uncertainties around the contribution to long-term carbon sequestration [36]. Furthermore, most populations of marine megafauna reside in the open ocean or cross international boundaries, which presents challenges when determining management and ownership of fish carbon sequestration [36]. Looking ahead to the future of sustainable fisheries, fish carbon could well be considered within fishery carbon budgets.

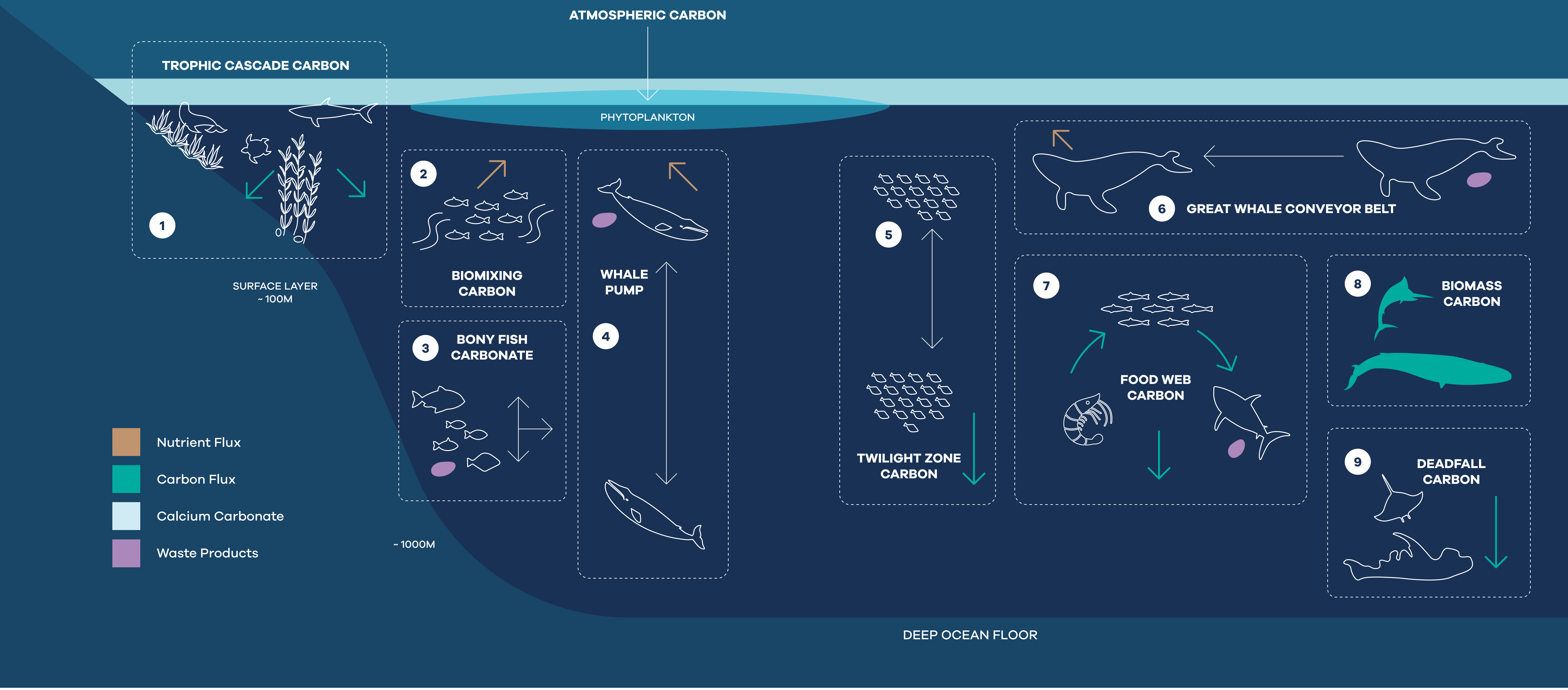


Figure 2. Examples of nine ways that marine vertebrates play a role in the oceanic carbon cycle. (i) Predatory species support the growth of coastal wetlands; (ii) the swimming movement of fish stirs up nutrients to the surface and are used by phytoplankton as they grow, thus absorbing carbon; (iii) bony fish excrete carbon in the form of calcium carbonate, which raises the pH of seawater and could provide a buffer to ocean acidification; (iv) as whales move between the deep sea and sea surface they excrete fecal plumes which support phytoplankton growth; (v) fish that feed on the surface but migrate to deep waters at night bring carbon to deep waters, where it can be released as fecal pellets and sink to the seafloor; (vi) whales that move between nutrient rich feeding grounds to nutrient poor areas excrete urea that is rich in nitrogen and can stimulate phytoplankton production; (vii) through the marine food web fish eat and repackage food into carbon-rich fecal-pellets, which can contribute to long-term carbon storage; (viii) all living things are made of carbon and serve as carbon reservoirs throughout their lifespans - the larger the animal the more carbon is stored; (ix) when large vertebrates die, their carcasses sink and can be incorporated into marine sediments. Source: Lutz et al., 2018 Oceanic Blue Carbon. Arendal: GRID-Arendal.

Economic valuations of blue carbon ecosystems

Scientists have valued coastal wetlands globally at US $447 billion in terms of avoided storm damages to communities and estimate that wetlands save 4,620 lives per year from extreme weather events [124].

Economic values of blue carbon ecosystem services vary from place to place. In the UK the carbon sink capacity of tidal marshes, mud flats and sands alone were estimated to have a value of between £742 million and £4,259 million in 2019 [125]. If all UK carbon-capturing components were included in this assessment the value would likely be much greater. The current extent of European coastal blue carbon has an accounting stock value of about US $180 million, but conversely, extensive ecosystem loss could mean economic losses as high as $1 billion by 2060 [126]. Coastal wetlands in the United States are estimated to provide $23.2 billion per year in storm protection services [127]. At a time when the frequency and intensity of storms is increasing, the protection and restoration of these natural buffers is increasingly important and of significant value. However, the global rate of coastal wetland loss demonstrates that conversion to other uses and economic gain is still prioritised over conservation in some countries [11]. To halt global degradation of blue carbon ecosystems the full value of their ecosystem services needs to be calculated and represented in management decisions [128].

Image credit: Alex Tattersall

The status of blue carbon in the UK

The UK is required by law to cut emissions by 78 per cent by 2035 compared to 1990 levels and achieve net-zero emissions by 2050 [129]. In 2019, net territorial emissions in the UK were 454.8 million tonnes of carbon dioxide equivalent (CO_2e), of which 80 per cent was carbon dioxide [125].

Conservation of, and investment in blue carbon components presents two policy actions: protection, keeps their large carbon stores in the ground, and restoration, enhances further removal of atmospheric CO_2 and long-term carbon burial. The UK's local Exclusive Economic Zone (EEZ) covers 75.7 million hectares and a further 603.2 million hectares including UK Overseas Territories. All blue carbon components discussed in this report are present within these areas.

UK blue carbon ecosystems sequester an estimated 11 million tonnes of CO_2 a year, which is most likely a significant underestimation and equates to 2 per cent of all UK emissions [134]. This corresponds to nearly 30 per cent of all CO_2 sequestration achieved by natural ecosystems in the UK.

The sequestration rate of tidal marshes, mud flats and sands in local UK waters are estimated to range between 10.5 million and 60.1 million tonnes of CO_2e per year [125]. The higher range is double the carbon sequestration rate of UK terrestrial habitats of 28 million tonnes per year [125]. Another study estimated that UK saltmarshes, seagrasses and shelf sea sediments protected 220 million tonnes of carbon [130]. Given that only three blue carbon components have been quantified in each study, the actual potential contribution of blue carbon is likely higher and can play an important role in the UK's carbon budget.

HABITAT	EST. AREA	EST. ANNUAL CARBON SEQUESTRATION RATE	NOTES
Salt marsh	44,000 ha	2.35–8tCO_2e/ha	The UK is home to 30 per cent of saltmarsh in Europe, with over half of that being located in England.
Seagrasses	7,000 – 9,000 ha	4.2 – 1.36tCO_2e/ha	The UK carbon stock in seagrass may be one of the largest in Europe. Sequestration rates vary due to water quality, sediment type, and species.
Macroalgae	32,000 ha	6.03tCO_2e/ha	All the UK mangroves are in UK Overseas Territories, with the majority within Turks and Caicos.
Kelp	400,000 – 800,000 ha	1.47tCO_2e/ha	Most of the kelp is in Scotland. There is substantial variation of sequestration potential within kelp due to temperature and species.
Maerl reefs	700,000 ha (based on modelling	Unknown	Maerl reefs have low growth rates but can store a vast amount of carbon even when they are dead. Most maerl reef habitats are in Scotland, but habitats all around the UK are threatened due to trawling and dredging.
Seafloor mud and sands	75,664,000 ha	0.01 – 2.17tCO_2e/ha	UK sea shelf sediment protects an estimated 205 million tonnes of carbon. Sequestration rate depends on location and sediment type, but it is estimated to be 106,000 tonnes a year in the UK.

Figure 11: The estimates of extent and carbon sequestration capacity of different blue carbon ecosystems around the UK including overseas territories. Important to note that all of these values are estimates and could be scaled higher or lower [135].

Tidal marshes:
At about 44,000 hectares tidal marshes in the UK are able to sequester about 36,000 tonnes of carbon a year. In 2015, the Natural Capital Committee final report estimated that tidal marshes in England and Wales had the potential to increase by 22,000 hectares. If that is achieved, the blue carbon potential of UK tidal marshes would increase by more than 18,000 tonnes of carbon a year [132].

Seagrasses:
There is very little data available on sediment carbon within UK seagrass meadows and this is an area that demands further research. Preliminary research in southwest England indicates that the mean carbon stock of UK *Zostera marina* seagrass meadows for the top 100 cm of sediment (about 140 tonnes of carbon per hectare) was just short of the global average of about 194 tonnes of carbon per hectare, but within the upper range of seagrass meadows recorded in the rest of Europe [143]. Seagrass carbon stocks and sequestration rates vary among regions and species and require local research to determine the potential contribution to the UK's carbon budget.

Seabed sediment:
Blue carbon research is increasingly focusing on seabed sediments because the size of the seabed makes marine sediments on the ocean floor the largest pool of carbon storage in the world. In Wales, at least 113 million tonnes of carbon in the top 10 cm is stored in marine sediments [131]. In Scotland, an estimated 9.4 million tonnes of organic carbon and 47.8 million tonnes of inorganic carbon is estimated to be held within Scottish Special Areas of Conservation and Nature Conservation Marine Protected Areas alone [133]. Fishing practices that include bottom trawling and dredging can have significant impacts on seafloor fauna, flora and sediment and might disturb long-term carbon capture [46]. Bottom trawling and dredging are only banned in 2 per cent of UK seas [132], which makes the fishing industry, combined with its high carbon footprint, an important consideration of carbon emission policies.

Despite the significant extent of these natural habitats and the potential scale of carbon sequestration within them (Figure 11), blue carbon ecosystems in the UK are not currently included in the national GHG inventory. Therefore, there is little focus on the protection of and investment in these ecosystems. This is mostly due to the lack of scientific evidence, and high levels of uncertainty surrounding the true extents and sequestration capabilities of these ecosystems.

However, research and interest in these habitats is growing, as evidenced by the UK Government's new regional Marine Plans including blue carbon value considerations, and proposed pilot projects for highly protected marine areas that include their carbon sequestration potential. The UK has made commitments on being nature positive by 2030 and has promised to contribute £3 billion pounds to nature-based solutions all over the world to help offset emissions [136].


Image credit: Alex Tattersall

THE BLUE CARBON MARKET

Driven by the climate emergency, governments, corporations and individuals across the globe are seeking to mitigate their carbon emissions through purchasing carbon offsets in global voluntary carbon markets (VCM). The VCM enables organisations to compensate for unavoidable emissions through financing the avoidance or removal of emissions from other sources.

Image credit: Chris Scarffe

It is globally accepted that a carbon credit or offset represents the reduction, avoidance or removal of one metric tonne of carbon dioxide equivalent, whose purchase and sale allows emissions to be traded and offset-generating projects to be funded. When used alongside direct emissions reductions, the VCM allows organisations to accelerate immediate climate action through compensating for emissions that have not yet been eliminated.

For a project to generate carbon credits or offsets, it needs to demonstrate that the achieved emission reductions or removals are real, measurable, traceable, permanent, additional and independently verified (to globally accepted standards such as Verified Carbon Standard (VCS) or Gold Standard).

Voluntary and compliance carbon markets

Carbon credits are verified to a certain standard which includes accounting, monitoring, verification, and certification standards, and registration and enforcement systems.

Compliance markets are created and regulated by mandatory international, regional, and subnational carbon reduction schemes such as the Clean Development Mechanism regulated by the Kyoto Protocol, the European Union's Emissions Trading Scheme (EU-ETS), and the California Carbon Market.

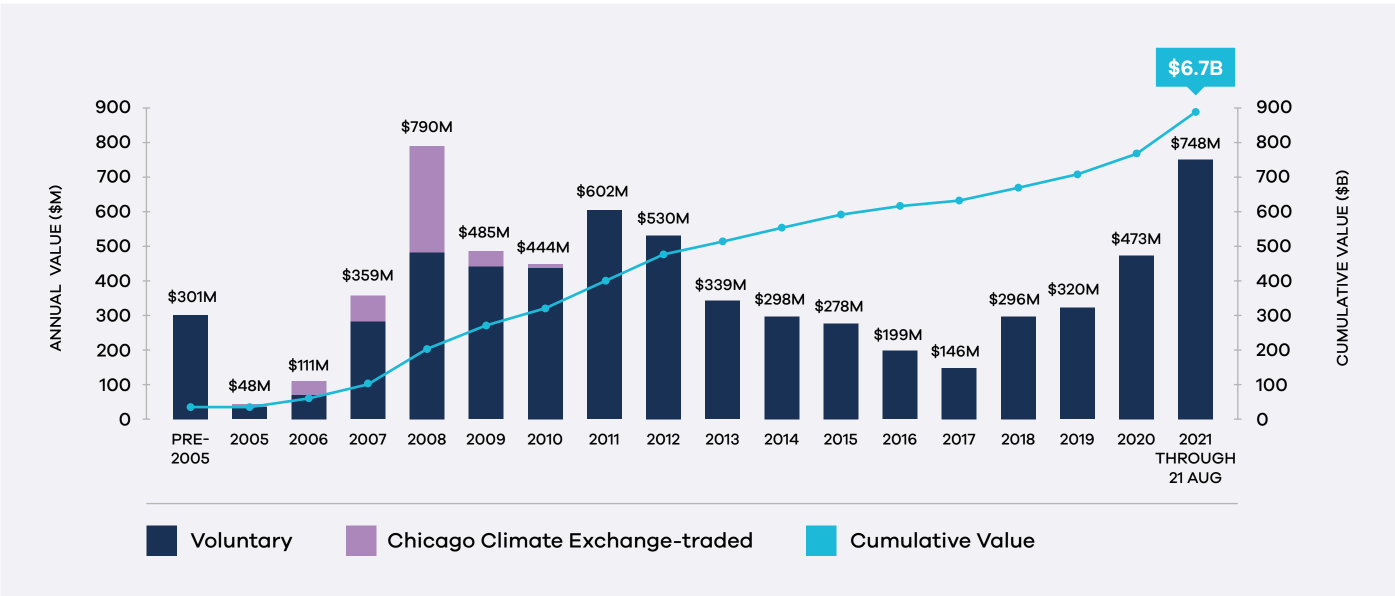
Voluntary carbon markets function outside of the compliance markets and enable companies and individuals to purchase carbon offsets on a voluntary basis. For example, individuals who seek to offset their CO^2 emissions and companies who would like to become climate neutral can buy an equivalent in terms of offsets to "neutralise" their carbon footprint.

Voluntary carbon market – volume estimates

Ecosystem Marketplace estimates the size of the VCM to be $473 million in 2020. As of August 31, 2021, market transactions had already exceeded $748 million, implying that 2021 is likely to be the highest annual value ever tracked, potentially exceeding $1 billion.

Figure 7: Market Size by Traded Value of Voluntary Carbon Offsets, pre-2005 to 31 August 2021.

Source: Ecosystem Marketplace.



The Taskforce for Scaling Voluntary Markets (TSVCM) estimates that this market is expected to grow significantly, up to 15 times in volume (an associated increase in value terms from approximately $0.4bn to up to $25bn) by the year 2030 and by a factor of 100 by 2050.

Global demands for voluntary carbon credits could increase by a factor of 15 by 2030 and a factor of 100 by 2050.

Voluntary demand scenarios for carbon credits, gigatons per year

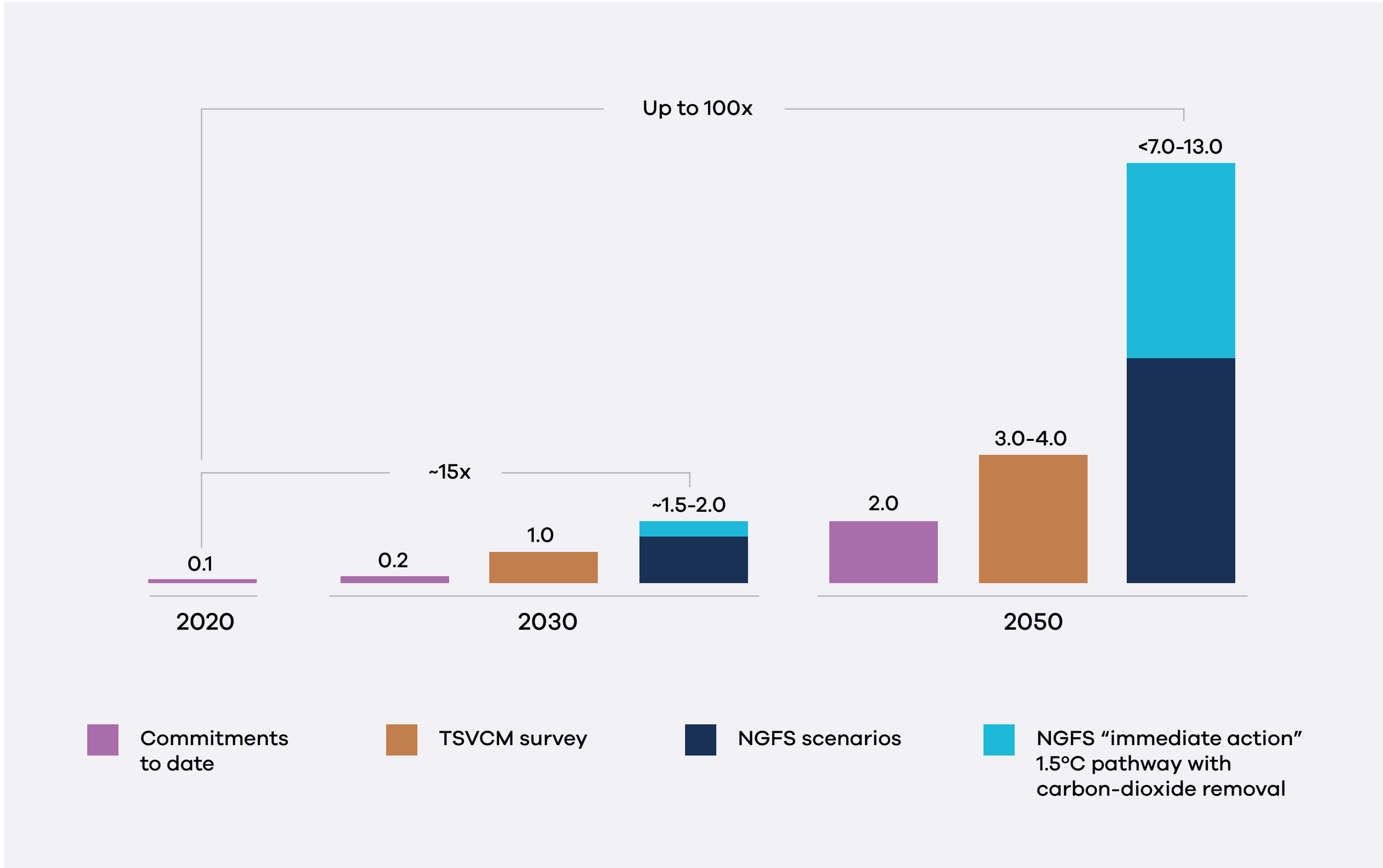


Figure 8: Voluntary demand scenarios for carbon credits between 2020 and 2050. The amounts reflect demand established by climate commitments of more than 700 large companies. They are lower bounds because they do not account for likely growth in commitments and do not represent all companies worldwide. NGFS = Network for Greening the Financial System. Source: McKinsey Sustainability.

Blue carbon credits currently comprise a small fraction of the voluntary markets, but there are a number of coastal and marine projects underway that are expected to significantly increase the issuance of blue carbon credits over the next few years.

This significant growth in demand for voluntary credits necessarily implies that development of projects would have to ramp up at an unprecedented rate. Most of this supply of offsets is expected to come from nature-based solutions; and blue carbon projects will play a key role in meeting market demand. This in turn requires large scale funding sources, designed to overcome the time lag between investment and sale of verified offsets.

The voluntary blue carbon market

The VCM includes a broad range of projects that fall into four broad categories: (i) avoided nature loss (including deforestation); (ii) nature-based sequestration, such as reforestation; (iii) avoidance or reduction of emissions such as methane from landfills; and (iv) technology-based removal of carbon dioxide from the atmosphere.

To date the global VCM has been dominated by terrestrial nature-based and technology-based projects due to the relative ease of implementation and availability of quality scientific data and verification standards for carbon benefits. However, with multiple competing pressures for land use and recognition of the dual climate and biodiversity crisis, blue carbon projects can meet the growing need for emissions reductions and removals, while generating income to support coastal community livelihoods and precious marine habitats.

The voluntary blue carbon market is in the very early stage of its development. Blue carbon projects face implementation challenges such as clear regulatory frameworks for carbon credits in certain countries, the availability of scientific evidence for certain habitats such as seaweed or seagrass, established verification standards and the funding needed to develop early-stage projects.

However, a number of institutions are working towards standardising and scaling the voluntary carbon markets and have made several policy recommendations, such as creating global standards and a global registry of offsets, uniformity in accounting standards, tax incentives, reporting principles to enable transparency, and product innovation based on nature-based solutions (NBS) standards. These measures are intended to create the required market structure which will of course support the blue carbon market as it develops over the next few years.

Pricing of blue carbon credits

The voluntary markets are still nascent (especially the blue carbon segment), with a limited number of participants; and hence pricing is typically negotiated on a bilateral basis between buyers and sellers. Often, a large proportion of the income is taken as fees by market brokers, and hence not paid to the project itself. The current state of the voluntary markets invariably leads to considerable variation in prices.

Currently available blue carbon credits are typically priced at $10 - $15 each, though prices as low as $3 or as high as $25 have been observed. These prices for blue carbon credits tend to be higher than those of terrestrial credits (as shown in the chart below) due to their smaller scale, cost and complexity to implement, and their potential to deliver significant co-benefits beyond carbon, such as biodiversity, climate mitigation and supporting local community livelihoods.

	2019		2020		2021 (THROUGH AUGUST)	
	Volume ($MtCO_2e$)	Price (USD)	Volume ($MtCO_2e$)	Price (USD)	Volume ($MtCO_2e$)	Price (USD)
Africa	16.1	$3.94	14.9	$4.24	23.9	$5.52
Asia	45.6	$1.80	63.0	$1.60	91.8	$3.34
Europe	1.1	$2.92	1.7	$9.47	0.8	$2.96
Latin America & Caribbean	15.3	$3.45	18.9	$4.17	36.6	$3.74
North America	15.5	$3.51	11.6	$6.31	10.0	$5.13
Oceania	0.5	$12.53	0.1	£20.57	0.1	$32.93

Figure 9: Transacted Voluntary Carbon Offset Volume and Average Price by Project Region 2019 – August 2021. Source: Ecosystem Marketplace.

Climate, community and biodiversity

A recent but growing trend in carbon offset projects is to monitor and account for not just carbon sequestration but co-benefits such as biodiversity and community benefits. A project that can demonstrate these additional benefits can potentially realise higher prices for its carbon offsets which reflect both the true social value of these ecosystems and the additional costs required to deliver these co-benefits.

The Climate, Community and Biodiversity Alliance (CCBA), a partnership of leading international NGOs founded in 2003, has established standards for site-based projects, developed by the CCBA and managed by Verra since November 2014.

The CCB Standards:

- → Identify projects that simultaneously address climate change, support local communities and smallholders, and conserve biodiversity;
- → Promote excellence and innovation in project design and implementation; and
- → Mitigate risk for investors and offset buyers (since these projects are more aligned with local communities and are hence more likely to succeed with their buy-in) and hence increase funding opportunities for project developers.

Ecosystem Marketplace estimates that these CCB standards are increasingly being combined with VCS standards – in 2019, two-thirds of all voluntary offsets were VCS or VCS+CCB. The average price per credit for VCS+CCB credits is considerably higher than for credits without the CCB standard – these two standards make up the majority of the voluntary market.

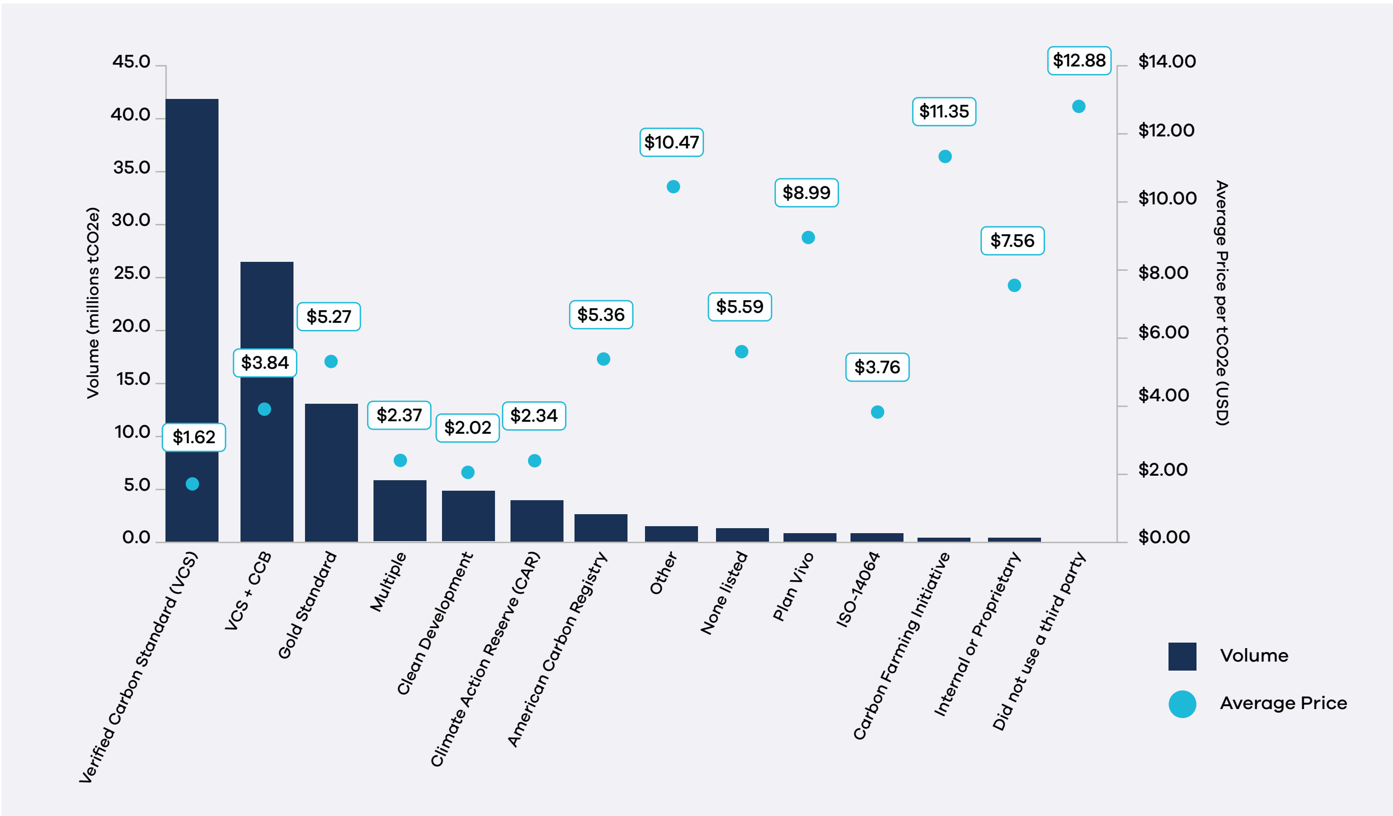


Figure 10. Average price and volume by voluntary carbon credit standards, 2019. Some of the difference is likely due to specific characteristics in individual projects, but it is commonly accepted that buyers favour projects with a wide range of benefits and are willing to pay a premium for offsets that deliver these co-benefits. Source: Forest Trends' Ecosystem Marketplace.

A VOLUNTARY BLUE CARBON MARKET FOR THE UK?

Image credit: James Bowden

Introduction

There are several compelling reasons for developing and scaling a UK market for voluntary carbon offsets derived from the extensive, diverse marine and coastal habitats in its territories.

The recent IPCC report has reinforced the urgent need to reduce GHG emissions, and increase corporate net-zero commitments which has focused the attention of industry bodies and governments on the importance of a functional voluntary carbon market.

This section outlines the significance of blue carbon habitats to the UK, and the opportunity to quantify carbon sequestration rates to generate offsets to meet public and private commitments. The conclusion draws on several recently published reports to emphasise the basic market and policy requirements for a scalable VCM to be developed.

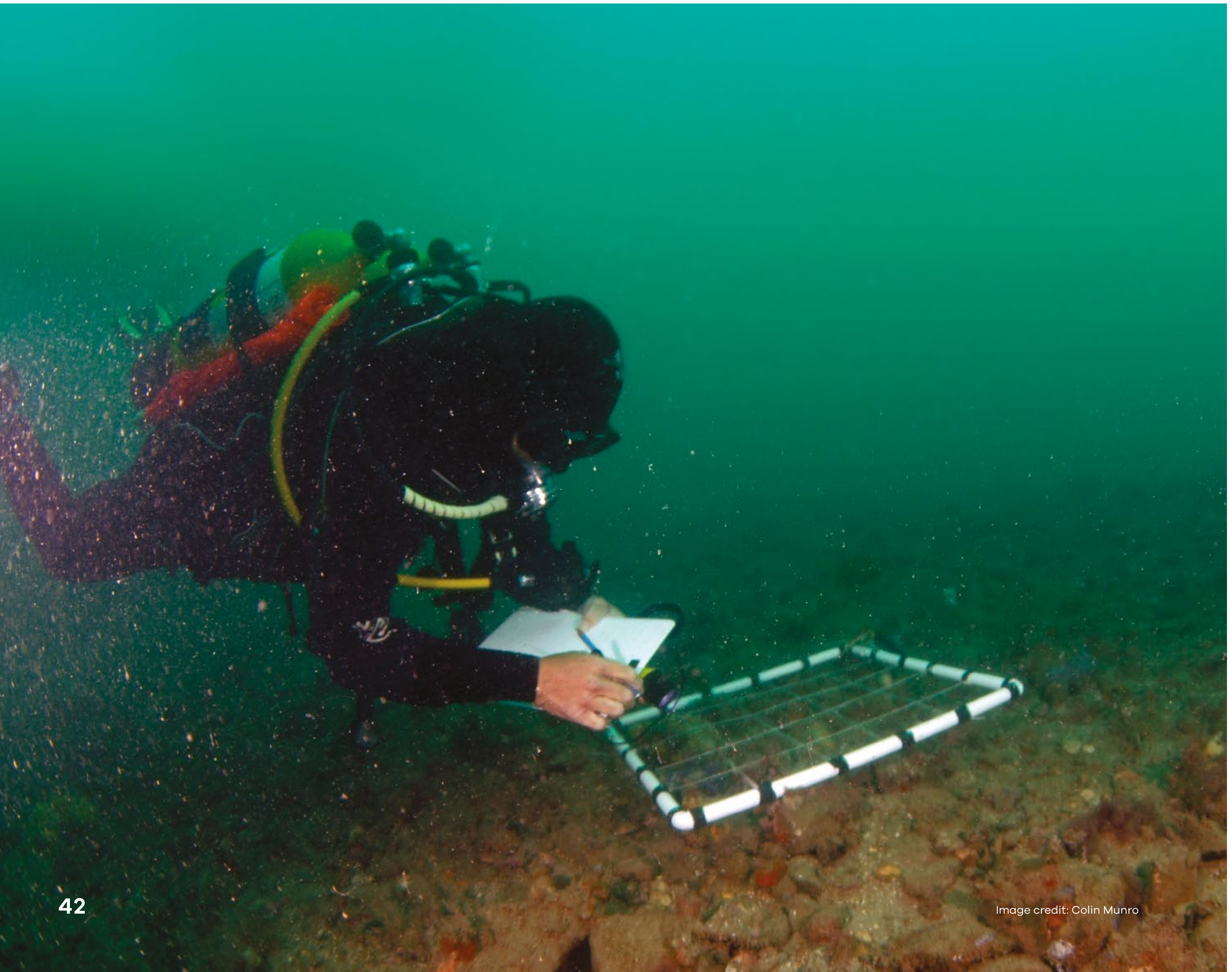


Image credit: Colin Munro

The significance and opportunity of blue carbon in the UK

Protecting and restoring coastal and marine ecosystems in the UK can unlock significant benefits related to biodiversity, food security through fish stock recovery, climate adaptation and coastal resilience, improvement of water quality, and social wellbeing from assisting local communities and livelihoods.

In addition to the above, there is increasing interest in the carbon sequestration potential in these ecosystems, how this potential can be turned into voluntary offsets and how these offsets can be used by governments and corporations to meet their net-zero commitments. This is very relevant as up to 75 per cent of the gap in the voluntary carbon market will need to be filled by nature-based solutions (Figure 2); which include protection and restoration of blue carbon ecosystems.

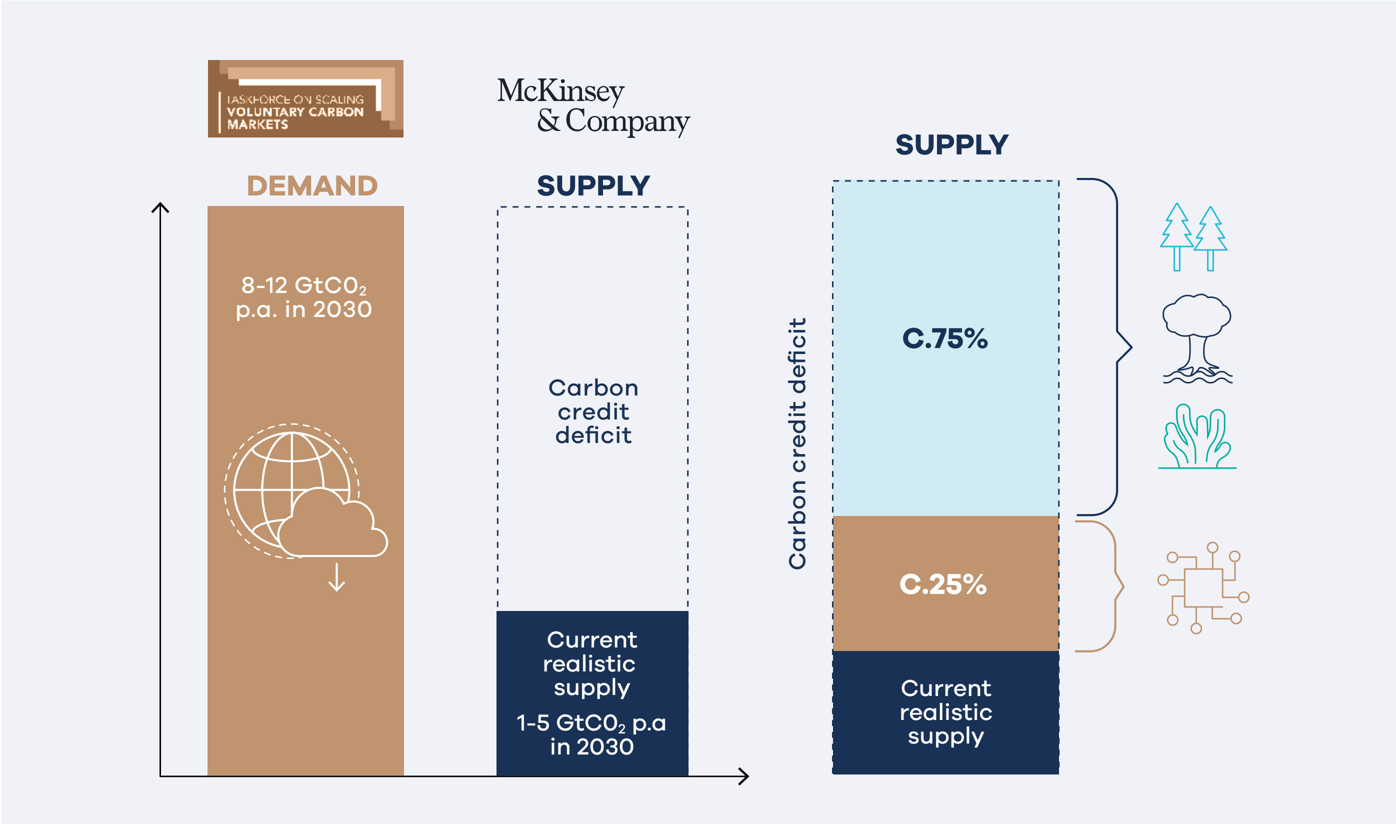


Figure 12: About 75 per cent of all carbon offsets are expected to come from nature-based solutions – both terrestrial and marine/coastal [137].

These 'co-benefits' associated with blue carbon habitats can be quantified too, and valued as desirable additions to carbon offsets. This is particularly relevant in a UK context where climate risks include coastal flooding and erosion, which can be mitigated by coastal vegetative ecosystems. These benefits are often easy to quantify and could contribute meaningfully to the value of carbon offsets.

Blue carbon ecosystems need to be recognised for their potential in order to achieve the UK's NDCs. Research suggests that there is significant sequestration potential in ecosystems such as saltmarsh and sea shelves, but coastal and marine ecosystems remain understudied in their contributing role in increasing sequestration capabilities through restoration, protection, and habitat enhancement.

The current NDC timeframe allows for necessary improvements to scope, methodologies, and data to further explore the prospective sequestration of blue carbon habitats [138]. Until this happens, time and resources need to be invested into these ecosystems in order to protect their carbon stock as well as the essential climate adaptive services, they provide by protecting people from coastal floods and preventing coastal erosion.

The creation of high-quality carbon offsets requires independent verification. Currently, UK-specific verification methodologies exist for peatland and woodland, and there is ongoing work to establish a saltmarsh carbon code which will further standardise offsets and may motivate further investment [139].

The UK has a unique opportunity to set the benchmark for a well-designed, scalable voluntary market, with high standards of transparency, integrity and standardisation. This would greatly help address and mitigate some of the common concerns about the voluntary markets - weak regulation, inconsistent verification methods, varying standards, and the difficulty of cohesively accounting for co-benefits [140]. These issues, coupled with the scientific uncertainty of blue carbon ecosystems, can be problematic for investors due to distrust in the quality and standards of the carbon credits. Establishing homogenous and rigorous verification standards, that ensure transparency and legitimacy is a challenge faced by all VCMs, particularly in the blue carbon realm.

An essential component to the establishment and growth of a Voluntary Carbon Market for blue carbon in the UK is improvement in mapping and monitoring of blue carbon. Initial investment is required to accelerate research that quantifies and reports on the true distribution and carbon sequestering capacity of the UK's coastal ecosystems. Investment in protecting existing blue carbon stores could be ramped-up in a phased manner, starting with marine habitats such as saltmarsh, seagrass and kelp, while further evidence is collected.

Furthermore, ensuring that saltmarsh habitats are incorporated into nature recovery network and into the UK GHG inventory would be essential to protect the carbon stores and reduce the risk of flood saltwater intrusion and coastal erosion. Currently the UK government is funding a project to establish a salt marsh code, advancing the blue carbon potential further [139].

Image credit: Alex Tattersall

A blue carbon VCM for the UK – The roadmap to market development

There are two fundamental objectives of a functional VCM: (i) to channel funding towards nature-based projects to allow them to reduce or avoid CO_2 emissions, conserve local habitats, and help local communities with sustainable livelihoods; and (ii) to facilitate the creation of high-quality offsets that can be used (by buyers who are aligned with and committed to decarbonisation) to meet their net-zero commitments.

Emphasising the results of several recently published reports, it is essential that a well-designed and scalable VCM have certain basic characteristics.

1 A supply of credible offsets

The offsets themselves need to be of high quality, verified by credible independent agents according to well-established methodologies. Scientific evidence for additionality is critical to the value of the offsets. Co-benefits need to be specified and quantified where possible by a trusted, independent third-party body (please see the CCB standards for a good example) – this is especially relevant to coastal and marine habitats which are able to provide more co-benefits than traditional terrestrial forestry projects. The projects and developers should be able to demonstrate the value of their projects towards conversation or restoration of habitats. Verification is a key question, with several existing routes having various levels of relevance for UK projects (such as VCS, Plan Vivo and Gold Standard not to mention the writing of domestic codes). This subject remains under discussion with clear preference among the scientific community to focus on the writing of independent codes. Something of this nature is also being attempted by Wilder Carbon.

2 Clear demand signals

Current demand for voluntary offsets is increasing rapidly – some reports estimate a 15x rise in demand by the year 2030. However, demand is often affected by market forces, the performance of the wider economy and regulation. It is generally accepted that the demand for offsets needs to be increased and encouraged, leading to higher prices that are more commensurate with the true 'climate cost' of emissions. This increase in demand needs to be supported by industry consensus on the acceptability of the VCM and regulatory support.

3 Market infrastructure

A transparent mechanism for pricing and trading of offsets needs to be established. This is relevant to blue carbon offsets which are likely to carry co-benefits, and which still form a small part of the global VCM. Price discovery via bilateral negotiations could be gradually replaced by a central exchange. Trading contracts can be standardised and digitised – both of which are fundamental to scaling any market using technology. Also, a government entity could act as a 'central bank' for the VCM, providing a liquidity backstop (or 'buyer of last resort') for blue carbon offsets. This would encourage both private participants as well as smaller projects, who would have some assurance of revenues to compensate for relatively high project set-up costs.

4 Universal registry

One of the frequently mentioned drawbacks of the current global VCM is the risk of double counting. This risk is magnified by the disparate registry systems where ownership of offsets is recorded. A UK VCM with a transparent, secure, universal registry (including offsets owned by private entities and counted for NDCs by the government) would be a significant step towards establishing a global standard for effective accounting of offsets.

5 Financing for projects

As mentioned above, one of the basic objectives of the VCM is to channel appropriate funding to the projects and communities that run them. This is particularly true for smaller projects, projects in overseas territories, and projects with habitats where mapping or scientific measurement is not established. Funding from private and public sources is essential to overcome the high project set-up costs, including verification, measurement and monitoring. The possibility of generating and trading significant volumes of high-quality offsets should encourage the creation of innovative blended finance structures that can ensure equitable profit sharing with local communities.

6 Public policy

Public policy and government regulation is integral to the creation and functioning of the VCM. In this case, it is imperative that blue carbon is integrated into the UK's national GHG reduction strategy and included in the NDCs. It is encouraging to see the government endorse the Voluntary Carbon Markets Integrity Initiative (VCMI). Their report on aligning a VCM with a 1.50°C pathway reinforces a number of conclusions and recommendations made in other reports from industry bodies as well as the TSVCM.

It is estimated that marine carbon sequestration and storage in the UK has an estimated value of £57.5bn annually. A well-designed, streamlined VCM in the UK is essential to unlock this value within a reasonable timeframe.

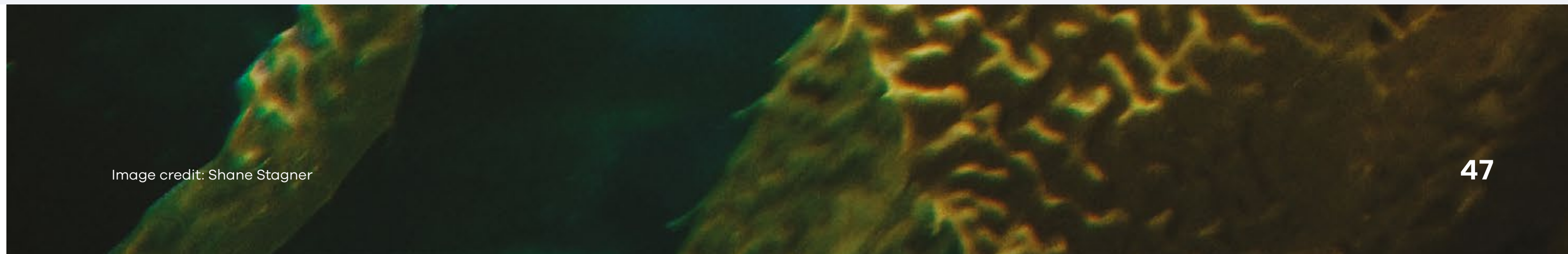


Image credit: Shane Stagner

UK blue carbon case studies

Saltmarsh

Though restored saltmarsh habitats store less carbon than intact and existing saltmarsh habitats, the storage values balance out after 100 years [143]. Saltmarsh restoration can occur through a variety of methods, depending on the condition of the area being restored and its location. One method is realignment, which leads to regeneration through flooding the land with saltwater to encourage salt marsh growth [145]. Saltmarsh restoration costs vary and are estimated to range between £10,000 to £50,000 per ha, which equates to between £37 and £183 per tCO_2e after 100 years [142]. In Steart Marshes, Somerset, the Wildfowl and Wetlands Trust manage a restoration project that protects 300 ha of saltmarsh. The project uses the realignment method to compensate for habitat loss due to sea level rise in the Severn Estuary [144]. The project is funded by the UK Governments Higher Level Stewardship agri-environmental scheme which awards an amount of £120,000 annually.

There are high economic and ecosystem benefits of the project. The storage of floodwater by saltmarsh across the coastline of the Severn Estuary is valued at £5 billion due to the added protection to about 100,000 homes and businesses [145]. The co-benefits of this project include tourism, biodiversity, and grazing land for cattle, which have a total annual value estimated up to £914,000 [144]. Furthermore, the doubling of organic carbon content within the soils on the site bring an estimated added value between £15,375 and £46,125 annually priced using a 'non-traded price of carbon' that would be gained by carbon sequestered in the saltmarsh habitat [144]. Furthermore, management of the project included the local community in consultations. They also ensured to use land that is at a higher risk of flooding to reduce the effective cost for the landowners and to allow farmer's cattle to graze on parts of the saltmarsh [145].

Kelp

Kelp forest regeneration is relatively nascent in the UK with both the extent and the potential carbon contribution of kelp still requiring evaluation [135]. In 2021, the Sussex Inshore Fisheries and Conservation Authority introduced a Nearshore Trawling Byelaw excluding trawling from 304 km²/30,000 hectares of inshore coastal waters under lobbying pressure from the Sussex Wildlife Trust and others (including BLUE), to aid the regeneration of kelp [149]. The carbon benefits are currently under investigation and the overall costs of kelp restoration in the UK are currently unknown. Adur and Worthing councils aim to lease the seabed from the Crown Estate with the main intentions of investing in climate change measures and coastal habitat restoration [150]. With ambitious goals to set up a Marine Park and establish a trust fund for the continuous protection of their coastal marine habitats, there is great potential for blue carbon projects along the Sussex Coast.

There are extensive co-benefits of this kelp restoration project that go beyond carbon sequestration. Once established, the ecosystem is expected to support inshore fishing with economically valuable species such as sole, bass, black seabream, cuttlefish, and lobsters, reduce coastal erosion, and improve the surrounding water quality. According to Sussex IFCA (2020), the benefits of the enhanced value of ecosystem services from protected kelp forests will lead to an economic gain of more than £3 million a year [149].

Seagrass

Seagrass has a low natural regeneration rate and the restoration potential of seagrass in the UK is currently uncertain, with estimates ranging between 20,000 ha to 82,000 ha [135,148]. Detailed mapping of UK seagrass and site-specific data on carbon stocks and sequestration rates is urgently required before a reliable carbon estimate and carbon price for UK seagrass can be established. Seagrass restoration projects can be costly, as evidenced by a large-scale restoration project in Virginia, USA, and prices range from US$1,200/ha to US$4 million/ha [151, 148]. In the Virginia project, only 10 per cent of the restoration costs could be recovered by monetising carbon offsets, however, there is a multitude of long term environmental and economic co-benefits that emerge from seagrass restoration.

While it is difficult to provide an exact estimate, seagrass restoration projects in the UK are priced slightly lower than the US. For example, the cost of Ocean Conservation Trust and Life ReMEDIES project of restoring seagrass in the Solent and Plymouth Sound has an estimated cost of £5.2 million (US$7.1 million) which equates to about £650,000 /ha (US$887,500 million/ha) [151]. This ambitious seagrass restoration project aims to restore 8 ha of seagrass over four years through the planting of millions of seagrass seeds, as well as targeting the seabed in an integrated restoration approach which involves restoring the seabed and seagrass simultaneously and encourages longevity of the restoration. A healthy and undisturbed seabed is vital for allowing seagrass to flourish, providing nursery grounds for young fish - including many commercially important species such as pollock, plaice and herring – offer food and shelter for protected animals, helping to reduce coastal erosion, and cleaning surrounding seawater [151]. Furthermore, there are employment and potential eco-tourism benefits that have been recognised by Life ReMEDIES. Another seagrass project established in the UK includes a 2 ha seagrass restoration in Dale Bay, Wales.

Seabed

It is acknowledged that seabed habitats protect a large amount of organic carbon if left undisturbed. The main threat to sediment carbon stocks are disruptive activities such as trawling and dredging that resuspend stored sediment carbon. It is estimated that in the UK EEZ between 7.3 $MtCO_2$ and 47 $MtCO_2$ is released due to trawling annually. The most effective protection of carbon stocks would be to ban such activities, most notably from carbon rich seabeds, however 95 per cent of MPAs in the UK still permit bottom trawling.

The co-benefits of such projects would be immense as a healthy seabed supports the expansion of healthy coastal floral and faunal ecosystems such as seagrass and kelp and encourage all of their associated benefits [151].

Recommendations & conclusion

Recommendations

1. Greater collaboration between government bodies, research institutions, the corporate sector and NGOs to support research, data collection and analysis of the mitigation and adaptation benefits of coastal and marine habitats in the UK including overseas territories.

2. Protecting UK marine habitats including kelp beds and seagrass meadows - safeguarding extent, carbon stores, and associated ecosystem services including climate change adaptation. Encourage investment in restoration of blue carbon habitats.

3. Accelerate development of appropriate methods to include these ecosystems in the UK GHG inventory.

4. Ensure a supply of high quality and high integrity credits with well-established verification methodologies.

5. Incentivise private sector participation and stimulate demand for blue carbon offsets.

6. Ensure transparency of findings and share with global stakeholders, allowing for future compliance with a regulatory market.

Conclusion

Coastal and marine ecosystems are critical to the natural capital and climate resilience of the UK and its overseas territories. The carbon sequestration potential of these ecosystems could be turned into offsets that might help to channel private capital towards restoration and conservation projects, as well as helping the UK meet its national obligations to limit the effects of climate change.

An initial investment into the mapping and sequestration potential of these habitats is required, especially given the vast extent and diversity of habitats in the UK. This data is fundamental to the creation of high-quality carbon offsets, especially to the smaller overseas territories who may lack the means to conduct independent research and verification.

Blue carbon offsets are valued for their co-benefits and frequently realise higher prices than terrestrial offsets. A robust market for UK voluntary offsets would encourage the development of new and potentially smaller conservation and restoration projects, with a high degree of quality, integrity, scientific evidence and co-benefits. Domestic codes, in the style of the peatland carbon code and woodland carbon code, may help to make smaller projects economically viable compared to some of the existing global standards. Significant progress towards a trusted, evidence-back saltmarsh carbon code by a group of leading academics is already being made. Corporate buyers are more likely to buy such offsets, increasing their market demand (benefiting the underlying projects) as well as establishing VCM prices that are more aligned to the regulated compliance markets.

The UK has a unique opportunity to demonstrate visionary leadership in creating a scalable VCM that actively incorporates blue carbon. The timing to create this VCM is fortuitous – with rapid developments towards standardising global voluntary markets, the ambition to accelerate net-zero commitments set by UK government and industry, and the urgent need for conservation and restoration of the invaluable natural capital throughout the UK seas.

Relying on philanthropic interventions to protect our marine environment will not mobilise sufficient capital to reach the 30 per cent of ocean needed to be protected to ensure sustainable levels of biodiversity [114,153,154]. A report from the Paulson Institute ('Closing the Global Biodiversity Financing Gap') identified a $711bn annual funding gap for nature-based solutions, while the Dasgupta report said that: "large-scale and widespread investment in Nature-based Solutions would help us to address biodiversity loss and significantly contribute to climate change mitigation and adaptation, not to mention wider economic benefits, including creating jobs."[152] If the blue carbon market were to develop at scale, then it could change the way we value the protection of nature in the ocean and unlock significant capital to the benefit of climate, biodiversity and communities.

The ocean is the world's biggest carbon sink. By placing a value on the protection and restoration of biodiversity in the ocean, we could potentially avert the runaway climate change which is currently threatening humanity.

Image credit: Alex Tattersall

Glossary

A quick guide to blue carbon terminology:

Blue carbon: The carbon stored in coastal and marine ecosystems, particularly in algae, mangroves, tidal marshes and seagrasses, in their biomass and sediments. Blue carbon also relates to carbon stored in seabed sediments, fish and shellfish.

Carbon sequestration: The process by which carbon dioxide is removed from the atmosphere, for example by trees, grasses and plants through photosynthesis, and its long-term storage as carbon in biomass, soils and sediments.

Carbon pool: A system with the capability of storing and releasing carbon, such as the ocean, soils, plants and atmosphere.

Carbon sink: An area or habitat that absorbs more amounts of CO_2 from the Earth's atmosphere than it releases and stores it in the form of carbon, thereby reducing the effects of global warming. Worldwide, the ocean and vegetation are the two most important carbon sinks.

Carbon stock: The total amount of organic carbon stored in a blue carbon ecosystem or carbon pool(s) of a known size.

Eutrophication: Excessive richness of nutrients such as phosphorous and nitrogen in a body of water, which causes a dense growth of algal and plant life. Eutrophication is mostly caused by human-actions, such as sewage or agricultural run-off from land. The enrichment of nutrients can result in deteriorated water quality, oxygen depletion and death of fish.

Ocean acidification: As a result of human-activities, such as burning fossil fuels, the ocean absorbs increased levels of CO_2, which leads to an ongoing decrease in pH of the ocean. Ocean acidification reduces the amount of carbonate in seawater, making it more difficult for organisms such as coral and shellfish to form and maintain skeletons and shells.

Primary production: The transfer of chemical or solar energy to biomass. Most primary production occurs through photosynthesis.

Trophic cascade: The simplest top-down interaction: (i) predators suppress herbivores and allow plants to thrive, and (ii) apex predators suppress smaller predators, releasing herbivores to suppress plants.

A guide to blue carbon units

Scale of units:

Value	Symbol	Name	Value in tonnes of carbon
10^3 g	kg	Kilogram	0.001 tonne
10^6 g	Mg	Megagram (tonne)	1 tonne
10^9 g	Gg	Gigagram	1000 tonnes
10^{12} g	Tg/Mt	Teragram/Megatonne	1 million tonnes
10^{15} g	Pg/Gt	Petagram/Gigatonne	1 billion tonnes

Metric conversions:

1 hectare	10,000 m^2/0.01km^2
1 km^2	100 hectares

1 tonne of carbon (1 MgC) = 3.67 tonnes of carbon dioxide (CO_2)

Carbon dioxide equivalent (CO_2e or CO_2eq) is a term used to describe the amount of CO_2 that would have the equivalent global warming impact of other atmospheric greenhouse gases [1]. For example, CO_2 has a global warming potential index value of 1, but methane and nitrous oxide cause 25 times and 298 times respectively more warming over a 100-year period than CO_2. The CO_2e or CO_2eq metric accounts for these differences.

Carbon offset credits:
1 carbon credit or Verified Carbon Unit (VCU) = 1 tonne of CO_2e

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BLUE CARBON IN THE UNITED KINGDOM
— UNDERSTANDING THE OPPORTUNITY

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