DEVELOPING A UK SEAGRASS CARBON CODE

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See the two-page summary based upon this report for more information.

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EXECUTIVE SUMMARY

Seagrass meadows are highly valued worldwide for the vital ecosystem services they provide. These services include supporting biodiversity and fisheries, improving water quality, protecting shorelines, and holding significant social and cultural value. Recent research has also highlighted the important role of seagrass meadows in mitigating climate change, as they can permanently store large amounts of carbon in sediments. However, the UK has experienced a staggering loss of up to 92% of its seagrass habitat, resulting in significant negative impacts on both nature and people. Nevertheless, this loss also presents an opportunity for recovery and climate change mitigation. Although some restoration and protection efforts are already underway, additional investment is needed to achieve habitat recovery goals and restore these crucial ecosystem functions.

The emergence of carbon markets is creating new funding opportunities for nature-based solutions (NbS), including habitat restoration and protection. Many industries are now considering habitats beyond forests, especially those they may impact directly. Therefore, carbon offset funds from industries related to maritime activities or water quality, for example, could contribute to scaling seagrass habitat recovery. However, this requires a robust, science-based seagrass carbon code, accompanied by an appropriate financing framework to ensure there are no resulting negative consequences to nature or people.

While globally applicable carbon codes do exist for seagrass meadows, no seagrass restoration projects have been fully verified for carbon offsets, and no UK-specific code yet exists. These global codes can act as starting points for a UK seagrass code, but scaling them to the size, costs, markets, and unique policy and governance contexts within the UK make evident the need for regionally specific tailoring. This report addresses the significant potential for the protection and restoration of seagrass meadows to contribute to high-integrity offset projects, mitigating climate change through carbon sequestration while simultaneously supporting biodiversity and benefiting coastal communities. Here, we identify the existing UK institutional and policy landscape within which a carbon code must fit, along with key gaps in knowledge and procedures that must be addressed to advance a viable pathway towards the implementation of a UK seagrass carbon code. We suggest that existing global seagrass codes can be utilised to guide the biogeochemical carbon accounting principles, and UK-specific codes for other habitats (e.g., peatlands) can guide the financial, regulatory and governance aspects. Given the paucity of available data within the UK and globally, we identify the need for better data on seagrass spatial extent and condition, and on net carbon sequestration associated with seagrass restoration. Key identified data needs include sediment carbon sequestration rates and methane and nitrous oxide emissions associated with seagrass restoration and protection projects, collected before, during and after project implementation.

The emergence of carbon markets is creating new funding opportunities for nature-based solutions (NbS), including habitat restoration and protection.

Such a seagrass carbon code should be aligned with other habitat-specific UK codes (e.g., saltmarsh, peatland, woodland) to ultimately support a multi-habitat, holistic UK carbon code framework that enables an integrated land-sea approach to restoration and ecosystem recovery. In this report, we also explore the complex regulatory and governance frameworks in which existing UK seagrass management occurs, suggesting opportunities to alter existing permitting processes to enable wider implementation of seagrass restoration and protection. By detailing these specific gaps and needs, we identify key recommendations to move towards adoption of a UK seagrass carbon code (Figure 1).

RECOMMENDATIONS

BUILDING KNOWLEDGE

Data gaps

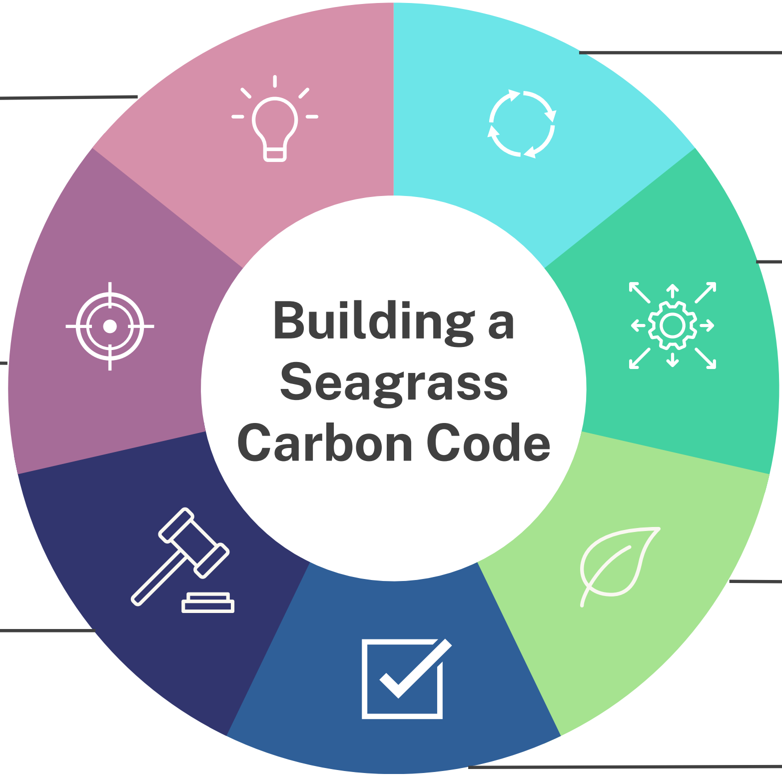
Fill existing data gaps, both internationally & within the UK, on seagrass extent, restoration, carbon flux etc.

Prioritisation

Use seagrass mapping and site context information to prioritise restoration actions

Address barriers

Address policy & regulatory barriers to create an environment for enabling seagrass restoration



CODE DEVELOPMENT

Compatability

Ensure code compatibility with existing financial, regulatory & governance structures

Translation

Translate key components from evidence-based codes to seagrass habitats

Beyond carbon

Include criteria beyond carbon to benefit biodiversity, ecosystem health and people

Verification

Verify that credit purchasers are committed to reducing & avoiding emissions

Figure 1: To develop and adopt an implementable, feasible and rigorous seagrass carbon code within the UK, we make seven key recommendations that build upon the existing body of work.

1. REPORT AIMS

With the emergence of carbon markets globally, significant funds are being directed at nature-based solutions (NbS), with growing demands for carbon credit programs for blue carbon habitats, internationally and within the UK (NEIRF, 2022; UK Parliament, 2021). Seagrass habitats perform many essential ecosystem functions yet have greatly declined within the UK in recent decades, making them good candidates for restoration and recovery of accompanying carbon benefits. Early-stage seagrass restoration projects are now underway in the UK (Figure 1), and linking these projects to carbon credits could provide further restoration funding, compensate for residual emissions and contribute to national net-zero goals, while building climate change resilience (Gouldsmith and Cooper, 2022).

Despite a clear need for restoration and safeguarding of seagrass habitats, channelling the interest in carbon credit programs and investment towards seagrass carbon projects requires a credible implementation framework for awarding carbon credits. There is a globally applicable seagrass carbon code, but while several carbon codes exist or are emerging within the UK, including a saltmarsh code, there is currently no UK-specific seagrass carbon code. While global codes can act as starting points for a UK-specific code, scaling a global seagrass code to the size, costs, markets, and unique policy and governance contexts within the UK create the need for regional tailoring. This report aims to lay the groundwork for development of a UK seagrass carbon code.

First, we introduce the need and context for development of a UK-specific seagrass carbon code. We then assess available data, identify key knowledge gaps, compile a list of best practice criteria from other carbon codes, and list key financial, regulatory, and governance considerations. Finally, we recommend a pathway for development and adoption of a UK seagrass carbon code.

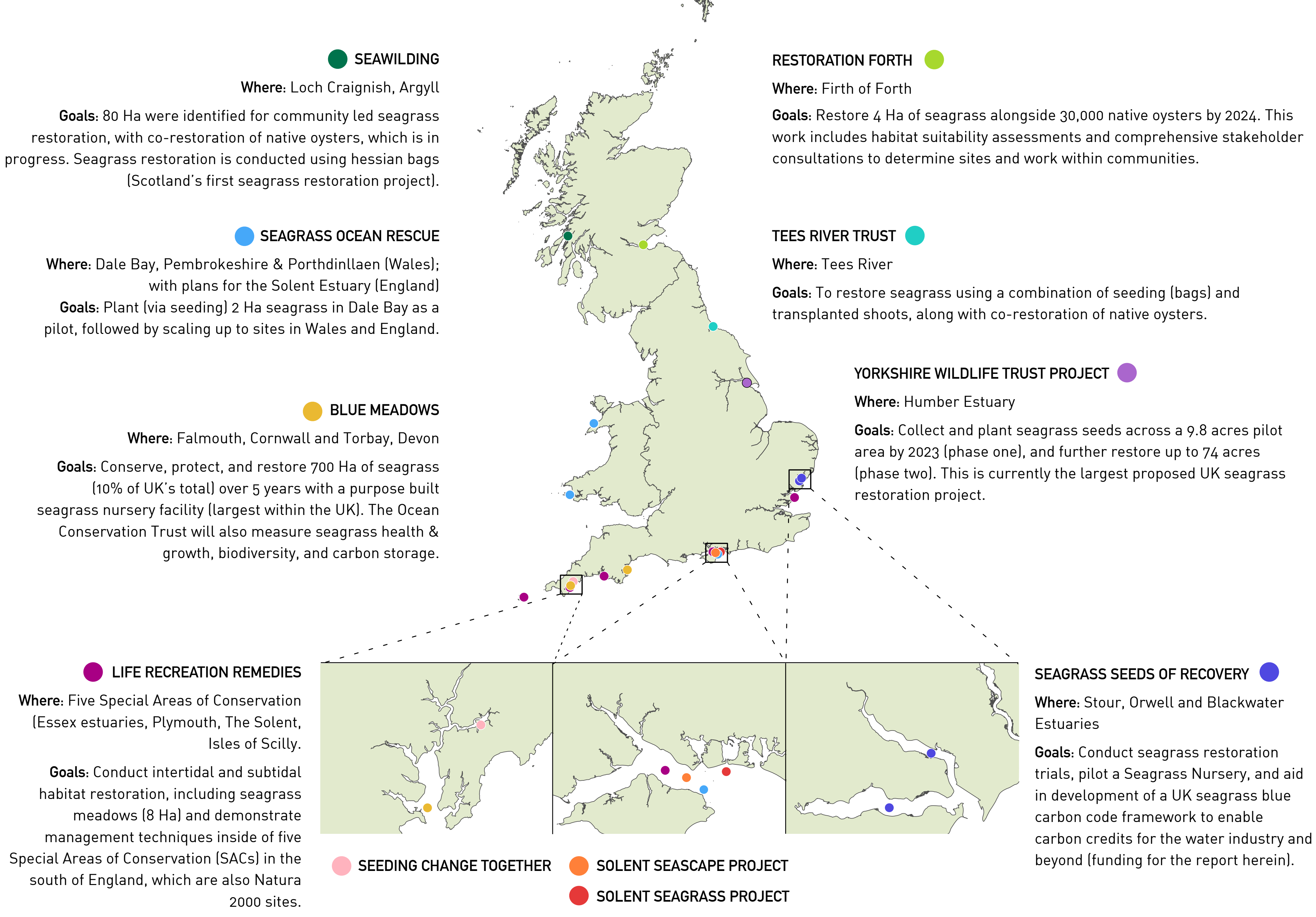


Figure 2: The locations of select seagrass restoration programs within the UK. Each program is described in detail in Table S2.

2. THE NEED AND CONTEXT FOR A UK SEAGRASS CARBON CODE

2.1 Global seagrass importance

Seagrasses are marine flowering plants that provide extensive coastal habitat supporting marine biodiversity in coastal waters from the tropics to polar regions (Cullen-Unsworth and Unsworth 2018). Seagrass meadows provide valuable ecosystem services (e.g., see Nature's Contributions to People) supporting ecologically and economically valuable species, improving water quality, sequestering carbon, and protecting shorelines against coastal erosion (James et al. 2021), storm surge and sea level rise (Short et al. 2011; Nordlund et al. 2016; Orth et al. 2020). Seagrasses typically co-exist within an interconnected mosaic of habitat types where functional linkages across the seascape are crucial for species, ecosystem functions and contributions to people (Robbins and Bell 1994; Barbier 2017). As well as being highly valued as economic assets, people also value seagrass meadows for their relational (cultural) and intrinsic value (Cullen-Unsworth et al. 2014). Growing awareness of these valuable ecosystem functions have elevated global interest in conservation and restoration of seagrass meadows.

Coastal blue carbon refers to the carbon that is stored and sequestered in vegetated coastal habitats, including mangrove forests, seagrass meadows, and tidal marshes (McLeod et al. 2011). An estimated 90% of carbon in the world's major reservoirs is stored in the ocean, meaning that marine ecosystems can play a vital role in reaching international greenhouse gas emission reduction targets (Sabine and Tanhua, 2010). Although there can be high regional and species-specific variability, seagrass meadows could contribute to as much as 20% of total ocean carbon sequestration, and store disproportionately high levels of carbon relative to other habitat types, making them extremely valuable in mitigating climate change (Duarte et al. 2010; McLeod et al. 2011; Macreadie et al. 2021).

Specifically, seagrass can facilitate carbon storage by trapping and accumulating organic carbon particles in underlying sediments. When undisturbed, the carbon stored in seagrass meadows can be preserved over long-term, millennial timescales as the low oxygen availability in sediments reduces organic carbon breakdown, while the stabilisation provided by seagrass roots and rhizomes inhibits sediment loss (Pendeton et al. 2012). Seagrass restoration can also avoid the environmental risks associated with alternative carbon dioxide removal geo-engineering approaches, such as ocean alkalinity enhancement, iron fertilisation or artificial upwelling (Hoegh-Guldberg et al. 2019).

Box 1: Biodiversity and ecosystem services

Seagrass meadows, both intertidal and subtidal, are a UK Biodiversity Action Plan Priority Habitat[1] (Joint Nature Conservation Committee habitat classifications LS.LMp.LSgr and SS.SMp.SSgr, respectively), and a feature of Conservation Importance that can lead to the designation of a Marine Conservation Zone. The OSPAR commission[2] recognises seagrass meadows as declining in the North Sea and Celtic Seas, and threatened in all areas where they occur, along with evidence showing significant UK-wide losses (Green et al. 2021).

Seagrass meadows within the UK are ecologically significant, stabilising coastal sediments and forming essential habitat structure for a range of organisms. They provide shelter and act as nurseries for fish, cephalopods and other taxa. Algae, anemone and sedentary stalked jellyfish can grow on seagrass leaves, and seagrass sediments can support rich communities of amphipods, bivalves, echinoderms and polychaetes (Tullrot, 2009). The epiphytic algae growing on seagrass blades also support diverse invertebrate communities, acting as food for small grazing animals that simultaneously keep blades clean and exposed to sunlight (Chen et al. 2021). The aquatic fauna supported by seagrass also provides food for coastal birds that forage either directly within the meadows, or on offshore fish that benefited from seagrass nursery habitat early in their life histories (Unsworth and Butterworth, 2021). Seagrass is also consumed directly by coastal birds such as Brent goose (*Branta bernicla*), wigeon (*Anas penelope*), mute swan (*Cygnus olor*) and whooper swan (*Cygnus cygnus*).

The rich biodiversity and large-scale ecological significance of seagrass beds mean they provide ecosystem services from which humans also benefit (Nordlund et al. 2016). The potential for seagrass to capture carbon and sequester it in sediments has most often been raised as a climate change mitigation benefit of seagrass bed restoration, as highlighted herein, but is also accompanied by additional services. The nursery role and biomass generated which can be consumed by higher trophic levels (i.e., fish and macroinvertebrates) mean that seagrass beds often underpin productive fisheries (Unsworth et al. 2019). Furthermore, seagrass can attenuate waves due to the presence of the plants changing flow structure, and limit erosion through their roots stabilising coastal sediments (Hansen and Reidenback, 2013), both of which may provide important adaptations to more intense coastal storms under climate change. In general, the numerous ecosystem services and biodiversity that seagrass meadows support make their recovery and conservation important tools in building resilience across the UK.

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[1] While the Biodiversity Action Plan has been superseded, the Priority Habitats remain important in country-level legislation under the UK Post-2010 Biodiversity Framework.
[2] The OSPAR commission is a 15-government consortium to facilitate protection of the marine environment in the North-East Atlantic, named after the original Oslo and Paris Conventions

2.2 Seagrass in the UK

There are two seagrass species of genus Zostera (eelgrass) present in the UK: Zostera noltii (dwarf eelgrass) in shallower and intertidal areas and Zostera marina (eelgrass) in intertidal to subtidal areas (Unsworth et al. 2021). A freshwater aquatic plant, Ruppia (tassel grass), is also found in shallow coastal waters, although it is not a true seagrass species. In the UK, seagrass loss has been severe, with habitat loss estimates up to 92% compared to historic levels (Green et al. 2021). This loss was likely due to a wide variety of stressors, some natural (e.g., marine disease) but the majority human-induced, such as coastal development, dredging, fishing practices, poor water quality and nutrient enrichment (Fraser and Kendrick, 2017; Gouldsmith and Cooper, 2022). For instance, Green et al. (2021) notes that a "wasting disease 'epidemic' has been perpetually attributed as the main cause of declines without consideration for the pervasive environmental degradation that occurred in the centuries before." One report concluded that targets to reach environmental conditions deemed suitable for surviving intertidal seagrass communities were met in some areas, though only 8 out of 475 coastal water bodies within the UK were assessed (Phillips et al. 2018). Modelling the extent of the key seagrass threats, which continue to occur, revealed a 2% loss in the area of predicted suitable seagrass habitat between 2010 and 2016 (Strong et al. 2018). This result emphasises the importance of evaluating the site-specific conditions for seagrass restoration projects, including consideration of broader land-sea context and actions such as restoring watershed health to reduce drivers of seagrass loss in tandem with consideration of interconnected coastal habitats and biological interactions.

This restoration gap highlights an opportunity to operationalise a UK seagrass carbon offsetting scheme that might support restoration and the associated return of essential ecosystem functions.

Seagrass mapping provides an estimate of current seagrass cover and geographic extent that can inform baseline understandings of carbon stocks and help to prioritise restoration and management efforts. It also provides information to underpin habitat suitability modelling and spatial risk assessments. Efforts to improve seagrass mapping in the UK are ongoing, though a comprehensive understanding of the historic geographic range of UK seagrass is still lacking, making it difficult to discern the true extent of seagrass habitat loss (Green et al. 2021; Rice et al. 2022). However, new models and assessments of suitable seagrass habitat demonstrate large opportunity areas where restoration could be successful (The Rivers Trust, 2020; Green et al. 2021; Howard-Williams, 2022; Environmental Agency, 2021). Promising plans are emerging across the UK, including recent funding for a seagrass nursery to supply seed and enable larger-scale restoration (Table S2). Nonetheless, seagrass restoration within the UK is relatively nascent, with the first projects only beginning restoration in 2019 and with little published evidence to evaluate and learn from successes and failures. This restoration gap highlights an opportunity to operationalise a UK seagrass carbon offsetting scheme that might support restoration and the associated return of essential ecosystem functions.

2.3 Restoration in the age of carbon markets

With the emergence of carbon markets, significant funds are now being directed at nature-based solutions (NbS) including habitat restoration and protection. Carbon codes allow agencies, individuals or companies to invest in NbS - such as habitat restoration - to compensate for their carbon emissions through the purchase of carbon credits, increasing overall climate resilience or helping reach climate targets, such as net-zero goals. However, much of the funding is being directed to tree-planting, including commercial forest plantations that place little emphasis on biodiversity and resilience (Lewis et al, 2019), producing a need to enable funding for a wider range of biodiverse habitats on both land and sea (Seddon, Smith et al., 2021). Small-scale restoration of seagrass ecosystems has been occurring across the globe for decades in an effort to regain the essential ecosystem functions they provide (Orth et al. 2020; Beheshti et al. 2022), even in the absence of carbon credit funding. While offset funding is not a panacea - especially as it is based on compensating for damage (through carbon emissions) elsewhere - emerging global and regional carbon markets can help to bolster seagrass restoration efforts, reduce total project costs, and enable larger project scales (Friess et al. 2022).

There is a growing demand in credit programs for blue carbon habitats from NGOs, the private sector, and governments internationally, including in the UK (NEIRF, 2022; UK Parliament, 2021). Many industries are now looking to offset their environmental impacts, in particular by supporting projects in habitats where their supply chains and impacts occur (i.e., via a process called insetting). This approach is particularly appealing to industries such as water resource management, marine shipping, and marine renewable energy sectors, making marine habitat restoration, including seagrass meadows, a significant area of interest. Potential financial contributions from carbon offsets are likely to change as the carbon market evolves, with fluctuations in the price of restoration and the value of carbon credits, as well as the scale of the project.

Channelling the interest in carbon credit programs and investment towards blue carbon requires the development, verification and validation of blue carbon codes to be used in the accreditation process. New blue carbon codes are emerging, one of which includes the restoration and protection of seagrass meadows (Emmer et al. 2021), although none are specific to the UK (Sapkota and White 2020; Emmer et al. 2021; Lovelock et al. 2021). As of 2021, Verra[3] has issued around 970,000 credits to blue carbon projects, principally from mangrove ecosystems (Jones 2021).

Blue carbon finance in the UK is a rapidly evolving field and although marine restoration projects are yet to attract funding from this source, international projects can serve as case studies.

Several countries such as Australia, Japan and the U.S. are creating and adopting carbon offset and accounting frameworks for blue carbon ecosystems (Sapkota and White 2020; Lovelock et al. 2022; Kuwae et al. 2022). One of the most widely accepted blue carbon codes is the VM0033 code developed by Verra, within the Verified Carbon Standard (VCS) protocol and endorsed by the International Carbon Reduction and Offset Alliance (ICROA) (Needelman et al. 2018; Emmer et al. 2021). Despite the inclusion of seagrass in this code, no seagrass projects have yet been fully accredited and awarded carbon credits (The Nature Conservancy and TerraCarbon LLC, 2021). The most advanced seagrass restoration project going through the voluntary carbon market accreditation process is the Virginia Coast Reserve Seagrass Restoration Project, located along the U.S. east coast (The Nature Conservancy and TerraCarbon LLC, 2021) currently underway within the Verra VCS programme (Shiavone, 2021). This project will be the first stand-alone seagrass restoration project to receive carbon accreditation. Although it is not within the UK, the species and biophysical setting are comparable, making it an important milestone in the context of accrediting UK seagrass restoration projects (Gamble et al. 2021).

[3] Verra is a U.S. based non-profit founded in 2007 that operates the world's leading voluntary carbon markets (VCM) program, known as the Verified Carbon Standard (VCS) Program (www.verra.org).

2.4 Carbon credits and other environmental incentives

In addition to carbon offsets, other forms of financial backing, such as biodiversity credits or impact investment, may also support seagrass restoration and conservation projects (World Economic Forum, 2022). Although a full review of these opportunities is beyond the scope of this discussion, combining carbon offset funds with alternative financial backing can broaden opportunities for seagrass recovery and advance timelines for restoration.

The Science Based Targets Initiative (SBTi) is an internationally recognised organisation that aligns with up-to-date climate science to verify net-zero targets for private businesses that are aligned with the Paris Agreement 1.5-degree warming scenario. The SBTi provides a clearly defined pathway for companies to reduce greenhouse gas (GHG) emissions, helping to prevent the worst impacts of climate change and future-proofing business growth. Currently, over 3,000 large corporations are working with the SBTi to reach net zero (SBTi Companies Taking Action, 2022), and this will grow in the coming years as more stringent environmental regulations are adopted across the globe.

While avoided emissions projects can be credible offset projects (i.e., seagrass protection without additional expansion of the habitat), the SBTi requires that carbon removal technologies are used to neutralise unabated emissions to reach net zero in the long term, rather than avoidance or reduction carbon compensation technologies (SBTi Net Zero Criteria, 2021). When a UK seagrass code exists, seagrass restoration credits will likely be classified as carbon removal credits; in other words, restoring seagrass to remove and store carbon from the atmosphere. As more companies set net-zero targets, we can expect the demand for carbon removal projects to increase, making a robust crediting system essential. Further, UK-based companies often seek to offset their emissions through UK-based projects, yet the current supply of projects will often not allow for this, resulting in investment in offset projects elsewhere. The financing of nature-based, carbon removal projects in UK waters can facilitate an established and effective supply of these types of projects in the future.

Of additional interest, companies and governments are also adopting biodiversity or nature-positive targets, with calls from organisations such as the Taskforce for Nature-Related Financial Disclosure (TNFD) and the Business for Nature coalition for businesses to disclose their impacts and dependencies on nature. The TNFD, for example, follows the model developed by the Task Force on climate-Related Financial Disclosures (TCFD), which sets a number of recommendations on how businesses should disclose financial risks and opportunities as a result of climate change. If nature and biodiversity related risks (e.g., if a company negatively impacts nature, resulting in direct loss of ecosystem services, potential financial penalties and reputational damage) and opportunities (e.g., activities that directly support ecosystem recovery and potentially generate financial credits) are better tracked and reported, there is financial incentive for investors to support more sustainable businesses, minimising damage and supporting nature recovery. Thus, there is a critical need to ensure that carbon offset projects also deliver biodiversity gains and avoid harm to biodiversity - something that existing carbon codes are beginning to address through more holistic approaches.

Box 2: Water quality and blue carbon: A nexus for opportunity

Driven by water companies' joint commitment to achieve net zero by 2030 in England and Wales (Scotland by 2040 and Northern Ireland by 2050), along with other directives, the water sector and wastewater companies are looking for nature-based solutions (NbS) to balance the industry's climate change impacts with stewardship to protect and preserve natural resources. NbS with natural capital benefits - such as seagrass restoration backed by a carbon code - could serve as a mechanism to help offset the water sector's operational emissions, while aligning offsets with habitats that could be affected by their activities.

Water usage requires energy to meet the demand of water supply and support the process of wastewater treatment. While water industry practices can contribute to GHG emissions, they also have many opportunities to reduce and offset emissions. Water quality in estuaries and coastal zones can be persistently poor from the excess nutrients caused by run-off and insufficient treatment of wastewater. These eutrophic, low-light environments can lead to blooms of micro- and macro-algae that can further exacerbate stressful chemical conditions and degrade seagrass meadows (Han and Liu 2014). As a result, significant loss of seagrass can be attributed to poor water quality (Fraser and Kendrick, 2017; Gouldsmith and Cooper, 2022). These system-wide water quality issues can lead directly to increased emission of CO_2 through remineralisation of organic carbon in the water column and the loss of carbon stored in sediments following seagrass degradation (Nguyen et al. 2022). There is consequently a tight linkage between seagrass meadows and water quality (Orth et al. 2006).

Simultaneously, healthy seagrass meadows provide an effective filtration, storage and cycling function for nutrients and contaminants that runoff from land (McGlathery et al. 2007; Reynolds et al 2013). For example, some restored seagrass meadows can remove nitrogen twenty times faster than neighbouring unvegetated sediments (Aoki, 2020), which is of additional interest given existing regulations requiring nutrient mitigation (PAS Nutrient Neutrality Programme). There is even some limited evidence that, once reduced below damaging levels, small anthropogenic nutrient flows into seagrass meadows can increase plant density (Vieira et al. 2022). The linkage between water quality and seagrass meadows therefore provides an immense opportunity for the water industry to improve water quality and utilise NbS as strategy to reduce CO_2 emissions. Reducing run-off of excess nutrients can reduce efflux of CO_2 from the water surface (Nguyen et al. 2022) while creating conditions that may be more suitable for seagrass. If also paired with restoration of seagrass, this can not only lead to significant additional carbon gains in sediment, but potentially support the return of numerous other essential ecosystem services such as fisheries enhancement and additional improvements to water quality through increased sediment retention (de los Santos et al. 2020; Orth et al. 2020).

[4] For example, in the Water Industry National Environment Program (WINEP), Action 4 states "water companies should consider the use of catchment and nature-based solutions wherever they are feasible".

2.5 UK context: Policy, governance and funding

As the UK moves towards an implementable framework for investment and carbon credits for seagrass restoration and protection, it is critical to understand the roles that the government, public bodies and regulatory agencies hold. The existing UK government framework overseeing the marine environment is a complex organisational structure with a number of interconnected departments and agencies. Each is tasked with specific marine management responsibilities and activities within their territorial seas and Exclusive Economic Zone (EEZ)[5], some with UK-wide authority and others with country or watershed-specific authority (Table S1; Figure 1).

The Crown Estate owns virtually all of the seabed around the UK out to 12 nautical miles (the territorial sea limit) and around half of the foreshore around England, Wales and Northern Ireland (some foreshore can be owned by private landlords). The Crown Estate Scotland manages marine activities in Scotland, branching from the Crown Estate of the UK under the Scotland Act of 2016. In addition, the Duchy of Cornwall[6] owns 53,000 hectares in 23 counties in England and Wales and is a key player in coastal land ownership. Complex coastal land ownership and management can be a challenge for seagrass restoration, management, and blue carbon projects, given many organisations (e.g., the EA, IFCA, MMO, NE and Crown Estate) can control and share responsibility for UK seagrass management, and approvals will be needed from all relevant parties (Green et al. 2021; Gamble et al. 2021). Seagrass restoration projects and activities within their jurisdictions require permission from the Crown Estate, Crown Estate Scotland or the Duchy, specifically for a lease agreement along with payment of related fees depending on the location and size of the project. For example, Swansea University secured a five-year lease from the Crown Estate to conduct seagrass restoration on a 2-hectare site in Dale Bay for a fee of £2500.

Depending on the project location and purpose, further approvals may be needed from other resource management agencies and organisations. For example, the Statutory Harbour Authorities (SHA) are primarily responsible for all harbour related activities, Natural England (NE) may be involved in licensing activities such as seagrass seed collection, and the Marine Management Organisation (MMO) may also charge licensing fees for restoration work. Local councils may also lead marine resource management programs or planning policies. One seagrass restoration project in Plymouth Sound lies adjacent to the Port of Plymouth, where the Ministry of Defence (MOD) operates the largest naval military operation in western Europe. Plymouth Sound lies within three SHAs and a Marine Protected Area, and the project falls within the Duchy of Cornwall estate boundaries. Thus, permissions will be required from the MOD, the Duchy, the related SHAs and potentially from the MMO and NE for additional permits and approvals. Each project will be unique given the complex and overlapping regulatory jurisdictions, requiring good stakeholder communication to implement projects effectively. Furthermore, activities should be coordinated through local multi-sectoral coastal partnerships (e.g., The Tamar Estuaries Consultative Forum).

Each agency and public body may be additionally engaged with the research, mapping and/or management of seagrass habitat, as well as the approval processes for implementation of a carbon code (Table S1). Equally, each of these bodies may also directly - or indirectly - influence steps in the process of developing a UK seagrass carbon code. Building relationships with the key organisations, as exemplified by UK Blue Carbon Forum, can elucidate and support a clear pathway to a UK Seagrass Carbon Code.

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[5] Territorial sea boundaries extend from the landward boundary of coastal waters from the foreshore (i.e., Mean Water High Springs) out to 12 nautical miles, extending to offshore areas from the territorial limit to the outer limit of the UK's Exclusive Economic Zone (EEZ) and may include the UK's overseas territories as well.

[6] The Duchy of Cornwall is a private estate established in 1337, which funds the public, charitable and private activities of the Prince of Wales and his family.

Governmental directives and marine management plans can also intersect with seagrass management. For example, HM Government aims to reach net-zero by 2050, primarily by reducing fossil fuel emissions, but also through NbS such as woodland and peatland restoration. Seagrass restoration represents another NbS opportunity eligible for funding to sequester carbon and meet climate goals. Outside of UK governance, other key seagrass stakeholders include non-profits, NGOs and charity organisations; academic research institutions; local councils and planning authorities; and many private businesses ('Partners' in Table S2). Local coastal partnerships are important regional multi-sectoral players that function to help coordinate coastal management and the development of marine nature recovery strategies (Stojanovic and Barker 2008). Some companies are seeking to fund NbS projects to strengthen their environmental, social and corporate governance commitments; some already trade carbon credits under other programs; while others retire them for their own use to compensate for unabated emissions. Blue carbon projects also affect local communities, businesses and industries, including those involved in recreation, tourism, fishing, dredging and mineral extraction. In line with the IUCN Global NbS Standard, successful projects will actively engage these stakeholders in co-designing interventions, resolving conflicts and managing trade-offs

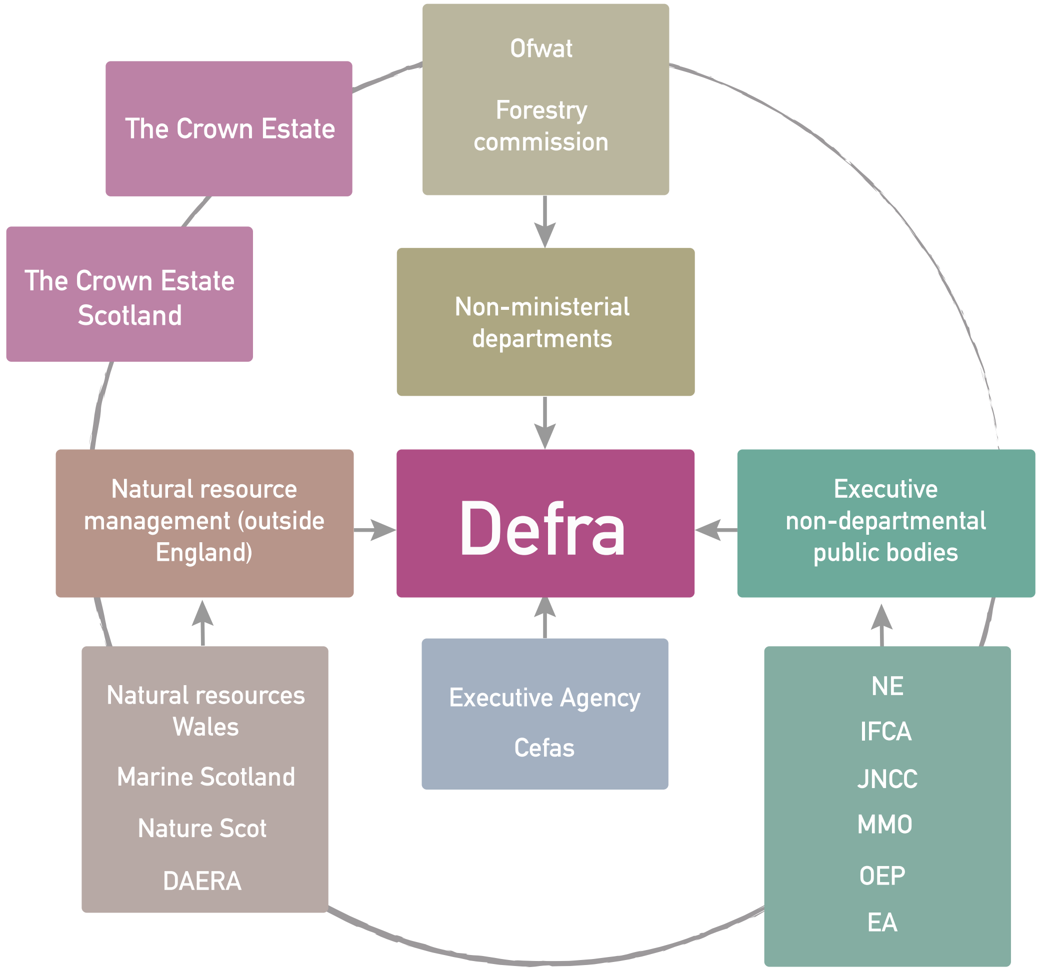


Figure 3: UK Government and Regulatory Ecosystem in relation to coastal resource management, including seagrass conservation. See Table S1 for further information. Acronyms include: *Defra* (Department of Environment, Food and Rural Affairs), *Ofwat* (Water Services Regulation Authority), *NE* (Natural England), IFCA (Inshore Fisheries Conservation Authorities), *JNCC* (Joint Nature Conservation Committee), *MMO* (Marine Management Organisation), *OEP* (Office for Environmental Protection), *EA* (Environment Agency), *Cefas* (Centre for Environment, Fisheries and Agricultural Science) and *DAERA* (Department of Agriculture Environment and Rural Affairs (Northern Ireland)).

3. DEVELOPMENT OF A UK SEAGRASS CARBON CODE

Given the clear interest across sectors in supporting seagrass restoration and protection for carbon offsets and other ecosystem benefits, the development of a seagrass carbon code is urgent. At present, the demand for blue carbon offset projects is far greater than the supply (Macreadie et al. 2022). Barriers toward adoption of a UK seagrass code can come in many forms, including a number of scientific data gaps and spatial planning challenges, along with the requirement for a code to fill the unique governance, financial, social and political needs within the UK. Despite these barriers, there is an existing body of evidence that can be tapped to rapidly advance code development. By working to overcome barriers internationally and within the UK, we can improve our ability to parameterise carbon sequestration in seagrass restoration projects, identify where projects can be co-developed with local community support, and build capacity to link future seagrass restoration projects with available financing.

3.1 State of the science: Barriers and opportunities

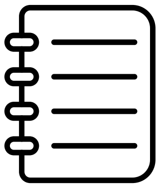
Here, we assess the state of scientific knowledge and identify evidence gaps. We highlight specific research questions which, if addressed, will help fill knowledge gaps and enable progress towards a UK seagrass blue carbon code that is inclusive of the broader benefits gained for nature and people from ecosystem recovery. These research questions should be addressed in seagrass restoration or preservation projects across the UK that span a variety of environmental conditions (e.g., depth, salinity, water temperature, water quality, substrate type, disturbance regime), in an effort to understand variability in associated carbon offsets and ecosystem services. Broadly, they address the need for improved data on key carbon parameters over the course of restoration projects, understanding opportunities and drivers of project success, and evaluation of co-benefits.

We outline six key needs, which are further elaborated in figure 4 below.

Research questions should be addressed in seagrass restoration or preservation projects across the UK that span a variety of environmental conditions.

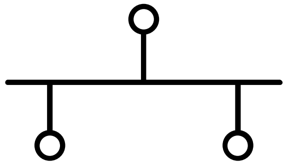
Scientific Needs for UK Seagrass Carbon Code

Data Collection



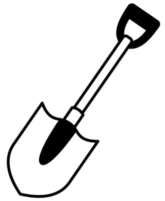
Estimate carbon sequestration rates (e.g. using dating techniques such as 210Pb), and emissions of methane and nitrous oxide.

Monitor



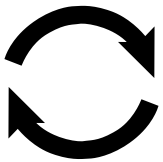
Monitor and measure carbon fluxes before, during, and after restoration in multiple seagrass projects to serve as pilot projects for code development.

Restoration



Improve understanding of the relative differences in carbon offsets gained through various seagrass project approaches, with climate and habitat changes over time.

Feedbacks

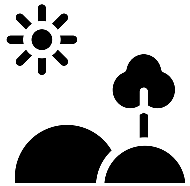


Understand positive and negative feedbacks that promote or hinder restoration success. (e.g. synergistic interactions with other species and with the biogeochemical cycling).

Enabling Conditions

Conduct spatial assessments across the land-sea continuum to guide site selection and increase chances of project success (e.g. considering social-ecological context, carbon offsets, land- & sea-based sources of stress, ecosystem services, biodiversity)

Wider Benefits



Evaluate wider benefits gained through seagrass carbon offset projects, for biodiversity, ecosystem health, and human communities (e.g. supporting fisheries, recreation and ecotourism, reducing coastal erosion).

Figure 4: Six key scientific needs that will advance progress towards a UK seagrass carbon code that is inclusive of the broader benefits gained for nature and people from ecosystem recovery.

3.1.1 Biogeochemical data

Existing carbon offset frameworks (e.g., VM0033) do not require that eligible offset projects directly measure *in situ* carbon removal before awarding credits (Emmer et al. 2021). Rather, they allow the use of data from similar regional offset projects, related habitats, modelled values or defensible values from the literature. However, these in situ carbon removal measurement substitutions come with the caveat that the project proponent must demonstrate that they are reflective of the actual carbon sequestration occurring within their project site (Emmer et al. 2021). For example, in the absence of measuring methane emissions within a project site, which can be challenging and expensive, the project proponent could use regional averages from the same habitat type, before and after restoration (or in the restored site and a neighbouring unvegetated site as a baseline indicative of "before restoration" conditions). In general, to attain acceptable substitution data that enable the broad application of a carbon code, existing codes for other habitats have been developed alongside pilot projects, which collect carbon fluxes *in situ*. Data from these pilots can then guide and justify carbon offsets in future projects, with less *in situ* data collection. This 'pilot project' approach was taken during development of the UK's woodland and peatland codes, and can reduce the time, cost and effort to conduct and credit future projects. As such, a first-step requirement to a UK seagrass carbon code is ensuring that sufficient data and pilot projects exist to robustly estimate carbon offsets from future projects. Pilot projects should be tailored specifically to a draft carbon code such that they can be used to demonstrate and iteratively improve the code.

At present, there are high levels of uncertainty in regional and local seagrass carbon offset potential, representing a real barrier towards their inclusion in programs aiming to meet carbon neutrality goals and offset emissions. Recent regional work on seagrass blue carbon stocks provides a basic understanding of carbon storage in UK seagrass meadows (Potouroglou et al. 2017; Green et al. 2018; Röhr et al. 2018; Lima et al. 2022). While stock data are valuable, they are limited in that they only document the carbon currently stored, primarily in underlying sediment, and in seagrass biomass itself to a small extent (Lima et al. 2022; Gregg et al. 2021). No flux data are yet available specific to the UK (Table 3). Here, we summarise existing, published data from within the UK on key seagrass carbon parameters, compare them to global values from meta-analyses on each, and note considerable variability within these values (Table 3)[7].

Although not as severely lacking as methane and nitrous oxide (N_2O) data, carbon accumulation rates within the context of seagrass restoration are sparse, and no UK data have been published in the peer-reviewed literature (via Pb210 or other dating methods) (Arias-Ortiz et al. 2018). Some global data syntheses exist on seagrass carbon sequestration rates (Duarte et al. 2013; Kennedy et al. 2022; Table 3), however, data are not typically collected within restoration sites and rarely are they estimated both before and after restoration. Other methods to estimate additional carbon accumulation from restoration exist, such as subtracting estimated "background" carbon in nearby unvegetated sediment from total carbon in restored seagrass sediments to estimate additionality (e.g., Oreska et al. 2020). However, this method is still uncommonly applied and imperfect, given that unvegetated sediments next to seagrass meadows can sometimes have higher relative carbon content (Ward et al. 2021).

[7] Global meta-analyses were identified through a literature review using search terms: 'seagrass' AND 'carbon' OR 'methane' OR 'nitrous oxide'. UK data were found by referencing recent UK-based publications and technical reports (Chambers et al. 2022; Gregg et al. 2021; Burrows et al. 2014).

Table 1: Summary of existing, published data on key seagrass carbon sequestration parameters within the UK. UK data are compared to values from available global meta-analyses on each parameter. 1: Potouroglou et al. (2017) estimate across 50cm depth, which we extend here to 1m for comparison to other published values (i.e., we assume no stock changes downcore within the top metre).

	Sediment carbon stocks (Mg C ha^{-1}). Mean (range)	Sediment carbon accumulation rates (g C m^{-2} yr^{-1}). Mean (range)	Methane (CH_4) fluxes (μmol m^{-2} day^{-1}). Median (range)	Nitrous oxide (N_2O) fluxes (μmol $m^{-2}day^{-1}$). Median (range)
United Kingdom	109.6 (29.88 - 219.2) Scotland, 50cm cores, extrapolated to 1m; Potouroglou et al. (2017) 141.0 (98.01 - 380.1) England (southwest), across 1m depth; Green et al. (2018) 103.1 (20.76 - 117.5) England (south), across 1m depth; Lima et al. (2022)	67.91 (19.91 - 106.05) From 6 cores within the Solent; Lima (2020) (not peer-reviewed). Rates have been used to estimate UK meadow sequestration but based on data from outside the UK (e.g., Gouldsmith and Cooper, 2022; Gregg et al. 2021). Data collection and analysis are planned and in progress from locations across the UK	No existing UK data, but goals for collection within Essex and other regions	No existing UK data
Global	108.9 (23.1 - 351.7) Temperate Z. marina, 25cm cores extrapolated to 1m; Röhr et al. (2018) 139.7 (median) (23.6 - 372) All seagrass species, combined estimate from short cores (20cm to 1m) extrapolated to 1m and full cores (1m); Fourqurean et al. (2012)	138 (45 -190); McLeod et al. (2011) & Kennedy et al. (2010)	64.80 (1.25 –401.50); Al-Haj & Fulweiler, (2020)	0.39 (0 – 5.2); Murray et al. (2015) Estimated based on N2O/N ratios of 0.001–0.06 (no direct flux measurements)

Seagrass meadows act as a nursery and refuge habitat for many juvenile organisms, including fish and invertebrates

Information on the flux of other GHGs from seagrass restoration projects is even more limited, again with no published data from the UK. Some studies cite negligible emission of methane and N_2O from restored seagrass meadows, while other work shows emissions that can significantly reduce the total carbon offset earned from the project (Oreska et al. 2020; Rosentreter et al. 2021). Such variability is likely to be site-specific, and the paucity of available data inhibits construction of models that can reliably predict emissions from seagrass systems. Moreover, given the requirements for projects to demonstrate additionality, data must also be paired with knowledge of emissions in the project site prior to project implementation. In existing global codes, project proponents can avoid reduction in associated carbon credits only if they can demonstrate no net increase in methane or N_2O emissions from the project's restoration or conservation activity (below a 5% *de minimis* threshold). However, this requires advanced knowledge of a site's emissions, or at the very least, emission estimates from comparable, neighbouring unvegetated sediments (i.e., space-for-time substitutes can be permitted). Documentation of emissions before and after restoration is relatively absent from the literature (though see Oreska et al. 2020), making this calculation extremely difficult to include into seagrass carbon offset projects. From this clear gap, we see the utility in conducting pilot projects that measure methane and N_2O emissions and can therefore greatly inform accreditation of future seagrass projects within the UK and globally.

In general, the current paucity of data and associated uncertainty will likely prevent awarding verifiable carbon credits to any current UK seagrass restoration project, without significant *in situ* data collection. As such, gathering UK specific data on these parameters will vastly improve our ability and confidence in assigning carbon offset values to future seagrass restoration projects. Additional, less pressing data needs may still exist to increase certainty surrounding project offset totals, such as parameterising lateral flows of carbon within project sites or the production of inorganic carbon. Nonetheless, the scientific needs we identify here represent key gaps and current barriers that must be investigated prior to developing and implementing a UK seagrass blue carbon code. As the broader scientific community in the UK and beyond fills these data gaps, the communication, standardisation and accessibility of data will also be integral towards their effective inclusion into carbon offset codes.

3.1.2 Understanding carbon offset variation from restoration, protection and management approaches

Broad brush estimates of seagrass carbon storage and offsets from seagrass can be conceptualised from our current understanding. Luisetti et al. (2019) suggest that, in total, UK seagrass contains around 0.4Mt carbon, with sequestration over the current area of around 2,500t per year, of which almost 500t per year would be lost without seagrass protection and climate change mitigation. Restoration to expand seagrass range back into areas from which it has been lost would also be expected to increase sequestration potential, with one study estimating gains of £0.8 to £2.8 million annually from carbon sequestered within the Essex Estuaries Special Area of Conservation alone (Gouldsmith and Cooper, 2022).

However, given the gaps identified in Table 3, these estimates were not parameterised with UK specific data. Further, there remains a lack of sufficient data to estimate offsets achieved through different seagrass restoration, protection and management practices, and how these offsets will change over time (Moritsch et al. 2021). For instance, a seagrass carbon offset project may 1) invest in improved safeguarding for an existing, threatened meadow, 2) actively restore seagrass through direct transplant or seeding, 3) encourage natural regeneration by reducing pressures on seagrass (such as by improving water quality, see Box 1) alter sediment characteristics through the removal of derelict equipment or reuse of dredged sediment (i.e., to raise the seabed surface to a suitable height for planting). Yet carbon gains in each of these approaches will vary in their underlying mechanism, in total quantity and in the way associated credits can be offered through time. For example, a project where a seagrass meadow would have ordinarily been dredged to 1 metre but was instead conserved is likely to have greater and/or more rapid net carbon gain per hectare than a project seeding an unvegetated area (although it would be considered an avoidance credit, rather than a removal credit). These gains also might be highly variable, depending on a large number of factors such as project duration, environmental setting and restoration success.

If a project proponent has limited funds to support a seagrass project with the goal of maximising carbon gains, how should they go about selecting or prioritising a project approach?

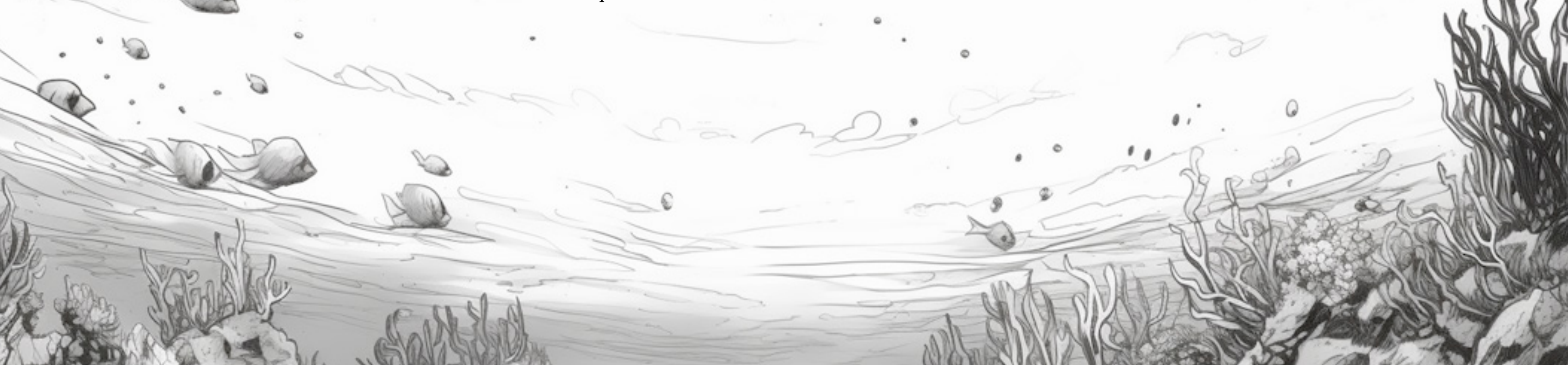
In order to address this key question, the project proponent would need to identify a suitable site where action (restoration or protection) was possible and likely to succeed (environmentally and with community and social support) and obtain information on how much carbon was likely to be offset through these various approaches over the duration of the project. Moreover, anticipating land-use changes (e.g., urbanisation, deforestation) that would impact water quality or climate change impacts (e.g., sea level rise) that would alter habitat suitability for seagrass adds a further layer of complexity that is poorly incorporated into most existing models (Conrad et al. 2023). For instance, considering future climate projections, can we effectively plan for existing salt marsh habitats to convert to seagrass meadow when sea levels rise? What are the implications for carbon offsets within these transitions, and over what duration can we expect these changes? Questions such as these will become increasingly necessary to address and incorporate within carbon offset codes.

Significant research is underway to tackle many of the data gaps discussed here, representing real progress towards an implementable seagrass carbon code (Table S2). As this work continues, it will be essential to take a coordinated approach to collecting the necessary data, while standardising methodologies and establishing a baseline of rigorous pilot projects to guide code development, iteration, and application.

3.1.3 Spatial prioritisation, planning information needs, and integrated land-sea approaches

When nested within broader, multi-habitat restoration efforts (e.g., of oyster reefs, kelp, salt marshes), seagrass restoration can play a valuable role in supporting human adaptation to climate change (Smith and Chausson, 2021). Evidence increasingly reveals important synergistic connections between seagrass meadows and the surrounding seascape and landscape that influence restoration success and carbon storage (Valdez et al. 2020; Dahl et al. 2022). For example, land-based restoration to reduce run-off (including regenerative farming and other agro-ecology approaches) can benefit adjacent coastal habitats (Halpern et al. 2009), seagrass and saltmarshes can trap sediment from land-based runoff benefiting oyster reefs, while oyster reefs can benefit seagrass by filtering pollutants (Reeves et al. 2020). Broadly, increased connectivity can further support functionality between interacting habitats across the land-sea continuum.

Coastal land and seascapes are highly variable and context dependent, in terms of the spatial composition and configuration of seagrass meadows and the surrounding patterns and processes, including land-sea interactions and cultural dimensions. The size of patches, interior and edge effects, the spatial arrangement of patches including the ecological consequences of fragmentation and the morphology of the seabed are all examples of seascape configuration (Boström et al. 2011). Interconnections with terrestrial landscapes, rivers and the wider seascape influence site conditions and suitability, which is particularly important to consider when scaling up NbS. Complex, cross-scale patterns and processes that influence site suitability and restoration outcomes can be addressed using a seascape/landscape ecology approach that applies systems thinking through a multi-scale scientific framework (Figure 2). Such an approach has great potential to inform the practice of site selection and restoration design through an explicit focus on the interlinked 4Cs: context, configuration, connectivity and consideration of scale (Pittman et al. 2021; Gilby et al. 2021). This integrative perspective can ensure that decision making in seagrass restoration and management does not occur in isolation from the surrounding context (Gilby et al. 2018) and fits within marine spatial planning efforts that consider existing and future stakeholders of the habitat, along with sustained, local support for the project (Macreadie et al. 2022; Howard-Williams, 2022). Considering spatial patterns and ecological processes at a range of spatial scales provides information that is operationally relevant to conservation planning and aligns with goals and advances in ecosystem-based management.



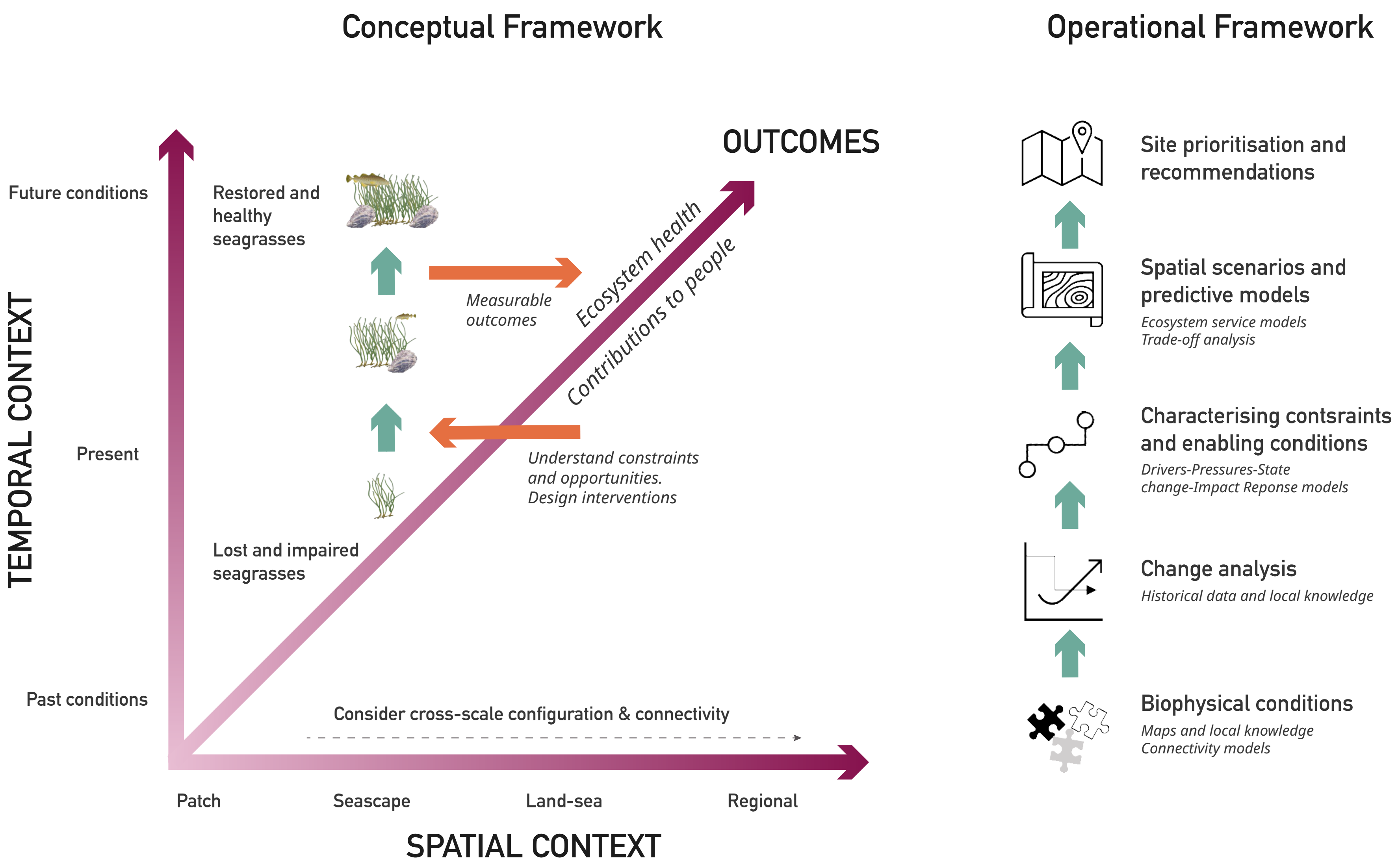


Figure 5: A holistic framework for integrating the 4Cs of seascape ecology (context, configuration, connectivity and consideration of scale) into multi-criteria site selection and restoration design. The framework considers whole-site conditions and supports strategies for scaling-up coastal restoration across interconnected land-sea ecosystems.

Box 3: A Seascape Approach to Restoration in Solent

A seascape restoration approach considers the influence of the site and its surrounding social-ecological context, including the interconnectivity and interdependence among species and habitats, including humans. The Solent estuarine area's remaining saltmarsh, oyster reef, seagrass and mudflat habitats provide refuge to important species and valuable contributions to people (e.g., erosion protection, flood defence, recreation). However, the area is densely populated and is used by various stakeholders with competing interests (Gallagher 2012), leading to high degradation and loss of some of the critical ecological connectivity between coastal habitats. The Solent Seascape Project and other projects in the region aim to restore this connectivity and associated ecosystem functions through a multi-habitat restoration approach.

The Solent Seascape Project led by Blue Marine Foundation and local partners highlights ongoing UK seascape restoration work - its aim is to reconnect 522 km^2 of the Solent's coastline into a functioning seascape by improving the condition, extent, and connectivity of key marine and coastal habitats, using protection and restoration initiatives. At present, intensive agricultural activity in the area results in nitrate run-off to the Solent. Given this land-based run-off has contributed to significant loss and degradation of local seagrass meadows, their restoration necessitates changes to land management. The Hampshire and Isle of Wight Wildlife Trust has proposed a nitrate neutrality scheme that would entail the transition of some agricultural land to natural and semi-natural habitats such as wetlands, woodlands, or traditionally grazed meadows (Hampshire & Isle of Wight Wildlife Trust, 2020). Oyster reefs and salt marshes can further absorb and reduce excess watershed nutrients, making their concomitant restoration with nutrient reduction schemes and added value (see Box 2 on 'Water Quality').

In addition to supporting nutrient cycling and water filtration, oyster reefs enhance biodiversity and hold significant cultural heritage. Yet over 50% of the UK's native oyster population has been lost in the last 25 years, representing loss of essential marine ecosystem structure and associated functions (Preston et al. 2020). The Solent supported a robust oyster fishery of the native oyster *Ostrea edulis* from the 1970's until its closure in 2013, following drastic overfishing, invasive species (slipper limpets, *Crepidula fornicata*), water pollution and disease (Kamphausen 2012). Thus, in 2017, the Solent Oyster Restoration Project (now expanded into the Solent Seascape Project) began native oyster restoration, using innovative nurseries hung below pontoons in marinas to act as larval pumps for increasing populations. In 2021, seabed restoration began in Langstone Harbour where cultch (shell and gravel material) was laid on to the seabed to provide a home for native oysters.

Alongside restoration of oyster reefs, the Solent will benefit from restored seagrass and saltmarsh habitats that are expected to deliver biodiversity gain and build system-wide resilience to future disturbance. The Solent's integrated land-sea approach emphasises the multi-habitat nature of holistic restoration programmes, and the breadth of ecological recovery that could result, acting as a valuable model for future work within the UK.

An integrated, land-sea approach that explicitly considers spatial and historical contexts, the spatial arrangement of habitat types and their connectivity, as well as scale-effects, could help implementation of a UK seagrass carbon code. Carbon sequestration and storage is a dynamic process that is also highly heterogeneous across space with exchanges between habitats ('lateral exchange') across land and sea. Recognition of these dynamics requires a spatially explicit framework when implementing a carbon code and when scaling up actions. In addition, evidence shows that larger carbon offset projects can often be more financially viable, further bolstering the value of restoring multiple habitats across the land-sea continuum (Canning et al. 2021). Despite the urgency, ecosystem restoration initiatives have been dominated by small-scale initiatives that neglect to include the wider seascape, few of which evaluate carbon gains or the cascading site-based ecological and social consequences and have high rates of failure (Bayraktarov et al. 2016; Beheshti and Ward, 2020; Beheshti et al. 2022). It is therefore time for restoration goals to shift the focus from single habitat efforts to restoring and rehabilitating the wider interconnected system, with capacity to optimise the flow and resilience of ecosystem services and blue carbon benefits (Gilby et al. 2018; Asplund et al. 2021; McAfee et al. 2022).

Even if sufficient data and a readily implementable code existed through which UK seagrass projects could receive funding for carbon offsets, many questions would remain regarding where to prioritise future projects - a challenge that is also reflected globally (e.g., see Fair Carbon, Enabling Conditions Map). For example, varying levels of carbon offsets might be awarded for different seagrass project types (see section 3.1.2). However, not all of these project types will be possible in any given location, and where a project proponent can conduct the work will depend on a suite of environmental and social factors (e.g., local regulations, sufficient protection for project durability, public perception of seagrass habitats, risk). Work being conducted by the UK Environmental Agency and partners has already begun to tackle many of these challenges within the UK, and can be further developed and supported (The Rivers Trust, 2020; Environmental Agency 2021).

A spatially-explicit, system-wide approach as advocated by seascape and landscape ecology can support the delivery of a portfolio of viable sites, improve the evaluation of risks and predicted outcomes and reduce uncertainty in investments.

Given spatial complexities, we stand to benefit from work that considers each of these factors to identify places where opportunities for restoration investment are greatest, and where mitigation action is required to improve site suitability. For instance, we might consider a seagrass restoration use case where the goal was to improve water quality and where carbon credits could be leveraged to offset the costs of interventions to improve water quality. The application of an integrated land-sea approach to prioritise and inform the design of seagrass restoration can assist in identifying and assessing areas where seagrass restoration offers optimal outcomes and the greatest cultural and ecological suitability. A spatially-explicit, system-wide approach as advocated by seascape and landscape ecology can support the delivery of a portfolio of viable sites, improve the evaluation of risks and predicted outcomes and reduce uncertainty in investments.

3.2 Lessons learned from existing carbon codes

3.2.1 Existing carbon codes

Carbon codes for numerous habitats are emerging in the UK, endorsed by the ICROA (Table 2), which can use more advanced codes and published tools for guidance. For example, a UK Saltmarsh Carbon Code is currently being developed, using lessons learned from pre-existing UK codes and from the globally applicable Verified Carbon Standard (VCS) VM0033 code entitled a "*Methodology for Tidal Wetland and Seagrass Restoration*" (Emmer et al. 2021). The VM0033 was developed to be applicable to any geographical region, and although it may not be scalable to smaller projects, it can serve as a valuable starting point for developing regionally or nationally-specific codes, including saltmarsh and seagrass habitats.

Adopting aspects of existing UK carbon codes' regional infrastructure, governance and financing structures will also be important for a carbon credit system that meets existing national criteria and fits within Nationally Determined Contributions (NDCs). Currently, details of all projects and units issued under the Woodland Carbon Code and Peatland Code projects must be recorded in the UK Land Carbon Registry database, which stores and shares data including ownership and use of carbon units. This concept, and existing components such as auditing, verification, insurance and legal frameworks, can all be translated into codes for new habitats, including seagrass meadows. Ensuring that the general code infrastructure is consistent across habitat types will facilitate projects that involve multiple habitats, which will be increasingly important as wider, more integrated land-sea programs are developed. This can also enable larger-scale projects, which may unlock additional funding avenues.

Ensuring that the general code infrastructure is consistent across habitat types will facilitate projects that involve multiple habitats, which will be increasingly important as wider, more integrated land-sea programs are developed.

Table 2: Existing or developing seagrass carbon offset codes (top), and UK codes for any habitat type (bottom).

Carbon Code	Locale - Habitat Type	Description	References
		Seagrass Carbon Codes	
VM0033 Tidal Wetland and Seagrass Restoration (VCS)	Global - Blue Carbon (including seagrass)	Methodology is applicable to a range of project activities, restoring and creating tidal wetlands, including seagrass. Thus far, this is the only global code applied specifically to a seagrass meadow project.	Emmer et al. 2021
VM0007 – REDD+ Methodology Framework	Global - Wetlands (including seagrass)	Methodology is applicable to a broad range of activities, but with emphasis on conservation. It has not yet been applied specifically to a seagrass meadow project.	VCS, 2020
Méthode protection des herbiers de posidonie	Europe - Seagrass Meadows (Posidonia)	New methodology focused on awarding carbon credits from the protection of meadows of Posidonia oceanica in Europe, currently being piloted on a project in France (Prométhée-Med project).	Carbon Credits, 2023; Compte et al. 2023
Gold standard (in development)	Global - Blue Carbon	Methodology is an "Afforestation/Reforestation (A/R) GHG Emissions Reduction & Sequestration Methodology" applicable to mangroves, with additional development underway for other blue carbon ecosystems (including seagrass).	IUCN, 2021

Carbon Code	Locale - Habitat Type	Description	References
UK Carbon Codes			
Woodland Carbon Code (WCC)	UK - Woodland	Formally launched in 2011, the WCC is the standard for UK woodland creation projects, which generates independently verified woodland carbon units. It is internationally recognised and ICROA-endorsed for its high standards of sustainable forest and carbon management.	Woodland Carbon Code, 2022
Peatland Code (PC)	Global - Peatland	The PC is a voluntary certification standard for peatland projects and includes assurances to voluntary carbon market buyers that the climate benefits being sold are real, quantifiable, additional and permanent. Developed with the IUCN, it now has 100 projects registered in the UK. The long-term, future objective is to expand to account for wider benefits for biodiversity and water supply (hence it is called the Peatland Code, not the Peatland Carbon Code).	Peatland Code, 2022
Saltmarsh Carbon Code (in development)	UK - Saltmarsh	A UK Saltmarsh Carbon Code is being piloted by a consortium led by the UK Centre for Ecology and Hydrology. They have determined the range of carbon sequestration rates and identified evidence gaps through literature review, and are developing a model to estimate carbon sequestration from variables such as salinity, vegetation and sediment type. The code will be used to develop saleable credits at three saltmarsh restoration pilot sites.	Mason et al. 2022
UK Farm Soil Carbon Code (UKFSCC)	UK - Farmland	The Sustainable Soils Alliance is developing a UK code for verifying increased soil carbon storage due to sustainable farming practices (e.g., cover crops, reduced tillage, addition of compost, etc.). It aims to deliver a set of minimum requirements so that it is usable by small farm businesses. A first version has been provided for consultation with stakeholders.	sustainablesoils.org/soil-carbon-code
Hedgerow Carbon Code	UK - Hedgerows	The Allerton Project is developing a code which will estimate the carbon stored in above and belowground vegetation (and eventually also in soils) based on the length, width and composition of a hedge, and also project the future impact of a given management regime (i.e., trimming frequency and height, etc.)	The Allerton Project, 2023

Wilder Carbon	UK - Woodland, Grassland and Fen	Wilder Carbon Standards aim to deliver high quality conservation projects with long-term carbon lock-up and real biodiversity gains. These projects are matched to approved UK buyers who are demonstrably reducing their own emissions.	wildercarbon.com
Pre-investment work on a Seagrass Carbon Code	UK - Seagrass	Funding from the Natural Environment Investment Readiness Fund (NEIRF) has recently been awarded to Plymouth City Council towards development of a Seagrass Carbon Code. Ofwat has provided additional support to Oxford University and Project Seagrass to support code development. Cornwall County Council are also working on a NEIRF Habitat Bank project that includes a pilot project to investigate the legal position of owning and charging for carbon sequestration and other ecosystem services from the seagrass within Falmouth Harbour, how these ecosystem services can be accredited and the practicality of selling them within the current market	NEIRF, 2022
Pre-investment work on kelp carbon potential market	UK - Kelp	The Sussex Kelp Restoration Project and Sussex IFCA are developing a NEIRF kelp research and trials programme in support of a “pre-investment” proposition for kelp carbon sequestration, while working in partnership with the Crown Estate to develop a trial “seabed lease for nature” and a charitable trust to create the necessary governance framework. They aim to develop a diversified “blue” portfolio to unlock multiple avenues for revenue generation for schemes across the land and seascape.	NEIRF, 2022

While the framework for infrastructure, governance and financing aspects of a seagrass carbon code can be based on other existing UK codes, there are some aspects of code development that will be unique to each habitat type. The process of estimating carbon gains in a woodland project will look very different from the process in a seagrass meadow, partly due to the underlying biogeochemical processes. For instance, much of the carbon sequestered in woodland projects occurs via growth or preservation of living biomass, while in seagrass meadows the majority of carbon is sequestered in underlying sediment. In these cases, using existing codes from other global locales from the same habitat type, such as VM0033, can be immensely beneficial given they have already robustly determined which essential carbon fluxes need to be measured for accreditation.

Lessons can also be learned from the shortcomings of past carbon codes, that do not always ensure the delivery of simultaneous biodiversity benefits. For example, many offset projects globally have resulted in large scale planting of non-native, monoculture tree plantations, with little or no biodiversity benefit or even adverse impacts (Lewis et al, 2019; Seddon et al. 2021). Not only does this miss the opportunity to address climate and biodiversity targets simultaneously, but biodiversity and habitat connectivity are crucial for underpinning long-term habitat resilience in the face of environmental change (Seddon et al. 2021). One emerging UK initiative, Wilder Carbon, offers 'Conservation Grade' carbon credits from habitat restoration projects run by approved partners that have been explicitly designed to deliver both carbon and biodiversity benefits, while ensuring buyers are committed to reducing their own emissions and have a credible plan to achieve net-zero emissions.

As the UK progresses towards a seagrass carbon code, learning from and incorporating the best aspects from domestic codes for other habitat types and global seagrass codes will facilitate more efficient and rigorous code development.

Through this integrated approach, we should aim for a UK seagrass carbon code that is not so complex as to be too difficult to apply, yet is rigorous enough to confidently estimate carbon offsets gained through seagrass restoration and protection (Lovelock et al. 2022). While such a process will be iterative, other countries and codes have now paved the way to reduce overall timelines for code uptake.

SCUBA divers collecting seagrass cores to estimate how much carbon is stored in their rich, underlying sediments

3.2.2 Carbon code criteria

A carbon code should enable a reliable estimate of the amount of carbon sequestered due to project implementation. There are many necessary components of a carbon code to ensure that it is accurate and scientifically rigorous (see Table 1). For example, independent validation and verification is needed to demonstrate that projects are responsibly and sustainably managed, so that carbon buyers are assured that they have invested in responsible schemes and can foresee provided benefits (OECD, 2001; Needelman et al. 2018). As a NbS, carbon codes should follow standards such as the IUCN Global NbS Standard or the recently-launched "High Quality Blue Carbon Principles and Guidance". Quality standards and guidance for domestic codes are also evolving within the UK (The Nature Investment Standards Programme).

These standards can ensure that projects are equitable, sustainable and well-governed, and that a future Seagrass Carbon code aims to:

1. Safeguard nature
2. Empower people and communities
3. Employ the best information and carbon accounting principles
4. Operate contextually and locally
5. Mobilise high integrity capital

We summarise these key principles below to help guide future development of a UK seagrass carbon code (Table 3).

Existing UK Carbon Codes also draw from Clean Development Mechanism (CDM) tools, which help to further identify and quantify essential elements required for any carbon code. For instance, CDM guidance requires that saltmarsh and woodland projects demonstrate a range of key elements such as 'additionality', 'permanence' and many other criteria (Table 1) (OECD, 2001; VCS, 2012; UNFCC, EB 35). For a seagrass restoration project, additionality would be demonstrated if carbon credit financing enabled a new seagrass area to be restored, with funds facilitating a change from the "business as usual" scenario where no seagrass restoration would have occurred (Gillenwater, 2012). These carbon code elements and requirements must be similarly incorporated into a future UK seagrass carbon code, as well as seeking endorsement from ICROA to ensure the carbon credits are of the highest quality (a process which will require input and cooperation from both Defra and the EA, see Table S1).

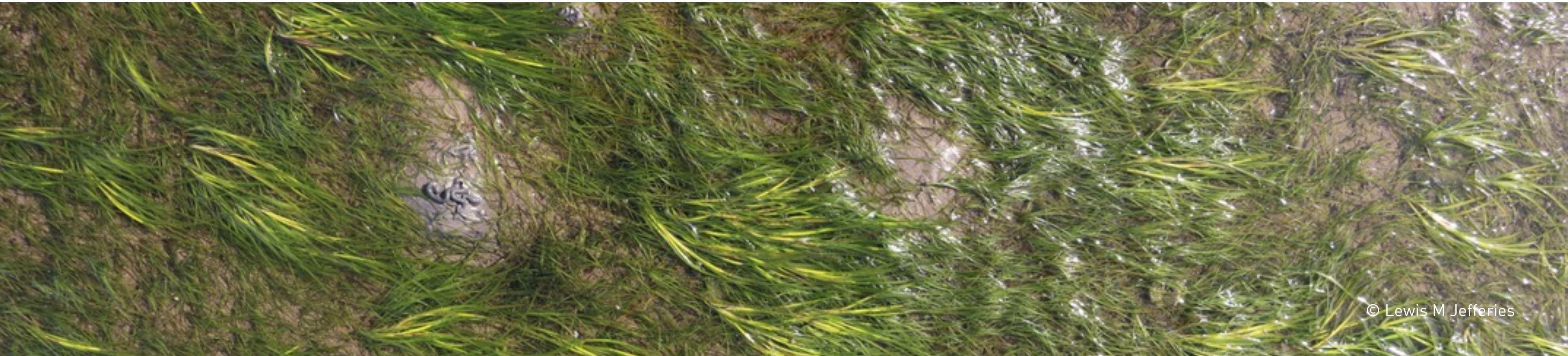


Table 3. Summary of general components required for a robust carbon code, as evidenced by development of other carbon codes (detailed within Table 2).

Component	Description
Eligibility	Rules defining eligible organisations, locations, habitat types, project types, restoration / protection / management methods, project timescales (start / finish dates), land ownership or licensing.
Consultation	Rules defining necessary stakeholder engagement and consultations required by projects, and criteria for demonstrating that all relevant stakeholders have been approached, dialogue has taken place and equitable solutions to any conflicts have been agreed where reasonable and appropriate.
Additionality	Criteria for demonstrating that the project would not have gone ahead without carbon credit funding. Criteria on whether and how to allow stacking of multiple benefits.
Double counting	Demonstrate that double counting of benefits has been avoided. In the UK, ensuring that credits only occur once on the UK Carbon Registry, and that they are cancelled or retired at the appropriate time (e.g., after being claimed as offsets in company reports).
Measurement and monitoring	Procedures for measuring baseline state of the ecosystem and ongoing changes (survey methods, etc.)
Methodology for quantifying benefits	Calculator for estimating net carbon sequestration over the course of the project and any wider benefits being taken into account.
Management plan	Definitions of must be included in project management plans.
Verification, validation and accreditation	Procedures for accrediting approved organisations who can approve the plan and verify the delivery of the carbon reductions. Procedures for verification and validation of projects and their benefits. Data collection and record keeping requirements.
Permanence	Agreed commitments to ensure longevity of the carbon sequestered and stored for an agreed period. Identification of risk and allowance of a buffer for risk of reversal due to ecosystem damage (e.g., from ocean warming, bottom trawling, coastal development, dredging, unregulated fishing and land-based sources of pollution).
Leakage	Plan to demonstrate that leakage through damage to other habitats outside the project area has been avoided.
Customer verification	Criteria for approving buyers including net-zero commitments, avoidance of certain activities and anti-money-laundering checks.
Statements	Agreed wording for credit purchasers to use when describing the benefits, and timing when they are allowed to report the benefits (e.g., after the emission has occurred and is verified).
Legal framework	Legal obligations, contract template, rules on resale of credits, etc.
Quality standards	Follow global and regional quality standards (e.g., IUCN Global NbS Standard; UK Nature Investment Standards Programme)

3.3 Financial, regulatory, and governance considerations

3.3.1 Finance

Funding is needed to support the development of a robust seagrass blue carbon code framework, including the scientific priorities identified above. This may come from government or private sources, including those organisations that recognise the demand for and need of the code. Even once a domestic seagrass carbon code has been established, the costs associated with applying the code to a project area and awarding credits include feasibility checks, implementation, monitoring, verification and validation, insurance, auditing and regulatory approvals.

Ecological restoration project costs, which could be supported by credits, can include project planning, site identification, approvals and related fees, baseline data collection, seed/shoot collection, seed/shoot processing and/or grow-out in a nursery, outplanting and ongoing monitoring to assess project success, among many other possible costs. Challenges include the high costs of permissions to work in marine habitats with complex management landscapes, which may include competing and conflicting uses inside of a proposed seagrass restoration project site. For example, some stakeholders may regard an area of seabed to have higher value without seagrass if they believe the seagrass would infringe on fishing territory, despite the fact that seagrass meadows support fisheries by acting as nursery habitat. In addition to the possibility of incurring extra costs, this potential for conflicting interests places additional importance on working within local communities to ensure local project support and sustainability.

The high costs of seagrass restoration projects could be partly, entirely or more than covered if the multiple benefits they deliver are taken into account.

High costs of restoration may limit the ability of carbon offset revenue to fully finance restoration projects. For example, a large-scale and long-term seagrass restoration project in Virginia, U.S.A., evidenced project costs ranging from US$1,200/ha to US$4 million/ha. In this case, carbon credits could have recovered 10% of the project's costs (with a voluntary market carbon price of $10/ton; a price of over $95/ton would be required for full coverage of projects costs) (Oreska et al. 2020; Orth et al. 2020; Save Our Seabed, 2021). Seagrass restoration projects are currently underway in the UK (Table S2) as well as internationally, though some projects may incur lower costs than seen in the U.S. example described above. In the case of the Life ReMEDIES and Ocean Conservation Trust seagrass restoration project, costs are an estimated £5.2 million (US$7.1 million), or about £650,000/ha (US$887,500/ha) (Norris et al., 2021).

Estimates of the potential contributions from carbon credits towards project costs will vary as the carbon market develops and the price of carbon fluctuates, and in relation to the project's scale and total costs. Due to the higher risk of reversal (from loss of carbon due to ecosystem damage) in some NbS offset projects, rigorous and frequent auditing and monitoring is required, making them more expensive compared to other types of carbon market projects (e.g., clean energy projects) (Sylvera, 2022). Data collection of numerous parameters - frequently across a decade of a restoration project's life to meet a blue carbon code's criteria - may not be financially feasible for many projects to support over the long term. Collecting data early and consistently throughout pilot projects may help to reduce this need by establishing standards, making the production of an implementable carbon code with streamlined methodologies possible (see section 3.1).

One possibility is the significant investment in nature recovery being made by climate philanthropies, whose funds could similarly support seagrass restoration projects (Gagern and Kapsenberg, 2021). Although having a carbon code is not mandatory for philanthropic investments in seagrass, a code could nonetheless guide the monitoring of these projects, allow project proponents to leverage additional funds and more broadly, maximise opportunities for other avenues to support seagrass restoration and protection. Similarly, although beyond the scope of this review, potential stacking or bundling of biodiversity credits (e.g., Natural England's Biodiversity Net Gain Scheme; Planning Advisory Service, 2022) or water quality credits (e.g., under the Nutrient Neutrality scheme) with carbon credits also offer alternative investment avenues. The high costs of seagrass restoration projects could be partly, entirely or more than covered if the multiple benefits they deliver are taken into account. However, there are currently strict additionality criteria that limit the scope to stack payments for multiple benefits. This highlights the need to incorporate additional quality criteria into a carbon code framework to ensure that projects deliver benefits for biodiversity, ecosystem health and local communities, in addition to carbon storage. Even if multiple benefits cannot be explicitly stacked, demonstrating these additional benefits could enable marketing of 'Premium' combined nature and carbon credits at higher prices, as is done by Wilder Carbon.

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3.3.2 Regulations and governance

As described in section 2.5, a large number of agencies may be involved in seagrass restoration, conservation, and blue carbon credit projects (Table S1 and Figure 3). This can make it challenging to determine jurisdiction or identify the overarching authority, which may mean that permitting and implementing seagrass restoration, management and potential seagrass carbon offset projects are complex and at times, costly. Thus, partnering with organisations already engaged in navigating these processes can help to support the establishment of a seagrass carbon code.

Numerous agencies have commissioned reports and taken positions on the potential investment in blue carbon and implementation of blue carbon codes (e.g., The Parliamentary Office of Science and Technology, 2021; AAPG, 2022). In the last few years, the UK government's Natural Environment Readiness Fund (NEIRF) has supported steps towards the development of a Saltmarsh Carbon Code, a UK Farm Soil Carbon Code, a Hedgerow Carbon Code, a Carbon Bank for woodlands, a kelp restoration and carbon storage project and most recently, a project supporting the early development of a seagrass carbon code (Table 2). Blue Marine Foundation and The Crown Estate have also commissioned Finance Earth and Pollination to lead an initiative to establish a vision for a marine natural capital market in the UK. The initiative aims to build consensus around priority barriers and solutions to a healthy UK marine natural capital market and design a roadmap to market development. An initial scoping period is underway and will be followed by a detailed second phase in 2023, with plans to publish a roadmap ahead of COP28. Also of note, Defra is facilitating the UK's Blue Carbon Evidence Partnership, whose stated aims are to "facilitate coordination and collaboration across UK administrations and progress the evidence base on blue carbon habitats in the UK by addressing key research questions related to blue carbon policy, thus advancing the UK's commitment to protecting and restoring blue carbon habitats as a nature-based solution" and "work to ensure that the UK has a joint and robust shared scientific understanding of blue carbon" (Cefas, 2020).

Despite these policies and initiatives, significant regulatory support is still needed to build a robust accreditation program that bolsters seagrass project implementation and ensures persistence of projects on relevant timescales. For example, the UK's first seagrass restoration project in Dale Bay, Wales (Table S2) has faced regulatory barriers from high licensing or lease fees, which were originally designed for damaging or extractive activities such as dredging or trawling. This could be addressed through the introduction of a policy - adopted by national regulators such as Natural England, Nature Scot, and Natural Resources Wales - that allows seagrass restoration projects meeting pre-approved criteria to bypass the normal regulatory pathway for allowing operations on the seabed. Similarly, the Crown Estate could authorise expedited seagrass restoration projects in approved locations inside their territorial sea bed boundaries with prior agreement to waive costs or approval requirements for activities that would normally incur a lease fee.

From a protection standpoint, seagrass meadows can be protected within the UK's 91 Marine Conservation Zones (MCZ). However, current MCZ designations may still allow for ongoing fishing practices, such as bottom trawling, that may damage seagrass habitats and release the carbon trapped in underlying sediments. Without regulatory changes, such practices could potentially put seagrass projects and any associated carbon offsets at risk. Recently, UK policy instruments (Sussex Nearshore Trawling Byelaw) supported a 200km2 kelp rewilding project to protect the nearshore seabed along the Sussex coast from bottom trawling. This action will prevent further degradation and allow kelp recovery over time, especially with the additional support provided by the River Adur 'Landscape Recovery' project to reduce agricultural runoff that might have hindered kelp recovery. This integrated approach stands as an example for other IFCAs to protect seagrass meadows and their blue carbon stores.

The UK's first seagrass restoration project in Dale Bay, Wales has faced regulatory barriers from high licensing or lease fees, which were originally designed for damaging or extractive activities such as dredging or trawling.

Broad lessons about the effective management, restoration and protection of seagrass can be learned from other global locales. In the U.S. state of Florida, the state government has designated areas available for restoration without charge. In many states, developers are required to fund seagrass restoration projects, as seagrass mitigation[8] is typically a condition of approval for private or public development projects that may harm seagrass (Rezek et al. 2019). Due to protections that call for no-net-loss of seagrass, California's history of seagrass restoration is far longer than the UK's. Specifically, a state policy (the California Eelgrass Mitigation Policy) requires that any project resulting in the loss of seagrass must mitigate at a 1.2:1 ratio (National Marine Fisheries Service, 2014). This policy has yet to include clauses requiring mitigation for carbon losses, as it only protects the seagrass itself. Even so, it can serve as a robust example of how policy instruments might be used to facilitate progress on seagrass management and could tie into future seagrass carbon codes.

Additional existing UK policies and targets could be leveraged to drive and inform needed support for seagrass restoration and carbon offset framework development. These include the commitment to deliver net zero carbon by 2050 and Defra's (Table S1) commitment to protect 30% of UK land and seas for nature by 2030. For example, peatland and woodland habitats are supported by well-developed policies that will ensure future continuation of habitat restoration and expansion projects, and that these projects are linked to robust and fully operational carbon credit systems. Local authorities can also play active roles as partners and leaders in seagrass restoration projects. The water industry is looking to offset current operations and reduce and minimise water quality impacts (Box 1) using NbS, with seagrass restoration included as one viable avenue. Collaborative, cross-jurisdictional efforts that engage policymakers, managers, restoration practitioners and community groups can therefore help to identify policy and governance needs for improved seagrass restoration and carbon offset code development, while simultaneously supporting the UK in reaching its climate and biodiversity goals.

[8] In compliance with the "no net loss" wetlands policy outlined in Section 404 of the U.S. Clean Water Act

4. CONCLUSION AND RECOMMENDATIONS

While the majority of seagrass habitat in the UK has been lost, the remaining areas are essential for supporting fisheries, retaining biodiversity and improving water quality (Unsworth et al. 2021). These valuable ecosystem services can be further maximised when nested within a healthy coastal land-sea continuum, exhibiting continuity with other habitats such as oyster reefs and saltmarshes. Thus, the need for holistic seagrass restoration and protection throughout the UK is clear and has been recognised by various governmental and other bodies, with steps toward action being implemented only recently. Although the UK seagrass restoration projects were only first implemented in 2019, there are now a large number of ongoing initiatives and projects occurring (Fig. 1; Table S2), representing a tremendous amount of progress and growth towards nature recovery.

As a result of the increasing development and prevalence of carbon markets and demand for blue carbon credits in the private sector, new funding streams are becoming available to support seagrass restoration projects while enabling funders to meet carbon offset or other climate goals. This requires a carbon code that ensures projects are equitable, ecologically sound, sustainable and rigorous in their evaluation of awarded carbon credits.

The code must be consistent with the UK's existing carbon offset frameworks, yet not be so complex that implementation proves too costly to support wider uptake. Balancing these needs will be a challenge, but one that organisations around the world are starting to address.

As a result of the increasing development and prevalence of carbon markets and demand for blue carbon credits in the private sector, new funding streams are becoming available to support seagrass restoration projects.

4.1 Key recommendations

To lead the way to an implementable, feasible and rigorous seagrass carbon code, we make several key recommendations to develop and build upon existing work:

1. Fill existing data gaps, both internationally and within the UK. This should include:

    a. Improved data on seagrass spatial extent and condition (e.g., Howard-Williams, 2022; Burrows et al. 2021; The Rivers Trust 2020).

    b. Data on net carbon sequestration through time, with respect to a pre-restoration baseline.

    c. Data on methane and N_2O emissions from intact and restored seagrass over time.

    d. Data on the restoration outcomes (i.e., gains in carbon, biodiversity and ecosystem services) from various approaches such as seeding, planting, use of dredged material and reduction of pollution.

2. Seagrass mapping and site context information (including ecosystem services assessment) should be used to prioritise carbon sequestration and biodiversity hotspots for coastal conservation or restoration (Wedding et al. 2021; Gilby et al. 2021; Pittman et al. 2022).

3. The code must include the key components required for other approved, evidence-based carbon codes, translated to apply to seagrass habitats, such as additionality, permanence, a project registry and a feasible system for monitoring and verification of credits (Table 1).

4. These components must be compatible with the UK's existing financial, regulatory and governance structures for both carbon sequestration and nature recovery. This will enable future offset projects to be included in national climate mitigation, adaptation and biodiversity targets, and into wider, multi-habitat projects across land- and seascapes.

5. Policy and regulatory barriers should be addressed to create an environment that enables seagrass management, restoration and protection. This might include adjusted permitting processes, improved seabed protections and implementation of compensatory mitigation to account for loss or degradation of seagrass and seagrass ecosystem functions.

6. In line with other emerging carbon codes (e.g., Peatland Code, Wilder Carbon, Table 1), a Seagrass Code should use a more regenerative approach, including criteria beyond carbon to guarantee the delivery of wider benefits for biodiversity, ecosystem health and people.

7. The code should seek to ensure that credit purchasers are already making strenuous efforts to reduce and avoid GHG emissions, only using carbon credits to offset residual emissions that cannot be feasibly addressed at the time of purchase (as in Wilder Carbon, Table 1).

As the UK reaches for an adoptable seagrass carbon code, lessons from previously developed codes can aid in ensuring effective incorporation of the wider seascape, ecosystem health and consideration of the unique social and governance contexts in which a code must operate. If the UK takes a targeted, careful and coordinated approach to address the gaps identified herein when developing a code, the nation will be well-poised to channel funding towards domestic projects that enable the rigorous use of carbon credits, whilst supporting biodiversity and ecosystem services, and progress towards restoration and emissions targets.

SUPPLEMENTARY INFORMATION

Supplementary Table 1: UK Governance: Key regulatory organisations, authority and relevance to seagrass restoration and blue carbon projects. Other stakeholders and regulatory bodies may exist for individual projects based on location- and project- specific jurisdictions and authorities.

Role	Stakeholder	Authority	Relevance to Seagrass and Blue Carbon Projects
Keystone organisation / department	Department of Environment, Fisheries and Rural Affairs (Defra)	Defra is a ministerial agency supported by 31 agencies and public bodies. Defra contains two non-ministerial departments - the Forestry Commission and the Water Services Regulation Authority (Ofwat). The remaining executive non-departmental public bodies (as described below) are responsible for marine management, and may present with overlapping authority in relation to seagrass management and protection.	Defra provides project funding, including for research and data collection. Examples include the Natural Environment Investment Readiness Fund (NEIRF), which supported Cornwall Council's Blue Natural Capital project; and Green Recovery Challenge Fund, for nature-based solutions with seagrass restoration (e.g "Blue Meadows" project).
Executive agencies	Centre for Environment, Fisheries and Agricultural Science (Cefas)	Cefas is one of four Executive Agencies under Defra, and is tasked with keeping the seas, oceans and rivers healthy and productive, and seafood safe and fisheries sustainable. Cefas works with Defra to provide data and advice to the UK Government and overseas partners. Cefas responsibilities include: surveying, mapping, sampling, and monitoring marine health; informing environmental planning, management and decision making for UK marine conservation and protection.	Cefas may survey, monitor and map seagrass within the UK. For example, Cefas conducted a Risk Assessment for intertidal Seagrass under the UK Marine Management and Assessment Strategy.

Role	Stakeholder	Authority	Relevance to Seagrass and Blue Carbon Projects
Executive non-departmental public bodies	Natural England (NE)	A non-departmental public body that holds an advisory role for marine management in English territorial waters (i.e., out to 12 nautical miles) particularly in regards to proposed activities within Marine Conservation Zones (MCZs).	Projects requiring approvals within or adjacent to MCZs and Sites of Special Scientific Interest (SSSIs) such as seagrass habitat and restoration areas must consult NE. Seagrass mapping information is available for English waters - current and historic geospatial datasets - a result of a collation of the available data by NE and EA (Natural England, 2022)
	Joint Nature Conservation Committee (JNCC)	A public body responsible for managing conservation in the offshore marine environment (12 nm to 200 nm). Acting in the role of Statutory Nature Conservation Body (SNCB), the JNCC advises the government and administration (e.g., Defra) on national and international conservation matters, including in the UK overseas territories. Within territorial limits, each country's nature conservation body advises the government (e.g., in Wales it is Natural Resources Wales, rather than the JNCC.)	Holds an advisory role for ensuring effective management of MPAs, which may contain seagrass. JNCC launched the MPA online mapper, an interactive resource for spatial data on 350+ MPAs in the UK network. In the JNCC's UK Biodiversity Action Plan , seagrass is listed as a Priority Habitat. Other JNCC reports include seagrass assessments and identifying impacts on seagrass (d'Avack et al. 2014)
	Inshore Fisheries Conservation Authorities (IFCA)	Ten IFCAs uphold the statutory regulations for management of inshore coastal fisheries and protection of MCZs within each district up to 6nm from England's coastline, along with related estuarine and fisheries resources The Marine Management Organisation, Environment Agency and Natural England each have a statutory seat on the IFCA.	IFCAs manage coastal areas, which are potential seagrass habitats. Each IFCA can introduce bylaws to manage fishing activities in their district, for example, by implementing measures such as prohibiting bottom trawling or shellfish dredging. In addition, IFCA can put management measures in place in support of seagrass protection and restoration to maintain healthy sustainable fisheries.

	Environment Agency (EA)	An executive non-departmental body sponsored by Defra. EA's management responsibilities in England include: water quality and resources, fisheries, conservation and ecology. Strategic action plan includes focus on climate resilience and adaptation, and creating healthy land, air and water by increasing biodiversity and improving the environment. Responsibilities for other UK regions lie with the Scottish Environment Protection Agency, Natural Resources Wales, and Northern Ireland Environment Agency. EA is the UK's Designated National Authority (DNA) and is responsible for determining applications for the approval of Clean Development Mechanism projects.	English EA is leading the ReMeMaRe project to restore saltmarsh, oysters & seagrass habitat. The EA's NEIRF provided funds to help develop operational domestic carbon codes (e.g., the Peatland and Woodland Codes). EA delivers the UK's 25 Year Environment Plan for England, launched in 2018. Relevant targets include marine restoration, healthy habitats and productive marine ecosystems; net zero GHG emissions by 2050; clean water; and achieving protection of 30% of the world's oceans by 2030 (30 x 30). Plan goals can support seagrass restoration and blue carbon credit development.
	Marine Management Organisation (MMO)	An executive non-departmental public body sponsored by Defra, supported by partnerships with NE and Cefas, and working closely with others like IFCA. MMO acts as the independent manager and regulator of England's seas, to protect and enhance the marine environment. By providing the licensing and regulatory framework, the MMO oversees marine planning, balancing marine environmental protection with marine industry activities such as sustainable fisheries, and offshore energy production.	MMO has the power to make byelaws which can prohibit or restrict activities inside of MCZs. For example, to ensure protection of the seabed, the MMO could prohibit activity such as anchoring to protect seagrass meadows. MMO develops policy instruments. For example, UK Marine Online Assessment Tool for surveying and monitoring extent of intertidal seagrass (Phillips et al, 2018)
	Office for Environmental Protection (OEP)	A new public body under Defra set up to protect and improve the environment by holding government and public authorities to account.	OEP is a watchdog that tracks government funded projects to ensure performance and compliance. This could include future seagrass projects funded for blue carbon accreditation.

Role	Stakeholder	Authority	Relevance to Seagrass and Blue Carbon Projects
Non-ministerial departments	Forestry Commission	One of Defra's non-ministerial departments, and responsible for protecting, expanding and promoting the sustainable management of woodlands.	The Forestry Commission helped to develop the Woodland Carbon Code (WCC), the UK's government backed standard for woodland carbon projects, from which new blue carbon codes may be adapted / developed.
	Water Services Regulation Authority (Ofwat)	One of Defra's non-ministerial departments and serves as the economic regulator for the water and sewerage sectors in England and Wales.	Ofwat supports seagrass restoration projects through funding provisions.
Wildlife management outside of England	Natural Resources Wales	A Welsh Government sponsored body that is responsible for the management of natural resources in Wales, oversees activities, reviews applications and issues marine licences. Natural Resources Wales may continue to refer to guidance produced by the Environment Agency.	Natural Resources Wales issues licences to allow for seagrass restoration activity in Wales.
	Marine Scotland	A directorate of the Scottish Government that manages Scotland's seas and freshwater fisheries along with delivery partners, NatureScot and the Scottish Environment Protection Agency.	Marine Scotland issues licences for inshore and offshore marine activities and ensures protection of species. Seagrass is considered a Priority Marine Feature (PMF) with 27 seagrass meadows protected in MPAs in Scotland. Records of seagrass distribution are available on Scotland interactive national marine plan.
	NatureScot (formerly Scottish Natural Heritage)	NatureScot acts as Scotland's Nature Agency and is responsible for wildlife licensing.	NatureScot issues permissions to enable seagrass restoration activity in Scotland (e.g., seed collection/translocations). They produced a study report to assess the carbon budgets and potential blue carbon stores of the coastal and marine environment around Scotland (Burrows et al. 2014)

Role	Stakeholder	Authority	Relevance to Seagrass and Blue Carbon Projects
	Department of Agriculture Environment and Rural Affairs (DAERA)	Oversees natural resources in Northern Ireland with additional protection measures implemented through designations of areas as MCZs	DAERA published the Northern Ireland Habitat Action Plan (2003) that called out the importance and need to protect seagrass meadows and initiated protection of 1500 Ha in Areas of Special Scientific Interest. DAERA seeks to develop a blue carbon action plan and support further seagrass habitat protection and restoration projects.

Supplementary Table 2: Seagrass restoration initiatives and related blue carbon projects in the UK. Project coverage goals are reported in hectares (Ha).

Title	Purpose	Location	Partners & Funding Support
Seagrass Seeds of Recovery	Goals: In addition to conducting seagrass restoration trials, this project will pilot a Seagrass Nursery and aid in development of a UK seagrass blue carbon code framework to enable carbon credits for the water industry and beyond	Stour Estuary in Essex and Suffolk Orwell Estuary in Suffolk Blackwater Estuary in Essex	Led by Affinity Water with Anglian Water Services Ltd, Project Seagrass, Department of Biology and Wadham College, University of Oxford, Natural England, Environment Agency, Salix River & Wetland Services, University of Essex Funding: Ofwat Innovation Fund
Seagrass Ocean Rescue (SOR)	Goals: Plant 2 Ha seagrass in Dale Bay as a pilot, followed by scaling up to sites in Wales and England. "The first full scale seagrass restoration project in the UK. Over the 2 years of the project, 1 million seeds were planted over a 2 Ha area (approximately two rugby pitches) in Dale, West Wales." - Project Seagrass	Wales and England 2019-2021 Pilot: Dale Bay, Pembrokeshire (W Wales), restore 2 Ha 2021-2026 Phase 2: Porthdinllaen, North Wales (N Wales). Plant 5m seeds, restore 10 Ha Large scale experimental trials in Solent, England.	Partners include WWF UK, Cardiff University, Swansea University, Project Seagrass, Pembrokeshire Coastal Forum, Pen Llŷn a'r Sarnau SAC, North Wales Wildlife Trust Funding: National Lottery Heritage Fund, Sky Ocean Rescue and WWF
Solent Seagrass Project	Goals: Restore seagrass to its historical levels in all locations throughout the Solent where possible, including volunteer and community engagement	England: Throughout the Solent.	Hampshire & Isle of Wight Wildlife Trust in partnership with Boskalis Westminster, Ltd

Title	Purpose	Location	Partners & Funding Support
Life Recreation ReMEDIES (Reducing and Mitigating Erosion and Disturbance Impacts affecting the Seabed) Project - Save Our Seabed	Goals: Conduct intertidal and subtidal habitat restoration, including seagrass meadows (8 Ha) and demonstrate management techniques inside of five Special Areas of Conservation (SACs) in the south of England, which are also Natura 2000 sites.	Five Special Areas of Conservation (SAC) 1. Essex Estuaries 2. Plymouth Sound & Estuaries (2.5 Ha) 3. Solent Maritime, Isle of Wight (1 Ha) 4. Fal & Helford 5. sles of Scilly	Led by NE under EU LIFE Programme in partnership with JNCC, Natura 2000, Royal Yachting Assoc., Marine Conservation Society, Ocean Conservation Trust, Wildlife Trusts, Plymouth City Council and Tamar Estuaries Consultative Forum Funding: EU Life Fund £1.5 million w/ £1 million match funding from NE & other partner organisations. See Howard-Williams, 2022.
Solent Seascape Restoration	Goal: To reconnect 522 km² of the Solent's coastline into a functioning seascape by improving the condition, extent, and connectivity of key marine and coastal habitats, using protection and restoration initiatives.	England: The project within the Solent's major shipping lane, spanning ~522 km²	A multi-partner project, involving Blue Marine Foundation, RSPB, Hampshire & Isle of Wight Wildlife Trust, Project Seagrass, Natural England, EA, Coastal Partners, Isle of Wight Estuaries Project, Chichester Harbour Protection and Recovery of Nature (CHaPRoN) and University of Portsmouth. (£5 million over 5 years)
Seeding Change Together	Goals: Expand an existing seagrass bed (Z. marina and Z. noltii species). Conduct seed collection and test restoration methods.	Fal Ruan Estuary at Cornwall Wildlife Trust's Fal Ruan nature reserve	Led by Cornwall Wildlife Trust & Funding: Seasalt Cornwall (£150k over 3 years)

Title	Purpose	Location	Partners & Funding Support
Seawilding	Goal: 80 Ha identified for seagrass restoration, with co-restoration of native oysters. UK's first community led project and Scotland's first seagrass restoration project. Used hessian bags filled with seagrass seeds. 2021: ¼ Ha restored w/ 120k seeds collected and planted in bags; restored native oysters (300k).	Scotland: Loch Craignish, Argyll Scotland (1/2 Ha total by 2022)	Partners: Project Seagrass; Scottish Association of Marine Science (SAMS); Heart of Argyll Wildlife Organisation; Ardfern Yacht Centre Funding: The Crown Estate and Scottish Government's Nature Restoration Fund managed by NatureScot
Restoration Forth	Goal: Co-restoration of 4 Ha of seagrass and 30,000 native oysters by 2024. This work includes habitat suitability assessments and comprehensive stakeholder consultations to determine sites and work within communities.	Firth of Forth Scotland	Partners: WWF UK, Project Seagrass; Marine Conservation Society, Fife Coast & Countryside Trust; The Ecology Centre, Edinburgh Shoreline Project; Heriot Watt University; Royal Botanic Garden Edinburgh, Scottish Seabird Centre; The Heart of Newhaven Community and Wardie Bay Beachwatch Funding: £2.4M with funding support from Aviva, the ScottishPower Foundation, the Moondance Foundation and supported by the Scottish Government's Nature Restoration Fund, which is facilitated by the Scottish Marine Environmental Enhancement Fund and managed by NatureScot.

Title	Purpose	Location	Partners & Funding Support
ReMeMaRe: Restoring Meadow, Marsh and Reef	Goals: A habitat restoration initiative to restore 15% of three priority coastal habitats in England by 2043: seagrass meadows, saltmarshes and native oyster reefs, in line with the 25-Year Environment Plan. Project outcomes: Seagrass Restoration Handbook (2021); Restoration project maps (The Rivers Trust, 2020); research into blending financial models of public, private and third-party investment to support restoration projects.	England	Led by the Environment Agency. Project partners include a steering committee: IFCA, Cefas, The Crown Estate, DEFRA, EA, JNCC, MMO, NE and NRW; and environmental organisations for restoration of England's estuaries and coast: BMF, Coastal Communities Alliance, Coastal Partnerships Network, Institute of Fisheries Management, LGA Coastal SIG, MCS, National Trust, New Economics Foundation, RSPB, Project Seagrass, The Wildlife Trusts, Wildlife and Countryside Link, WWF, WWT, Zoological Society London
Tees River Trust	Goals: To restore seagrass using a combination of seeding (bags) and transplanted shoots, along with co-restoration of native oysters.	England: Tees Estuary	Sits within the EA Stronger Shores initiative, with funding from Defra.
Yorkshire Wildlife Trust	Goals: Collect and plant seagrass seeds across a 9.8 acres pilot area by 2023 (phase one). Further restore up to 74 acres (phase two) - currently the largest proposed UK seagrass restoration project.	England: Humber Estuary	Funded by the Green Recovery Challenge Fund, developed by Defra, with partners Natural England, the EA, and Forestry Commission.

Title	Purpose	Location	Partners & Funding Support
Blue Meadows	Goals: Conserve, protect, & restore of 700 Ha of seagrass (10% of UK's total) over 5 years with a purpose built seagrass nursery facility (largest within the UK). Ocean Conservation Trust (OCT) plans to measure seagrass health & growth, biodiversity, and carbon storage. Duration: 3 years	Falmouth, Cornwall (phase one, 20 Ha) Torbay, Devon (phase two), including seagrass nursery. (with additional plans pending)	Lead: Ocean Conservation Trust (OCT) Partners: Harbour Authorities, businesses and scientific partners at Imperial College, Keele and Plymouth Universities; Nature Metrics; Salix; Falmouth Harbour (SHA); MDL Marinas; Torquay & Torbay Nursery funded by the Green Recovery Challenge Fund (DEFRA)
ReSOW UK: Restoration of Seagrass for Ocean Wealth	Goals: Develop a decision support tool to identify where and how to restore seagrass with maximum benefits and success, and integrate it into sustainable marine management for social, environmental & economic net gains in the UK. Creating spatial, social-ecological, and natural capital accounting tools. Refine seagrass maps to regional and local levels to identify best sites for future seagrass restoration at a national scale.	UK-wide	National Oceanography Centre, Project Seagrass, Swansea University, Stirling University, MMO, EA,NRW, GOAP, NE, Coastal Communities Network, Scotland. Funded by: Sustainable Management of Marine Resources (SMMR)
UK Blue Carbon Mapping Project	Goal: Produce a complete map of UK blue carbon stores. The UK Blue Carbon Mapping project will complete research in three regional phases. A final UK-wide report is due in 2023 (see Burrows et al. 2021).	Three UK Regions & Phases: 1. English Channel & Western Approaches 2. Irish Sea 3. Scotland	Led by SAMS Funded by: North Sea Wildlife Trusts, WWF, Blue Marine Foundation and RSPB. (Burrows et al. 2021)

Title	Purpose	Location	Partners & Funding Support
Blue Natural Capital Project	Goal: Determine carbon sequestration potential of mapped seagrass meadows in Cornwall. Aim: to provide NbS including carbon storage in support of Cornwall's aim to become carbon neutral by 2030	Seagrass areas in Cornwall, England: 1. Fal Estuary 2. Helford River 3. Mounts Bay	Led by Cornwall County Council University of Exeter analysis with Cornwall IFCA conducting seagrass surveys Funding: Natural Environment Investment Readiness Fund (NEIRF)
Blue Carbon Resources Assessment	Goal to evaluate blue carbon storage in Jersey and identify potential for creating carbon credits	Bailiwick of Jersey	Jersey Government Universities of Exeter and Plymouth
Mapping seagrass in Shetland	Goal: Using drones and ground truthing to calculate the extent of existing seagrass meadows.	Shetland, Scotland	Led by UHI Shetland Funding: Scottish Marine Environmental Enhancement Fund (SMEEF)
Great Seagrass Survey	Goal: Locate seagrass meadows and improve mapping using support from community member	UK wide	Led by BSAC in collaboration with. Seawilding and Project Seagrass Funding: Recreational diving
Sjøgras	Goal: Using drones and ground truthing to calculate the extent of existing seagrass meadows and Biodiversity Surveys.	Orkney, Scotland	Led by Project Seagrass in partnership with Heriot-Watt University, Orkney Funding: Highland Park Whisky Distillery

Title	**Purpose**	**Location**	**Partners & Funding Support**

Manx Blue Carbon Project	Goal: To map and survey blue carbon stores around the Isle of Man, and design and implement a blue carbon management plan. It is part of the Isle of Man Government's Phase 1 Climate Change Action Plan, and 2022-2027 Climate Change Plan	Isle of Man	Led by the Department for the Environment, Food and Agriculture. Partners: National Oceanography Centre, Swansea University Funding: the Climate Change Transformation Fund.

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ACRONYMS

CDM: Clean Development Mechanism

Cefas: Centre for Fisheries and Aquatic Science

DAERA: Department of Agriculture, Environment and Rural Affairs

Defra: Department of Environment, Food and Rural Affairs

EA: Environment Agency

ICROA: International Carbon Reduction and Offset Alliance

IFCA: Inshore Fisheries Conservation Authority

JNCC: Joint Nature Conservation Committee

MCZ: Marine Conservation Zone

MMO: Marine Management Organisation

MOD: Ministry of Defence

MPA: Marine Protected Area

NbS: Nature-based Solution(s)

NE: Natural England

NGO: Non-governmental organisation

OCT: Ocean Conservation Trust

OEP: Office for Environmental Protection

Ofwat: Water Services Regulation Authority

RSPB: Royal Society for the Protection of Birds

SAC: Special Area of Conservation

SAMS: Scottish Association of Marine Science

SBTi: Science Based Targets initiative

SHA: Statutory Harbour Authority

SMMR: Sustainable Management of UK Marine Resources

SSSI: Site of Special Scientific Interest

UKFSCC: UK Farm Soil Carbon Code

VCS: Verified Carbon Standard

VCM: Voluntary Carbon Market

WCC: Woodland Carbon Code

WWF: Worldwide Fund for Nature (known as World Wildlife Fund in the USA and Canada)

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