

Exploring Sublittoral Blue Carbon Habitat Suitability and Potential in the Shetland Islands

Tanya Riley & Rachel Shucksmith

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Authors:

Tanya Riley¹ & Rachel Shucksmith¹

¹ Shetland UHI, Scalloway Campus, Port Arthur, Scalloway, Shetland, ZE1 0UN

Corresponding author:

Tanya Riley

Marine Scientist

Marine Spatial Planning Team

Shetland UHI, Scalloway Campus, Port Arthur, Scalloway, Shetland, ZE1 0UN

tanya.riley@uhi.ac.uk

+44 (0)1595 772010

<https://pure.uhi.ac.uk/en/persons/tanya-riley>

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Executive summary

This report presents the first assessment of sublittoral blue carbon habitats within the Shetland Islands 12 nm limit, evaluating their spatial extent, ecological characteristics, and potential contribution to carbon sequestration and long-term storage. Blue carbon habitats – including seagrass meadows, kelp forests, brittlestar beds, horse mussel beds and maerl beds – play a crucial role in supporting biodiversity, stabilising sediments, and mitigating climate change through the capture and retention of organic carbon (OC).

The study combined high-resolution spatial data with species distribution modelling (MaxEnt) to predict the extent of blue carbon habitats across Shetland's 12 nautical mile (nm) zone. Modelled habitat distributions were developed using presence-only occurrence data and 11 environmental predictors. Validation metrics demonstrated high predictive accuracy (AUC > 0.97, TSS > 0.79), providing high confidence in the outputs.

Key findings*:

- Blue Carbon Habitat Extent
 - Total mapped blue carbon habitats cover 19.15 hectares,
 - Habitat suitability modelling suggests a potential extent of 62 km²,
 - Seabed sediments (dominated by mixed and coarse sediments) cover 12 044 km².
- Carbon Storage Potential
 - Combined mapped and predicted blue carbon habitats carbon storage potential was estimated at 6 358 tonnes (t) OC, with a potential annual production of 7 950 t C / yr.
 - Known maerl beds are estimated to hold the equivalent of ~446 tonnes of CO₂, while Shetland's seagrass meadows could hold ~92 tonnes, with an ~6 tonnes potentially sequestered each year.
 - Carbon stored in the known blue carbon habitats is equivalent to the annual emissions of over 100 Shetland residents, or over 2.5 million miles of car travel.
 - The annual carbon capture potential of Shetland's seagrass meadows alone is equivalent to the emissions from making 149 000 cups of tea or almost 30 million internet searches.
 - Seabed sediments were identified as the dominant long-term carbon reservoir, with an estimated OC stock of 1 353 kt and an annual storage capacity of 319 kt OC / year.

Despite their limited mapped extent, blue carbon habitats demonstrate high carbon density potential, with seagrass meadows containing eight times more carbon per unit area than sand and maerl beds containing four times more.

* All carbon stock and storage capacity estimates refer specifically to the top 10 cm of sediment.

The study identified a mosaic distribution of habitats within the Shetland Island, with high-value carbon habitats concentrated in small, discrete areas within larger expanses of lower-carbon sediments. Many predicted blue carbon habitats occur within existing Shetland Shellfish Management Organisation closed areas or Marine Protected Areas, suggesting current protection measures benefit carbon capture.

This analysis highlights critical data gaps, particularly the lack of site-specific measurements for carbon density, burial rates, and habitat condition. The use of national average values introduces uncertainty, as Shetland's specific hydrodynamic and ecological conditions differ from average values derived from mainland Scotland.

Recommendations for future research include:

- Field validation of modelled habitats using benthic survey techniques,
- Direct measurement of site-specific OC content and storage rates,
- Expansion of assessment to include nearshore and intertidal habitats,
- Research into the fate of exported kelp carbon and sediment dynamics in biogenic reef habitats.

This report provides a vital foundation for informing marine spatial planning and climate policy in Shetland. By identifying and protecting key blue carbon habitats, there is significant potential to enhance the region's role in supporting Scotland's net-zero targets, biodiversity conservation, and sustainable marine management.

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Definitions and Metric Conversions[†]

Blue Carbon

The carbon captured from the atmosphere and stored in the world's oceans. This includes carbon held in the biomass and sediments of marine ecosystems including algae, seagrass, and seabed habitats such as biogenic reefs.

Carbon Sequestration

Any process (natural or artificial) by which carbon dioxide is removed from the atmosphere and held in solid or liquid form[‡].

Carbon Stock

The quantity of carbon held in a habitat pool at any specified time is the carbon stock or store[†].

Priority Marine Feature (PMF)

In July 2014, Scottish Ministers adopted a list of 81 Priority Marine Features (PMFs). PMFs are species and habitats which have been identified as being of conservation importance to Scotland. Most are a subset of species and habitats identified on national, UK or international lists. PMFs help to focus action and to achieve our vision for sustaining Scotland's seas[§].

Table i - Standard metric unit conversions*

	Symbol	Value in tonnes of carbon
<i>Gram</i>	g	0.000001
<i>Kilogram</i>	Kg	0.001
<i>Megagram (tonne)</i>	t	1
<i>Gigagram (kilotonne)</i>	Kt	1 000
<i>Teragram (megatonne)</i>	Mt	1 000 000

1 hectare = 0.01 km²

1km² = 100 hectares

1 tonne of carbon (1 t C) = 3.6663 tonnes of carbon dioxide (CO₂)^{**}

[†] Norris, C., Roberts, C., Epstein, G., Crockett, D., Natarajan, S., Barisa, K., Locke, S. (2021) 'Blue Carbon in the United Kingdom: Understanding and developing the opportunity.

[‡] Riley, T. G. and Shucksmith, R. J. (2024) *Towards Net Zero: The role of marine habitats*.

[§] Tyler-Walters, H., James, B., Carruthers, M. (eds.), Wilding, C., Durkin, O., Lacey, C., Philpott, E., Adams, L., Chaniotis, P.D., Wilkes, P.T.V., Seeley, R., Neilly, M., Dargie, J. & Crawford-Avis, O.T. 2016. Descriptions of Scottish Priority Marine Features (PMFs). Scottish Natural Heritage Commissioned Report No. 406.

^{**} Toohey, E. C. (2018) 'Carbon sequestration: how much can forestry sequester CO₂', For. Res. Eng. Int. J, 2(3), pp. 148-150.

1 Introduction

The Shetland Islands, located in the northern reaches of the United Kingdom, encompass 12 305 km² (7 645 square miles) of marine habitat within its 12 nautical mile (nm) boundary. This region is known for its diverse marine ecosystems, which support a variety of species and habitats essential for ecological stability and human livelihoods. Scotland's seas, including the waters surrounding Shetland, are recognised for their environmental importance and provide crucial ecosystem services, such as biodiversity support, carbon sequestration, and coastal protection. However, these ecosystems face pressure from human activities and the accelerating impacts of climate change, which threaten their resilience and long-term ecological health (Baxter *et al.*, 2011). As the climate changes, alterations in temperature, ocean acidification, and changes in species distribution will directly impact Shetland's marine habitats, particularly those critical for blue carbon sequestration (Burrows *et al.*, 2014).

Blue carbon ecosystems play a key role in climate mitigation by capturing and storing atmospheric carbon dioxide (CO₂) in both living biomass – such as, seagrass meadows, kelp forests, and biogenic reefs and beds – and underlying sediments (McLeod *et al.*, 2011). In particular, seagrass is considered some of the most effective blue carbon habitats due to their rapid growth rates and ability to store carbon in both biomass and the underlying sediment (Nellemann and Corcoran, 2009). The effectiveness of these habitats as carbon sinks, combined with their vulnerability to disturbance, highlights the need for accurate, high-resolution spatial data to inform local marine management. Riley, Mouat and Shucksmith (2024) demonstrated that modelling undertaken at too low a scale, for instance for nation-wide purposes, can over represent habitat extents in a local region. Local high-resolution data and modelling is key for supporting place-based policy and marine planning decisions that reflect local environmental conditions.

The protection and management of these blue carbon habitats have been a growing focus within Scotland's marine policy. Existing species and habitats identified as Priority Marine Features (PMFs) for conservation importance in Scottish waters (Tyler-Walters *et al.*, 2016), including biogenic habitats such as seagrass beds and maerl beds also have high carbon potential. However, some habitats that may have blue carbon potential are not PMFs, such as brittlestar beds. Within the Shetland Islands some habitats with blue carbon potential are located within Marine Protected Areas and in areas which have been voluntarily closed to fisheries by the Shetland Shellfish Management Organisation (SSMO). These habitats not only support biodiversity conservation but also the carbon sequestration potential of marine ecosystems, which will be critical in addressing the global climate crisis.

1.1 Aim

The main purpose of this project is to ascertain and assess the extent, scale, distribution and potential of the current blue carbon sublittoral habitats (seagrass, macroalgae, biogenic reefs and benthic sediment) in the Shetland Islands by:

- reviewing the current spatial extent and distribution of each blue carbon habitat,
- modelling the potential extent and distribution of these habitats,
- estimating blue carbon stock, storage rates, and production for each habitat type, using both observed (mapped) extents and modelled (predicted) distributions.

2 Shetland's Sublittoral Blue Carbon

The marine environment surrounding Shetland supports a diverse array of habitats and species that contribute to the capture, transformation, and potential long-term storage of carbon. These blue carbon systems include both biogenic habitats and sedimentary environments that have the potential to act as reservoirs of organic and inorganic carbon (Figure 1). Within Shetland's sublittoral zone, key blue carbon habitats include brittlestar beds (2.2.3.1), horse mussel beds (2.2.3.2), maerl beds (2.2.3.3), kelp forests (2.2.2), and seagrass meadows (2.2). In addition to these biological habitats, marine sediments also represent potential long-term storage of organic carbon.

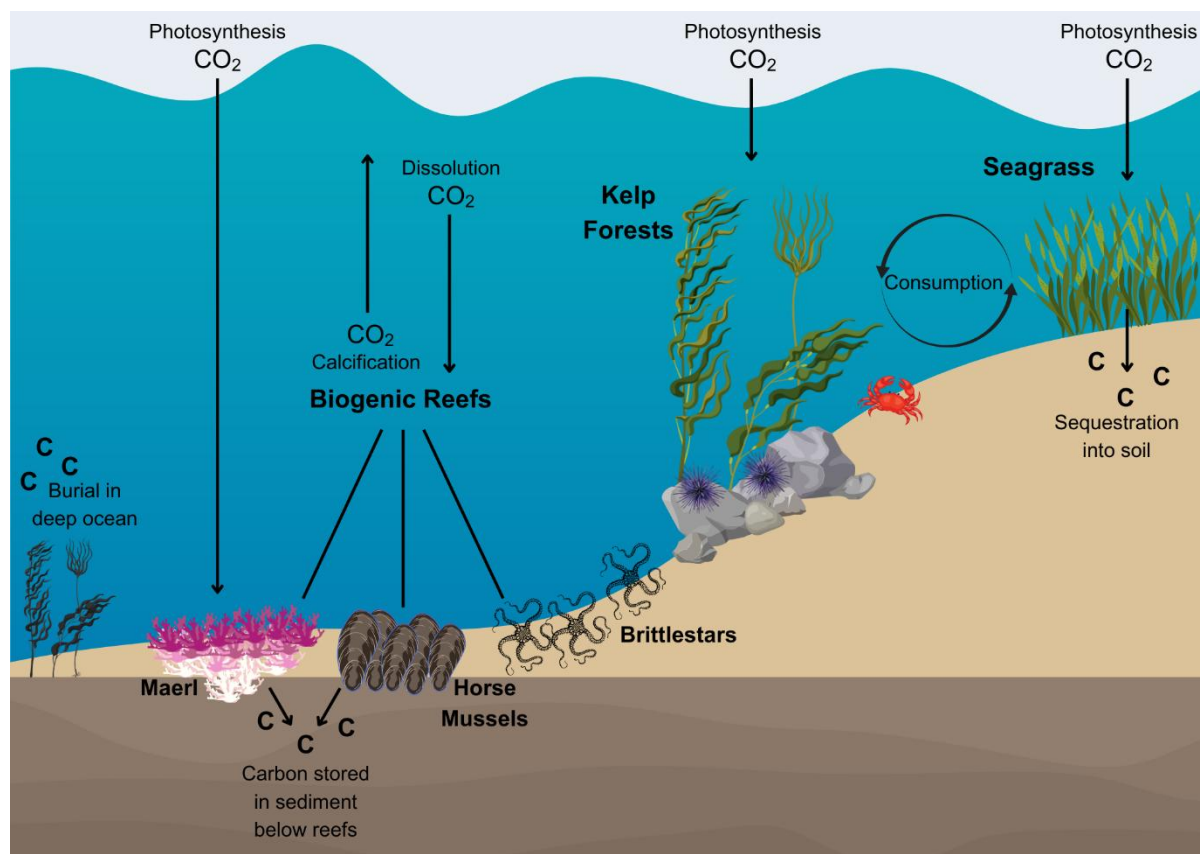


Figure 1 - Pathways for carbon capture and storage by sublittoral blue carbon habitats in the Shetland Islands.

2.1 Sediment

Marine sediments play a key role in the global carbon cycle, acting as long-term sinks for organic carbon (OC) over long periods of time. Carbon is transported to the seafloor via particulate organic matter from phytoplankton and detritus from benthic and pelagic organisms, known as sedimentation. Once deposited, a proportion of this organic material is buried and sequestered in the sediment, effectively removing it from short-term biogeochemical cycling.

The seabed surrounding Shetland is diverse (Figure 2), shaped by distinct natural processes, including the interaction of tidal systems from both the North Sea and the Atlantic Ocean. Within the 12 nm limit, the seabed comprises of a mosaic of differing substrate types, including bedrock, coarse sediments, mud, sand, and mixed sediments, reflecting the dynamic hydrodynamic conditions characteristic of the region.

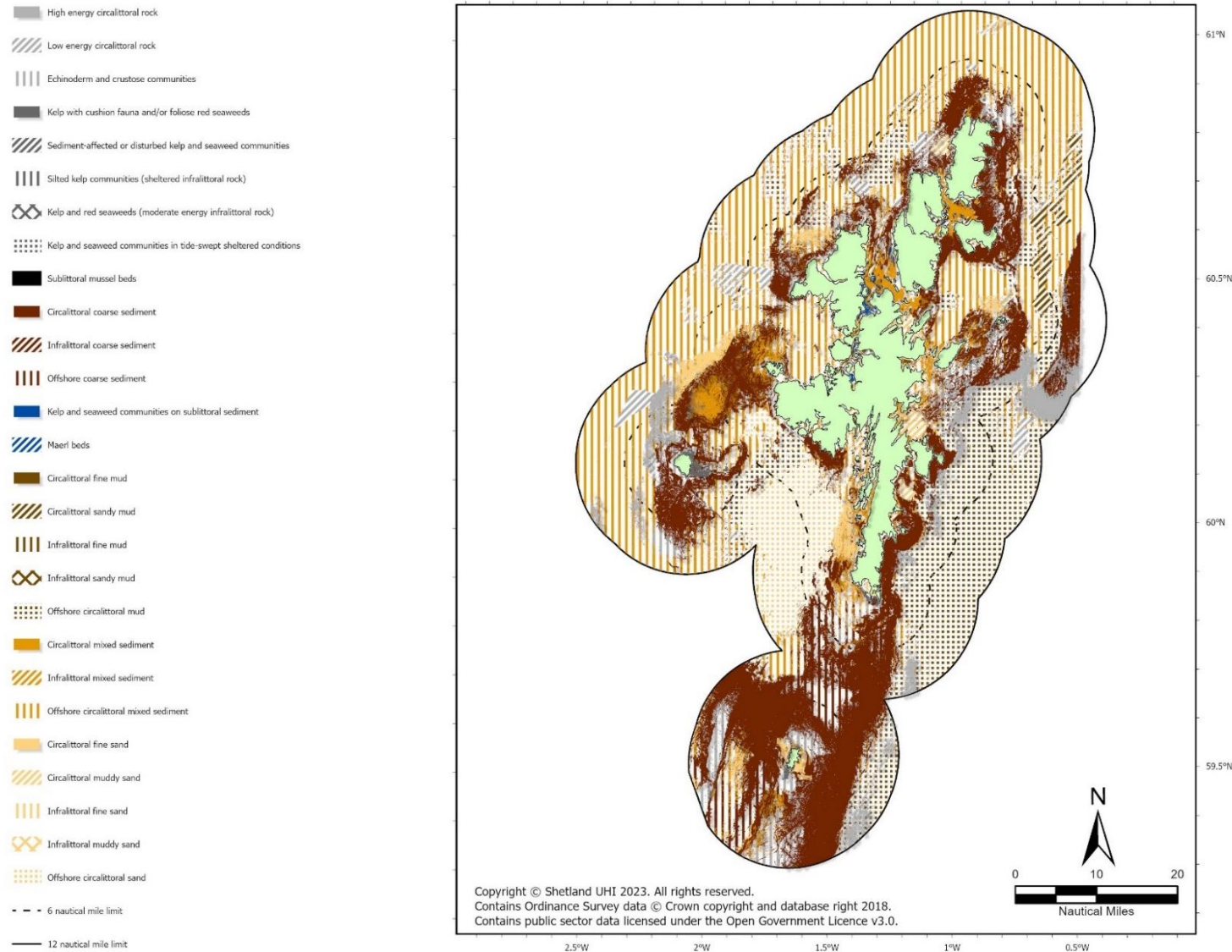


Figure 2 - Spatial distribution of the dominant benthic biotope identified across the Shetland Islands (Riley and Shucksmith, 2025).

2.2 Blue Carbon Habitats

2.2.1 Seagrass Meadows

Seagrass meadows are important marine environments for supporting biodiversity, stabilising sediments, and enhancing water quality, as well as playing a role in carbon sequestration (Figure 3). Globally, seagrasses play a key role in carbon sequestration through the accumulation of organic carbon (OC) in above-ground biomass (leaves and shoots), below-ground structures (rhizomes and roots) and in the underlying sediments through the deposition of detrital material.

In the UK, two species of marine seagrass are found: *Zostera noltii* (dwarf eelgrass), which typically inhabits the intertidal zone, and *Zostera marina* (common eelgrass), which occurs in the sublittoral to depths of up to 10 m (OSPAR, 2009). UK wide, seagrass beds are estimated to cover approximately 84 km² (8 493 ha; Green *et al.*, 2018, 2021), of which approximately 20.90 km² (2,090 ha) are in Scotland (Green *et al.*, 2021). With an almost even split between *Z. noltii* and *Z. marina*; 10 km² and 10.90 km² respectively (Green *et al.*, 2021; Cunningham and Hunt, 2023). They are protected as a PMF habitat.

In the Shetland Islands, historical records dating back to the 1800s document the presence of *Zostera* species in the heads of sheltered shallow voes. However, the extent of these meadows has declined, largely attributed to the impacts of wasting disease (Scott and Palmer, 1987). Recent work by Giesler, Allan and Shucksmith (2025) further highlights this trend, reporting that *Z. marina* was no longer present at 10 of the 12 historically recorded sites. Their study mapped the remaining seagrass meadows, identifying 14 individual beds across two sites, with a combined estimated area of 1.62 ha (0.0162 km², Figure 4).



Figure 3 - Seagrass meadow in the Shetland Islands formed of the species *Zostera marina* © UHI Shetland.

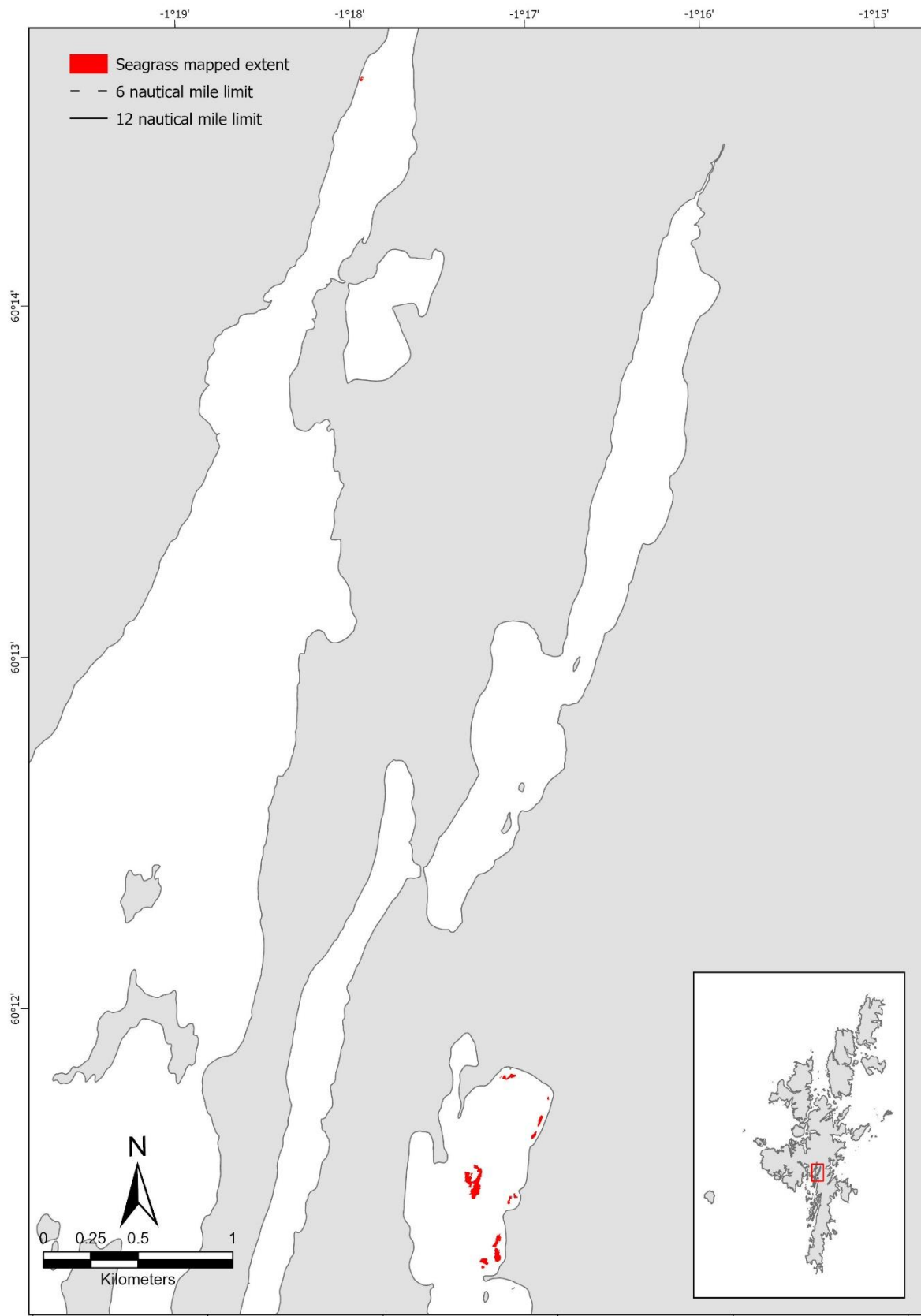


Figure 4 - Mapped extent of known seagrass meadows in the Shetland Islands (Giesler, Allan and Shucksmith, 2025).

2.2.2 Kelp Forests

Kelp forests are among the most productive and ecologically important marine ecosystems, providing a wide range of services including coastal protection, biodiversity support, and nutrient cycling (Figure 5). These habitats form the foundation of temperate rocky shore food webs and serve as nurseries for various commercially and ecologically significant species (Smale *et al.*, 2013).

Kelp does not sequester carbon directly within the sediment beneath the forest. Instead, it acts primarily as a carbon donor, producing large amounts of detrital biomass that is exported to adjacent or distant ecosystems (Krause-Jensen *et al.*, 2018). While this detritus does not accumulate within the kelp forest itself, it plays a role in supporting benthic food webs, especially benthic suspension feeding organisms such as mussels, barnacles, and limpets (Duggins, Simenstad and Estes, 1989; Bustamante and Branch, 1996). Kelp detritus contributes to long-term carbon storage if it becomes buried in sediment or incorporated into biomass in depositional environments (Krause-Jensen and Duarte, 2016; Duarte, Bruhn and Krause-Jensen, 2022; Smale *et al.*, 2022). However, the rates and mechanisms of long-term detrital incorporation into sediments remain poorly understood, making the quantification of kelp's role in carbon sequestration challenging (Krause-Jensen *et al.*, 2018).

In Scotland kelp forests are recognised as a PMF. These habitats are defined by the formation of extensive, structurally complex kelp-dominated communities comprised of several kelp species, including *Laminaria hyperborea* (tangle/cuvie), *Laminaria digitata* (oarweed), *Saccharina latissimi* (sugar kelp), *Alaria esculenta* (bladderlocks), and *Sacchoriza polyschides* (furbelows) (O'Dell, 2022), with *L. hyperborea* acting as the primary foundation species along most of the UK coastline (Smale *et al.*, 2020). However, presence of kelp species alone does not constitute a PMF kelp forest habitat. Although the current extent of kelp forests in Scotland is unknown, recent predictive habitat modelling has estimated it to be 4 778 km² (Burrows *et al.*, 2024).



Figure 5 - Kelp forest in the Shetland Islands © Rebecca Giesler/UHI Shetland.

2.2.3 Biogenic Reefs/Beds

Biogenic reefs and beds are formed by living organisms such as mussels (*Modiolus spp.*), serpulid worms (*Serpula vermicularis*), and cold-water corals (*Desmophyllum pertusum*) which create hard or semi-hard structures on the seabed. These organisms build biogenic frames that provide settlement surfaces for secondary species such as echinoderms and crustaceans (Langmead, *et al.*, 2008). Whether forming extensive reef structures or dense benthic beds, these habitats are structurally complex and ecologically rich (Poloczanska, Hughes and Burrows, 2004). They play a key role in ecosystem functions by enhancing habitat heterogeneity, supporting high biodiversity, and increasing ecological resilience.

In Scotland, these reefs and beds can be found across a range of coastal and offshore. These communities are characterised by sessile or sedentary suspension-feeders, which filter phytoplankton, zooplankton, and suspended detritus from the water column. While brittlestars are mobile, their presence in large aggregations makes them largely sedentary (Broom, 1975). Through their collective feeding activity, these organisms play a key role in enhancing the flux of organic carbon from the pelagic to the benthic environment (Hily, 1991).

The role and contribution of biogenic reefs and beds to blue carbon storage, however, is nuanced (Burrows *et al.*, 2024). The calcification processes involved in reef and/or bed formation (e.g. production of shells, skeletons, or tubes) releases CO₂, making these habitats sources rather than sinks of carbon (Frankignoulle, Canon and Gattuso, 1994). However, the reef and/or bed structures can have the capacity to enhance local sediment stability and trap organic material offering localised carbon accumulation through sediment retention and organic matter deposition (Turrell *et al.*, 2023).

2.2.3.1 Brittlestar beds

Subtidal brittlestar beds, made up on a variation of *Ophiothrix fragilis* (common brittlestar), *Ophiocomina nigra* (black brittlestar) and/or *Ophiopholis aculeata* (crevice brittlestar) are not considered "reefs" in the traditional sense or in the same manner as other habitats discussed in this section (Figure 6). These dense aggregations of benthic biomass are both widespread and abundant across Scottish waters, including Shetland (Hughes, 1998). While their contribution in the marine carbon cycling, through processes such as carbon flux and carbonate deposition, is increasingly recognised, it remains poorly understood (Lebrato *et al.*, 2010).



Figure 6 - Brittlestar bed taken by drop down video in Colgrave Sound, Shetland Islands © UHI Shetland.

2.2.3.2 Horse mussel beds

Horse mussel (*Modiolus modiolus*) beds are widespread throughout the shallow subtidal zones of Scotland, although many records refer to isolated individuals or sparse aggregations. In certain localities, however, horse mussels can form dense beds that support structurally complex and ecologically valuable habitats (Figure 7). These biogenic beds are associated with substantial sediment accumulation. A typical mean sediment thickness of 75 cm has been used in previous blue carbon assessments (Burrows *et al.*, 2014; Burrows *et al.*, 2017; Porter *et al.*, 2020). However, recent findings suggest that the organic-rich layer may extend deeper, with a mean depth of 0.78 m and total sediment depth averaging 1.37 m, reaching up to 3 m in some locations (Sheehy *et al.*, 2024a). This demonstrates the potential of horse mussel beds to contribute to organic carbon accumulation and long-term benthic carbon storage.

In total, mapped horse mussel beds in Scotland cover approximately 10.20 km², with an additional 13.80 km² occurring in mosaic habitats alongside maerl beds (Burrows *et al.*, 2024). The most extensive of these in Scottish waters is found at Noss Head, covering approximately 3.85 km² an area nearly five times larger than the combined extent of all other known horse mussel beds in the country. Within Shetland, the recorded extent (Figure 8) of horse mussel beds is 0.62 hectares (Shelmerdine and Mouat, 2020).



Figure 7 - Horse mussel bed (and brittlestars) taken by drop down video in Linga Sound, Shetland Islands © UHI Shetland.



Figure 8 - Mapped extent of known horse mussel bed in the Shetland Islands (Shelmerdine and Mouat, 2020).

2.2.3.3 Maerl Beds

Maerl beds, composed of calcifying red algae such as *Phymatolithon calcareum*, *Lithothamnion corallioides* and *Lithothamnion erinaceum* (Burrows *et al.*, 2024), form structurally complex and ecologically diverse marine benthic habitats (Figure 9). Their complex 3D structures as well as providing stable habitats for a wide range of flora and fauna, support several ecosystem services including water quality enhancement, nutrient cycling, and the provision of nursery grounds for commercially valuable species such as fish, scallops, and crabs (Kamenos, Moore and Hall-Spencer, 2004a; Kamenos, Moore and Hall-Spencer, 2004b). As calcifying organisms, maerl contributes to blue carbon processes by incorporating carbon into calcium carbonate (CaCO_3) skeletons. However, the calcification process simultaneously releases CO_2 , complicating their role as a net carbon sink.

Maerl are slow growing, typically around 1 mm per year (Blake and Maggs, 2003; Bosence and Wilson, 2003), with individual thalli living up to 100 years and some beds thought to be over 1,000 years old (Mao *et al.*, 2020). Beyond calcification, carbon may also be sequestered within the fine sediments that settle between and beneath the maerl beds. The dynamics and rates of this long-term carbon burial remain poorly understood.

In Scotland, maerl beds are distributed along the west coast, the Western Isles, Orkney, and Shetland. They are recognised as a PMF, reflecting their ecological importance. On Scotland's west coast, live maerl deposits have been observed reaching thicknesses of up to 60 cm, with dead layers extending deeper (Kamenos, 2010). Surveys in Orkney have found maerl beds with an average thickness of 1.08 m (Sheehy *et al.*, 2024b), suggesting a considerable potential capacity for carbon accumulation over time.

Mapping efforts have identified approximately 31.40 km² of maerl beds in Scotland, with an additional 13.80 km² occurring in mosaics with *Modiolus modiolus* (horse mussel) beds, and 14.60 km² in combination with coarse shell gravel (Burrows *et al.*, 2024). In Shetland, all identified maerl beds (Figure 10) are protected from scallop dredging through designated closed areas (Shelmerdine *et al.*, 2013; Riley and Shucksmith, 2024; Riley *et al.*, 2025), with 16.91 ha of beds currently protected (Shelmerdine and Mouat, 2020).



Figure 9 - Maerl bed (and brittlestar) showing living (pink) and dead (white) maerl taken by drop down video in Mousa Sound, Shetland Islands © UHI Shetland.

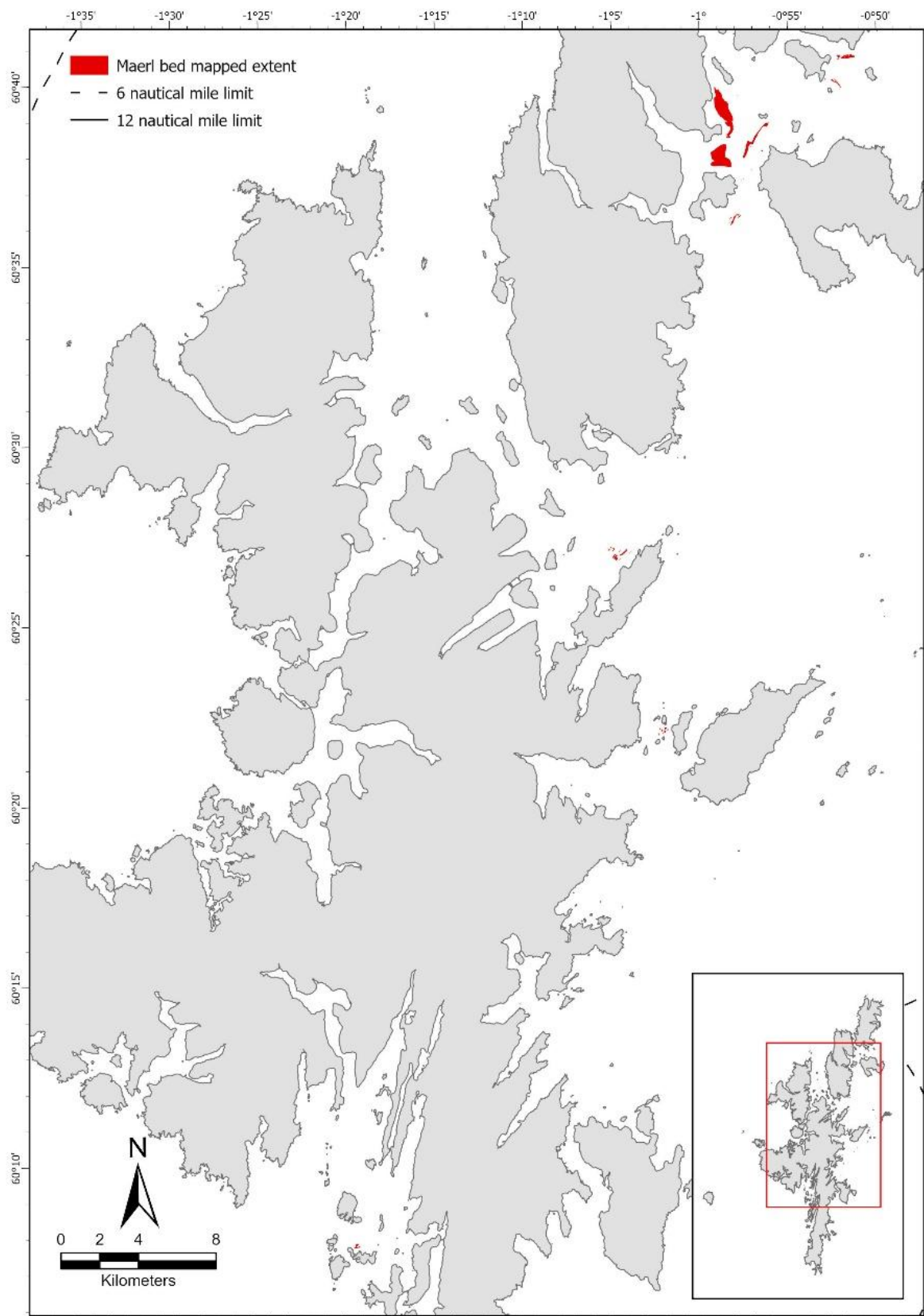


Figure 10 - Mapped extent of known maerl bed in the Shetland Islands (Shelmerdine and Mouat, 2020).

3 Materials and Methods

3.1 Sediment Data

Seabed sediment classifications within Shetland's 12 nm limit were derived from the 2024 update of the Shetland Islands Dominant Marine Biotope dataset (Riley and Shucksmith, 2025), which provides a high-resolution, locally informed representation of benthic habitats across the region. This dataset is based on the hierarchical biotope classification system described by Connor *et al.* (2004) which ranges from Level 1 (broad habitat, e.g. marine) to Level 6 (specific sub-biotopes, e.g. *Saccharina latissima* and filamentous red algae on infralittoral sand). Biotopes are defined as ecological units characterised by substrate type, associated species assemblages, and position within the marine environment.

To estimate the spatial extent (km²) of sediment types within the 12 nm zone, biotope polygons were aggregated at Level 3 of the classification system, into four primary sediment categories: Coarse Sediment, Mixed Sediment, Mud, and Sand (Appendix 1). Areas identified as circalittoral and infralittoral rock were combined to form a composite 'Rock' category. This does not include nearshore areas, so the total area represents the full 12 nm sublittoral seabed extent.

Other seabed types, including macrophyte-dominated and biogenic reef habitats, were not included in the sediment classification but are represented under a generalised 'Other Sediment' category for the purpose of estimating total seabed coverage within the 12 nm limit. These habitat types are modelled and quantified separately as blue carbon habitats.

3.2 Habitats Data

Blue carbon habitat data for this study was collated from a range of sources (Table 1; Appendix 2) including GeMS⁶ (JNCC, 2023), DASSH⁷, Shelmerdine and Mouat (2020) and Giesler, Allan and Shucksmith (2025). GeMS data is quality controlled to Marine Nature Conservation Review standards and follows consistent guidance and best practice (Parry, 2019). To ensure the highest accuracy of the dataset, any records of 'uncertain' identification, as stated by the determiner, were removed.

3.3 Distribution Models

Predicted extent of blue carbon habitats – seagrass meadows, kelp forests, maerl beds, brittlestar beds and horse mussel beds – was modelled using MaxENT, version 3.4.4 (Phillips, Anderson and Schapire, 2006; Phillips and Dudík, 2008) and follows the standard protocol for species distribution modelling (Zurell *et al.*, 2020; Appendix 3). MaxEnt's raw output delineates the relative importance of each environmental variable in determining potential distribution and produces a continuous map of relative habitat suitability across the model region (Ward *et al.*, 2016).

MaxEnt models are developed using known presence-only point data and environmental predictor variables. Initially, 35 environmental variables were compiled, including bathymetry, backscatter, sediment type, and oceanographic parameters. To reduce the risk of multicollinearity, pairwise Pearson's correlation analysis was conducted (Appendix 4), and variables with correlation coefficients exceeding 0.7 were excluded (Davies and Guinotte, 2011), resulting in a final set of 11 environmental predictors for use in the model (Appendix 5).

⁶ Geodatabase of Marine Features in Scotland - [GeMS Scottish Priority Marine Features](#)

⁷ Data Archive for Seabed Species and Habitats - [DASSH](#)

Table 1 - Summary of habitat types, data sources, and records used in blue carbon habitat suitability modelling.

	Type	Reference/Origin	Records used in model	Range	Historical Records ⁸	
<i>Seagrass meadows</i>	Point and Polygon	<i>Giesler, Allan and Shucksmith (2025)</i>	51	1978-2024	35 (68.63%)	<i>Appendix 2a</i>
<i>Kelp forests</i>	Point	GeMS				
<i>High energy</i>			67	1986-2016	33 (49.25%)	<i>Appendix 2b</i>
<i>Medium energy</i>			167	1974-2019	93 (55.69%)	<i>Appendix 2c</i>
<i>Maerl beds</i>	Point	GeMS	158	1986-2019	9 (5.70%)	
	Polygon	<i>Shelmerdine and Mouat (2020)</i>				<i>Appendix 2d</i>
<i>Brittlestar beds</i>	Point	GeMS	95	1986-2024	10 (10.53%)	<i>Appendix 2e</i>
<i>Horse mussel beds</i>	Point	GeMS and DASSH	68	1974-2019	43 (63.24%)	
	Polygon	<i>Shelmerdine and Mouat (2020)</i>				<i>Appendix 2f</i>

⁸ Defined as pre-1995

Models were configured using a 10-fold cross-validation approach, where the occurrence dataset was randomly partitioned into 10 subsets, with each subset used once for model testing and the remaining for training (Hernandez *et al.*, 2006). To assess model variability and robustness, this process was combined with 10 replicate runs, and the number of iterations was increased from the default of 500 to 5000 to support optimal model convergence and reduce predictive anomalies (Young, Carter and Evangelista, 2011).

Model performance was evaluated using the Area Under Curve (AUC) and the True Skill Statistic (TSS). AUC values range from 0 to 1, where 0.5 indicates performance no better than random, and values are classified as follows: 0.5-0.7 (poor), 0.7-0.9 (good), and 0.9-1.0 (excellent) (Baldwin, 2009; Jiménez-Valverde, 2012). True Skill Statistics values range from -1 to +1, where +1 indicates perfect agreement between predictions and observations, and values ≤ 0 imply performance no better than random (Allouche, Tsoar and Kadmon, 2006). The TSS value was calculated using the 10th percentile training presence threshold, consistent with recommendations for presence-only models (Liu *et al.*, 2005; Davies and Guinotte, 2011; Fourcade *et al.*, 2014).

3.4 Shetland Blue Carbon Extent

To calculate an initial predicted spatial extent for each individual habitat, cells with a predicted probability of occurrence ≥ 0.9 were extracted, with total area calculated within ESRI ArcGIS Pro version 3.2.1 (ArcGIS; ESRI, 2024).

To produce a complete blue carbon habitat map within the 12 nm boundary of the Shetland Islands while minimising the risk of double counting, it was necessary to address areas where multiple habitats were predicted to overlap when clipped to ≥ 0.9 . This was particularly important in regions such as Yell Sound, where habitats like maerl and horse mussel beds occur in a mosaic and are likely to both be classified as suitable in this area.

To resolve this, the "Highest Position" function was utilised in ArcGIS. This function evaluates multiple raster datasets on a cell-by-cell basis and identifies the position of the raster with the highest value at each location, thereby assigning dominance to a single habitat type per cell (Appendix 6). This approach was first applied separately to the kelp forest habitat suitability rasters (Appendix 6a), and subsequently to all blue carbon habitats collectively (Appendix 6).

3.5 Carbon Sequestration

Organic carbon (OC) stock, annual production and storage capacity were estimated using a standardised, area-based carbon accounting approach. This method integrates spatial extent data with published values for OC density ($\text{g C} / \text{m}^2$), production rates ($\text{g C} / \text{m}^2 / \text{yr}$), and carbon burial or storage rates ($\text{g C} / \text{m}^2 / \text{yr}$), published in Burrows *et al.* (2024), which provides values for the top 10 cm of sediments for calculations, as there is a general data limitation on sediment thickness (Table 2).

For sediment types, stock (1000 tOC) and storage capacity (1000 tOC / yr) were calculated as follows:

$$\text{Stock (1000 tOC)} = \frac{\text{OC density (g C/m}^2\text{)} \times \text{extent (km}^2\text{)}}{1000} \quad (1)$$

$$\text{Storage capacity (1000 tOC/yr)} = \frac{\text{storage rate (g C/m}^2\text{/yr)} \times \text{extent (km}^2\text{)}}{1000} \quad (2)$$

For predicted extents of blue carbon habitats, stock (tOC), total production (t C / yr) and storage capacity (tOC / yr) were calculated as follows:

$$\text{Stock (tOC)} = \text{OC density (g C/m}^2\text{)} \times \text{extent (km}^2\text{)} \quad (3)$$

$$\text{Total production (t C/yr)} = \text{production rate (g C/m}^2\text{/yr)} \times \text{extent (km}^2\text{)} \quad (4)$$

$$\text{Storage capacity (tOC/yr)} = \text{storage rate (g C/m}^2\text{/yr)} \times \text{extent (km}^2\text{)} \quad (5)$$

For mapped known extents of blue carbon habitats, stock (tOC), total production (t C / yr) and storage capacity (t OC / yr) were calculated as follows:

$$\text{Stock (tOC)} = \frac{\text{OC density (g C/m}^2\text{)} \times \text{extent (ha)}}{100} \quad (6)$$

$$\text{Total production (t C/yr)} = \frac{\text{production rate (g C/m}^2\text{/yr)} \times \text{extent (ha)}}{100} \quad (7)$$

$$\text{Storage capacity (tOC/yr)} = \frac{\text{storage rate (g C/m}^2\text{/yr)} \times \text{extent (ha)}}{100} \quad (8)$$

To estimate the CO₂ equivalence of OC stored within Shetland's mapped blue carbon habitats the mass of OC (tonnes) was converted to CO₂ equivalent (t CO₂e) using the molar mass ratio of carbon to carbon dioxide (C : CO₂ = 1 : 3.6663) (Toohey, 2018). The CO₂e values are subsequently used to generate comparative metrics against typical household CO₂ emissions.

Table 2 - Organic carbon (OC) density, annual production rate, and storage rate for dominant sediment types and blue carbon habitats in the Shetland region. Values are derived from Burrows *et al.* (2024) and refer to the top 10 cm of sediment. Empty cells indicate no available data.

	OC density (g C / m ²)	Production rate (g C / m ² / yr)	Storage rate (g C / m ² / yr)
Sediment			
Rock	0	0	0
Coarse and Mixed Sediment			
Mud	550		155.20
Sand	180		0.20
Blue carbon habitats			
Seagrass meadows	1547	274	100.40
Kelp forests	218	332	0
Maerl beds	720		
Brittlestar beds			
Horse mussel beds			

4 Results

4.1 Individual Sublittoral Blue Carbon Habitat Suitability Models

The predicted habitat suitability models (Appendix 7) demonstrate strong performance across multiple validation metrics. Model AUC values exceed 0.97 (Table 3) and are significantly different from that of a random prediction of AUC = 0.5 (Wilcoxon rank-sum test, $p < 0.01$). The high AUC scores are supported by high test gain, indicating that predicted presence locations are more probable than that of a random background pixel (Davies and Guinotte, 2011). The models exhibit an omission rate of 9-10% at the 10-percentile training presence threshold (Table 3), indicating the proportion of training localities that fell below the threshold prediction value. Model TSS values ranged from 0.79 to 0.85 (Table 3), indicating the models as 'good' to 'excellent' in predictive accuracy (Coetzee *et al.*, 2009; Gama *et al.*, 2017). Collectively, these metrics confirm the robustness and reliability of the habitat suitability predictions.

Table 3 - Model validation statistics and environmental variable importance across different blue carbon habitats in the Shetland Islands.

	Seagrass meadows	Kelp forests (high energy)	Kelp forests (medium energy)	Maerl beds	Brittlestar beds	Horse mussel beds
Records used in SDM	51	67	167	158	95	68
Range	1978-2024	1986-2016	1974-2019	1986-2019	1986-2019	1974-2019
Historical records ⁹	35 (68.63%)	33 (49.25%)	93 (55.69%)	9 (5.70%)	10 (10.53%)	43 (63.24%)
Validation Statistics						
Test AUC (SD)	0.99 (-0.80)	0.98 (0.01)	0.98 (0.01)	0.99 (0.00)	0.97 (0.01)	0.98 (0.01)
Test gain	5.94	3.18	2.91	3.96	2.76	3.34
Omission rate (threshold 10)	9.00%	8.33%	9.35%	9.17%	9.99%	9.45%
10 th percentile training presence	0.37	0.17	0.25	0.37	0.26	0.34
True Skill Statistic (TSS)	0.85	0.82	0.79	0.81	0.85	0.80

⁹ Defined as pre-1995

	Seagrass meadows	Kelp forests (high energy)	Kelp forests (medium energy)	Maerl beds	Brittlestar beds	Horse mussel beds
<i>Jack-knife of variable importance</i>						
Aspect	0.18	0.01	0.09	0.05	0.04	0.01
Benthic Light	1.23	0.96	1.55	2.67	1.60	2.64
Benthic Salinity	1.71	0.59	0.78	1.35	0.80	1.09
Benthic Temperature	2.05	0.43	0.64	1.63	0.80	2.62
Benthic Velocity	0.92	0.04	0.07	0.35	0.17	0.64
Curvature	0.00	0.38	0.40	0.31	0.36	0.11
Depth	4.78*	2.59*†	2.72*†	3.00*†	2.02*†	2.67*†
Sediment	5.21†	1.40	1.16	0.05	0.42	0.18
Slope	0.08	1.06	1.04	0.44	0.89	0.92
Surface Temperature	2.63	0.29	0.88	1.24	0.91	1.81
Tidal Velocity	4.07	0.08	0.48	0.40	0.11	1.11
<i>Test AUC for a single variable</i>						
Aspect	0.71	0.49	0.62	0.58	0.55	0.50
Benthic Light	0.87	0.86	0.92	0.97	0.94	0.98
Benthic Salinity	0.96	0.76	0.83	0.89	0.83	0.88
Benthic Temperature	0.97	0.74	0.80	0.95	0.83	0.97
Benthic Velocity	0.93	0.48	0.63	0.75	0.70	0.82
Curvature	0.50	0.82	0.77	0.86	0.83	0.72
Depth	0.99	0.97	0.98	0.98	0.96	0.97
Sediment	0.95	0.90	0.86	0.57	0.73	0.64
Slope	0.61	0.87	0.86	0.76	0.85	0.85
Surface Temperature	0.99	0.71	0.84	0.92	0.85	0.93
Tidal Velocity	0.99	0.54	0.72	0.79	0.61	0.83

* indicates the variable whose omission resulted in the greatest reduction in the model gain, suggesting it contributed the most unique information not captured by other variables.

† indicates the variable with the highest gain when used independently, reflecting the most informative variable in isolation.

The top 3 variables for each blue carbon habitat are highlighted in **bold**.

4.2 Blue Carbon Spatial Extent

4.2.1 Sediment

The analysis of spatial extent of sublittoral sediment within Shetland's 12 nm limit revealed a total mapped area of 12 043.97 km² (Table 4, Figure 11). 'Mixed sediment' and 'coarse sediment' were the two dominant habitat types, representing 61.88% of the total seabed area. Whilst 'other sediment' types, which includes blue carbon habitats such as macrophyte-dominated and biogenic reef areas, represented the smallest proportion of seabed coverage at less than 1%.

Table 4 - Extent (km²) and percentage area of seabed habitat types within Shetland's 12 nm limit, derived from the 2024 update of the Shetland Islands Dominant Marine Biotope map (Riley and Shucksmith, 2025).

	Extent (km ²)	Percentage area
<i>Rock</i>	1 212.91	10.07%
<i>Coarse sediment</i>	3 177.27	26.38%
<i>Mixed sediment</i>	4 305.76	35.75%
<i>Mud</i>	2 056.61	17.08%
<i>Sand</i>	1 235.06	10.25%
<i>Other sediment</i>	56.36	0.47%

4.2.2 Mapped Blue Carbon Habitats

The total mapped extent of confirmed blue carbon habitats in the Shetland Islands is 19.15 ha (0.19 km²), comprising of:

- **Seagrass meadows:** 1.62 ha (section 2.2; Giesler, Allan and Shucksmith, 2025),
- **Maerl beds:** 16.91 ha (section 2.2.3.3; Shelmerdine and Mouat, 2020),
- **Horse mussel beds:** 0.62 ha (section 2.2.3.2; Shelmerdine and Mouat, 2020).

4.2.3 Predicted Blue Carbon Habitats

Modelled potential habitat distribution, based on a probability threshold of occurrence greater than 0.9 (Appendix 8), predicts a total predicted potential extent of blue carbon habitats within the Shetland Islands of 62.04 km² (Figure 12), with individual predicted extents of:

- **Kelp forests (high energy):** 16.06 km² (Appendix 8a)
- **Kelp forests (medium energy):** 7.87 km² (Appendix 8a)
- **Maerl beds:** 1.38 km² (Appendix 8b)
- **Brittlestar beds:** 24.58 km² (Appendix 8c)
- **Horse mussel beds:** 12.15 km² (Appendix 8d)

No areas within Shetland's 12 nm exceeded the 0.9 probability of occurrence threshold for seagrass meadows¹⁰.

¹⁰ See discussion for further notes

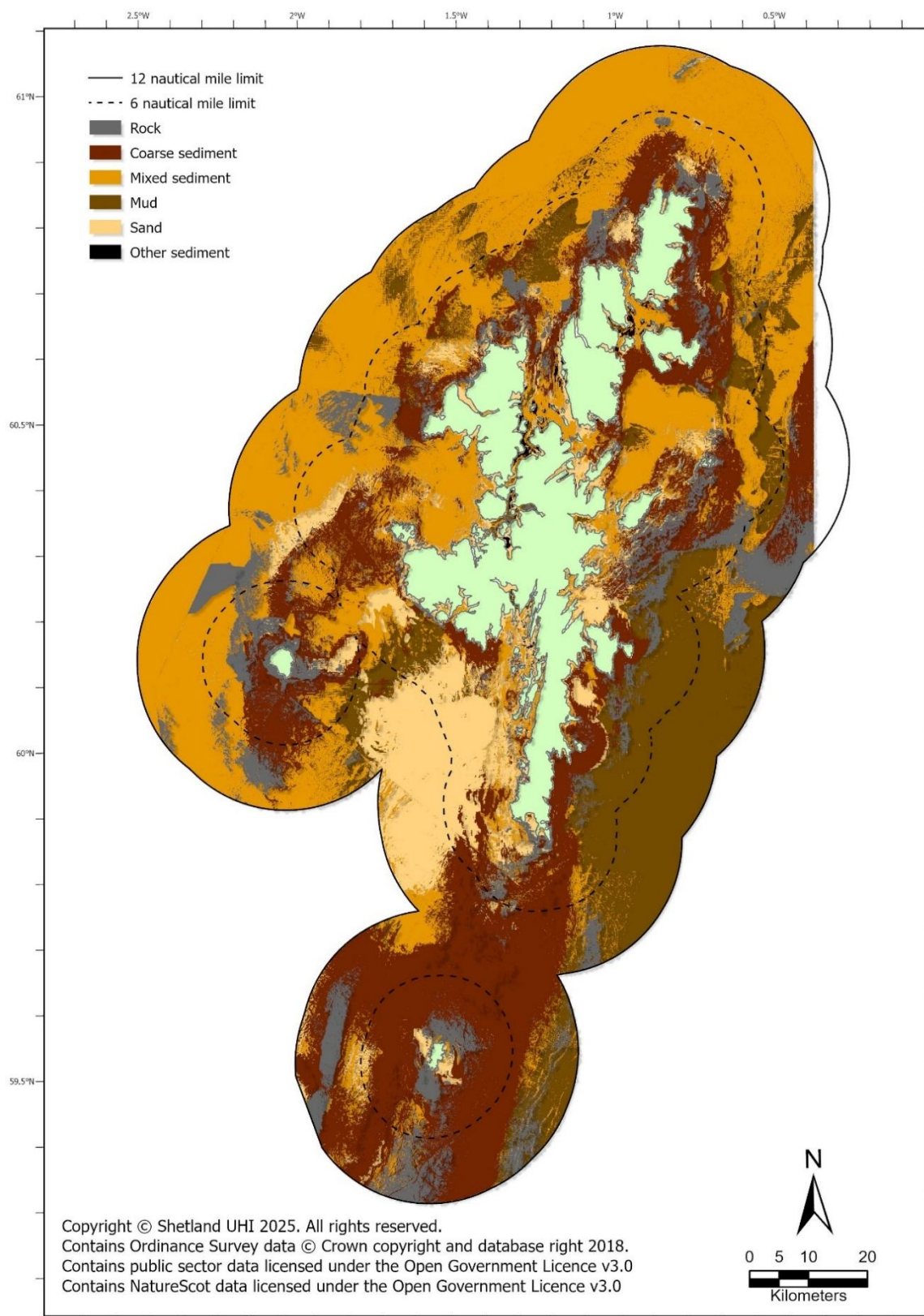


Figure 11 - Sediment types within the 12 nm zone in the Shetland islands, biotope polygons were aggregated at Level 3 of the biotope classification system derived from Riley and Shucksmith (2025)

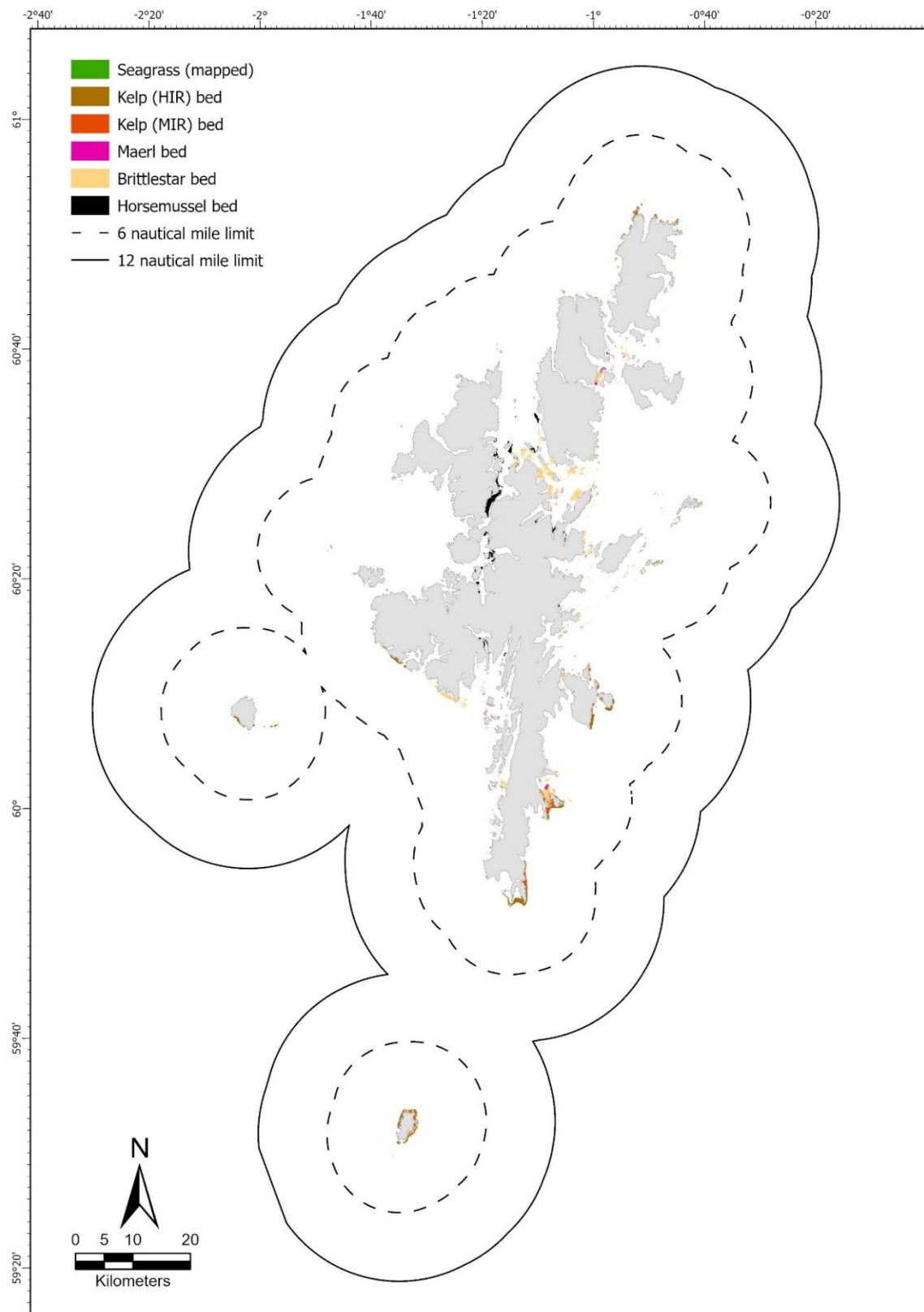


Figure 12 - Modelled distribution of all sublittoral blue carbon habitats (seagrass meadows, kelp forests, maerl beds, brittlestar beds, and horse mussel beds) in the Shetland Islands, showing areas with a predicted probability of occurrence ≥ 0.9 , with overlapping areas assigned to the habitat with the highest predicted probability.

4.3 Sublittoral Blue Carbon Potential

4.3.1 Sediment

Based on the sediment extents and values reported by Burrows *et al.* (2024), the total estimated sediment organic carbon (OC) stock in the Shetland Islands is 1 353.44 kt OC (Table 5). The annual storage capacity associated with these sediments is estimated at 319.44 kt OC / yr.

Table 5 - Benthic sediment extent and organic carbon (OC) density and storage rates, and total carbon storage capacity in the Shetland Islands. Values are for the top 10 cm of sediment. Areas in grey were parameters that had no values available. **Bolded** text are values taken from Burrows *et al.* (2024).

	Extent (km ²)	OC density (g C / m ²)	Stock (kt OC)	Production rate (g C / m ² / yr)	Total production (t C / yr)	Storage rate (g C / m ² / yr)	Storage capacity (kt OC / yr)
<i>Rock</i>	1 212.91	0	0	0	0	0	0
<i>Coarse and Mixed Sediment</i>	7 483.03						
<i>Mud</i>	2 056.61	550.00	1 131.13			155.20	319.19
<i>Sand</i>	1 235.06	180.00	222.31			0.20	0.25
Total	11 987.61		1 353.44		0		319.44

4.3.2 Mapped Blue Carbon Habitats

Mapped seagrass meadows within the Shetland Islands are estimated to hold OC stock of 25.06 t OC, with an associated annual storage rate of 1.63 t OC / yr (Table 6). The annual total production rate is estimated at 4.44 t C / yr across the mapped extent. Mapped maerl beds have an estimated OC stock of 121.75 t OC. No data are available for annual production or storage rates for maerl or horse mussel beds. The total mapped organic carbon stock for all habitats is therefore 146.81 t OC.

4.3.3 Predicted Blue Carbon Habitats

From modelled distributions, predicted kelp forests (high energy) are estimated to store 3 501.08 t OC, corresponding to 5 331.92 t C / yr of total production (Table 6). Predicted kelp forests (medium energy) are estimated to store 1 715.66 t OC, with a total estimated production of 2 612.84 t C / yr. Modelled maerl beds are estimated to hold 993.60 t OC. No production or storage rates are available for brittlestar or horse mussel beds in this dataset. The total organic carbon stock for all predicted blue carbon habitats is 6 210.34 t OC, with a total production of 7 944.76 t C / yr.

When combined with mapped values, the total blue carbon habitat extent was 62.23 km², and the total organic carbon stock was 6 357.15 t OC, and total combined production was 7 949.20 t C / yr.

Table 6 - Blue carbon habitat extent (mapped and predicted) and organic carbon (OC) density and storage rates, and total carbon storage capacity in the Shetland Islands. Values are for the top 10 cm of sediment. Areas in grey were parameters that had no values available. **Bolded** text are values taken from Burrows *et al.* (2024).

	Extent	OC density (g C / m ²)	Stock (t OC)	Production rate (g C / m ² / yr)	Total production (t C / yr)	Storage rate (g C / m ² / yr)	Storage capacity (t OC / yr)
Mapped	(ha)						
Seagrass meadows	1.62	1547	25.06	274	4.44	100.40	1.63
Maerl beds	16.91	720	121.75				
Horse mussel beds	0.62						
Total	19.15		146.81		4.44		1.63
Predicted	(km ²)						
Kelp forest (high energy)	16.06	218	3 501.08	332	5 331.92	0	0
Kelp forest (medium energy)	7.87	218	1 715.66	332	2 612.84	0	0
Maerl beds	1.38	720	993.60				
Brittlestar beds	24.58						
Horse mussel beds	12.15						
Total	62.04		6 210.34		7 944.76		0
Total	62.23		6 357.15		7 949.20		1.63

4.4 Sublittoral Blue Carbon Potential CO₂ equivalence

The carbon storage and sequestration potential of mapped blue carbon habitats in the Shetland Islands totals an estimated equivalence of ~538 tonnes of CO₂. Maerl beds are estimated to hold the equivalence of ~446 tonnes of CO₂, while seagrass meadows are estimated to hold ~92 tonnes of CO₂. Seagrass meadows also have the potential to sequester ~6 tonnes of CO₂ annually (Table 7).

To contextualise this contribution, additional comparative analysis illustrating the equivalence of the carbon storage potential to various everyday activities and energy use are provided in Figure 13 and Table 7.

The amount of carbon held within Shetland's known carbon storing marine habitats is equivalent to any of the following

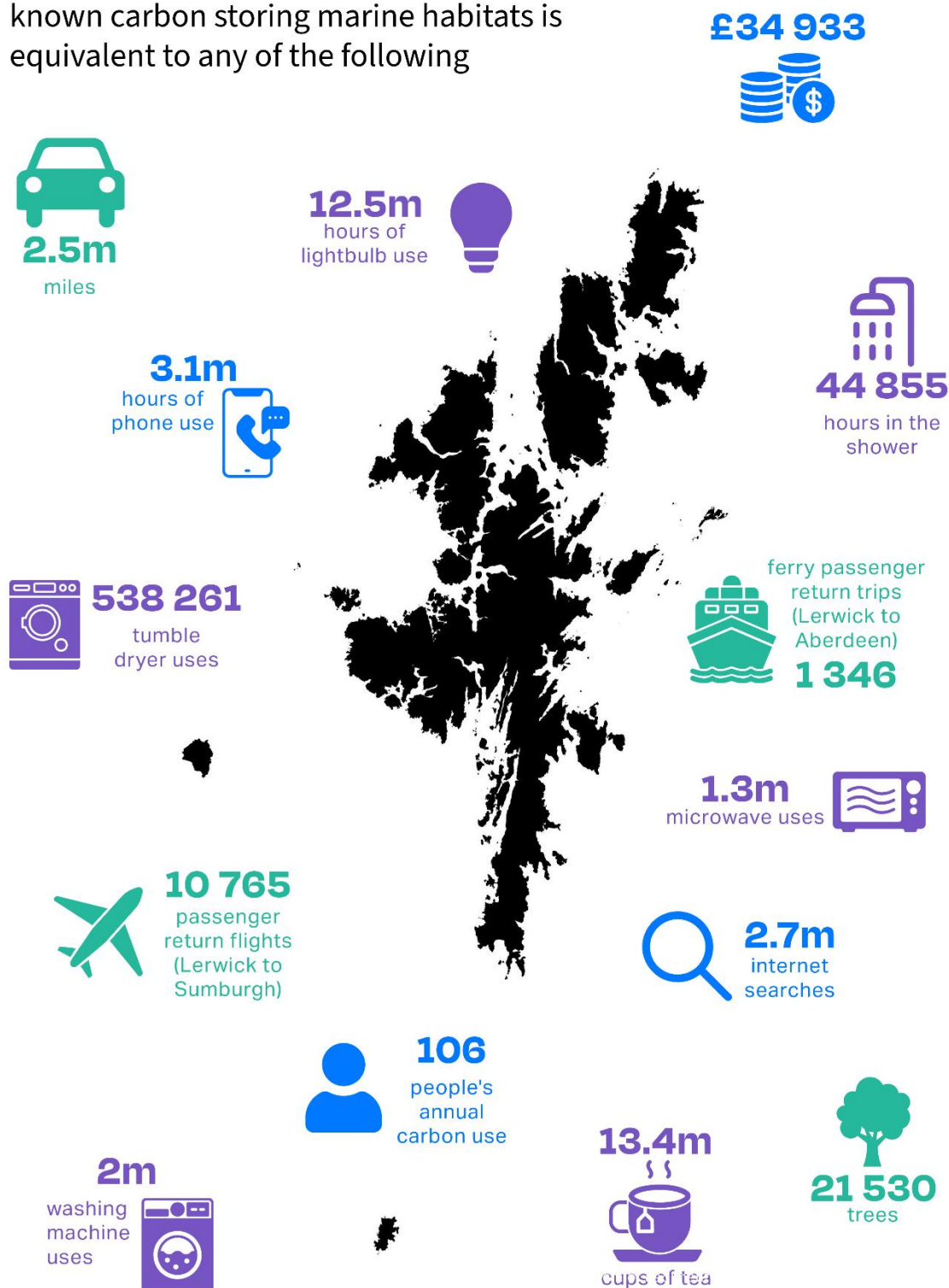


Figure 13 - Estimated CO₂ equivalence of known blue carbon habitats in the Shetland islands, based on the top 10 cm of sediment illustrating how the potential carbon stored in these habitats could offset everyday emissions from typical activities. All comparative figures are detailed in Appendix 9. Values marked with "m" denote millions.

Table 7 - CO₂ equivalence of known blue carbon habitats, total stock and annual storage compared to everyday activities. All comparative figures are detailed in Appendix 9.

	Seagrass meadows (Total Stock)	Maerl beds (Total Stock)	Seagrass meadows (Annual Storage capacity)
<i>t CO₂ equivalent</i>	92	446	6
<i>Per capita</i>	18	88	1
<i>Cost (£)</i>	5 963	28 970	387
<i>Trees</i>	3 675	17 855	239
<i>Car journey (1 mile)</i>	435 050	2 113 539	28 235
<i>Return travel (Shetland – Aberdeen)</i>			
<i>Ferry passenger</i>	230	1 116	15
<i>Flight passenger</i>	1 838	8 928	119
<i>Household uses</i>			
<i>Cups of tea</i>	2 297 065	11 159 484	119 263
<i>Internet searches</i>	459 413 054	2 231 896 788	29 815 818
<i>Mobile phone use (1 hour)</i>	534 201	2 595 229	34 670
<i>Microwave uses</i>	229 707	1 115 948	14 908
<i>Washing machine uses</i>	334 119	1 623 198	21 684
<i>Tumble dryer uses</i>	91 883	446 379	5 963
<i>Lightbulb use (1 hour)</i>	2 136 805	10 380 915	138 678
<i>Shower use (10 minutes)</i>	45 941	223 190	2 982

5 Discussion

The results of this study demonstrate that the Shetland Islands support a diverse seascape in which carbon storage is highly variable, identifying a range of blue carbon habitats and seabed sediment with the potential to contribute to carbon sequestration and long-term storage. Seabed sediments represented the largest and potentially most stable carbon reservoir in Shetland's marine environment. These values align with regional estimates across Scottish waters (Burrows *et al.*, 2024; Smeaton and Austin, 2022) and reinforce the role of sediments in long-term carbon sequestration. However, despite limited mapped extent of blue carbon habitats, their high organic carbon (OC) density demonstrates their importance. Mapped seagrass meadows and maerl beds account for only a small fraction of total blue carbon habitat extent in the Shetland Islands, yet they have relatively high carbon densities per unit area based on averages taken from Burrows *et al.* (2024). Seagrass meadows, for example, contain approximately eight times more carbon than sand and nearly three times more than mud, while maerl beds hold approximately four times more than sand and 1.3 times more than mud. It should be noted that much of Shetland's seabed is composed of carbon-poor sediment – including sands, mixed and coarse sediments, and bedrock – creating a varied mosaic in which high-carbon habitats are dispersed within larger areas of low-carbon substrate.

It is important to note that the carbon estimates presented here represent a conservative calculation, representing only the top 10 cm of the seabed. Evidence from other regions suggests that organic-rich layers in biogenic habitats can extend much deeper. Horse mussel beds in the Orkney Islands have been shown to have an average depth of 78 cm and maximum depths of up to 300 cm (Sheehy *et al.*, 2024a). Live maerl deposits on Scotland's west coast reach 60 cm, underlain by extensive dead layers (Kamenos, 2010), while surveys in the Orkney Islands report average maerl bed thicknesses of 108 cm (Sheehy *et al.*, 2024b). If current estimates were extrapolated across these depths, carbon storage potential could be between 6 to 30 times greater than values presented here. The differences observed between different sites of the same habitat type, highlight the need for accurate, locally relevant carbon estimates.

Predictive models suggest substantially larger areas of potential blue carbon habitat extending beyond mapped extents. No seagrass areas were predicted with a suitability score above 0.9, likely reflecting limitations of the modelling resolution in very shallow nearshore environments where seagrass predominates. Other predicted blue carbon habitats remain largely unverified, highlighting the need for targeted ground-truthing through exploratory methods such as drop-down video surveys which would confirm the presence, density, and ecological quality of predicted blue carbon habitats.

The model results presented here estimate a substantial OC stock associated with predicted high and medium energy kelp forests. However, this assumes that kelp does not contribute to long-term carbon sequestration due to uncertainty surrounding the fate of exported kelp material. Although kelp is highly productive and plays a key role in carbon fixation and export, it is thought that much of the detritus is either decomposed or transported to environments where it may not be permanently buried (Pessarrodona *et al.*, 2018). This reflects a broader knowledge gap regarding the sequestration pathways and permanence of macroalgal carbon. The lack of clarity on whether exported kelp-derived carbon is ultimately sequestered in deep-sea sediments or other depositional environments remains a critical limitation in current carbon accounting frameworks. Addressing this gap through targeted

research is key to refining sequestration estimates and to better understand the role of kelp forests in climate mitigation strategies.

5.1 Management Implications

The spatial diversity of carbon storage in Shetland's marine environment has direct implications for environmental management and decision-making. High-carbon habitats, such as maerl beds and seagrass meadows, are often concentrated in relatively small, dispersed areas, whereas large areas of seabed sediments contain moderate to no carbon. This distribution indicates that the most valuable carbon stores are located in discrete patches, highlighting the potential for targeted protection or restoration to deliver disproportionate benefits. Currently in the Shetland Islands, many of these predicted habitats overlap with spatially managed zones such as the SSMO closed areas and existing national marine protected area designations. These areas have been voluntarily closed to protect vulnerable benthic habitats from mobile fishing gear. Reduced physical disturbance in these zones may not only preserve existing blue carbon features but also create conditions favourable for the natural expansion or recovery of these habitats. Understanding the interplay between protection measures and habitat resilience will be key to improving carbon stock estimates and informing future spatial planning and conservation strategies. Protective measures like these, informed by local data, can deliver large carbon benefits by safeguarding high-value sites, demonstrating how existing conservation frameworks can serve dual biodiversity and climate mitigation objectives.

5.2 Recommendations for Future Research Work

While modelled habitat distributions offer valuable insight into the potential extent of blue carbon ecosystems in the Shetland Islands, several uncertainties remain that limit the completeness and precision of the resulting carbon budget. A primary limitation is the absence of site-specific data on OC density, storage rates, and annual productivity. Without these key metrics, it is not possible to generate a fully representative or comprehensive estimate of Shetland's marine carbon stocks and sequestration potential.

Additionally, the reliance on national averages values, whilst useful, introduces further uncertainty. These averages may not accurately reflect the environmental conditions of Shetland's marine ecosystems, due to differences in terms of hydrodynamics, temperature regimes and substrate composition. Such local-scale variability can influence both carbon storage capacity and ecological functioning of blue carbon habitats.

To improve the resolution and reliability of blue carbon assessments in Shetland, future research should prioritise:

- **Field validation** of predicted blue carbon habitats through methods such as drop-down video surveys;
- **Measurement of site-specific carbon values**, including OC content in sediments and biomass productivity;
- **Inclusion of nearshore and intertidal zones**;
- **Improved understanding of carbon fate**, particularly for habitats like kelp forests where exported material may or may not contribute to long-term sequestration.

These efforts will enable more accurate local carbon accounting, better inform marine management, including marine spatial planning and marine conservation, and support the development of climate mitigation policies that integrate marine ecosystem services.

Table 8 - Knowledge gaps in the Shetland Islands blue carbon habitats, adapted and expanded from Porter *et al.* (2020).

<i>Habitat Type</i>	<i>Knowledge Gap</i>
<i>All</i>	- Ground truthing predicted distribution models - Variability in sequestration capacity under differing environmental conditions - Lack of data on ▪ site-specific organic and inorganic carbon values for Shetland waters ▪ carbonate sediment depth underlying beds ▪ age of beds ▪ accumulation rate of beds
<i>Seagrass meadows</i>	- Limited understanding of growth rates and seasonal variability
<i>Kelp forests</i>	- Limited understanding regarding the fate and burial potential of exported kelp detritus in Shetland waters - Absence of sequestration potential amongst different species - Absence of long-term sequestration data
<i>Maerl beds</i>	- Uncertainty in the role of maerl mosaics in long-term carbon storage
<i>Brittlestar beds</i>	- Limited knowledge on the long-term role of brittlestars in carbon storage
<i>Horse mussel beds</i>	- Lack of organic carbon values for the tissue and shell components of horse mussels
<i>Sediment</i>	- Limited knowledge on depth of sediments - Limited knowledge on carbon accumulation and burial rate data for finer sediments

6 Conclusion

This study provides the first assessment of sublittoral blue carbon habitats in the Shetland Islands, integrating mapped observations with predictive spatial modelling to estimate habitat extent and carbon sequestration potential highlighting three key findings:

1. habitats such as maerl beds and seagrass meadows provide high carbon densities but occupy limited spatial extent;
2. seabed sediments, though variable in carbon density, cover extensive areas and represent the largest overall current carbon store in the Shetland Islands;
3. blue carbon habitats and sediments create a diverse mosaic of varying carbon values across Shetland's marine environment, with high-value carbon stores concentrated in relatively small, discrete areas.

The findings provide an initial estimate towards natural climate mitigation, of importance when considering Scotland's net-zero ambitions, and ecological value of Shetland's marine environments. Although the total mapped extent of blue carbon habitats is currently small (19.15 ha), predictive modelling suggests a much broader potential distribution (62.04 km²). These modelled habitats, many of which overlap with existing spatial protection zones, present an opportunity for nature-based climate mitigation and biodiversity co-benefits through targeted conservation and management.

Moving forward, this baseline assessment highlights the importance of local-scale carbon measurements, habitat ground-truthing, and enhanced monitoring to refine regional carbon budgets. These improvements are essential not only for accurate carbon accounting but also for shaping marine spatial planning and policy decisions that align with Scotland's net-zero targets.

7 References

- Allouche, O., Tsoar, A. and Kadmon, R. (2006) 'Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS)', *Journal of applied ecology*, 43(6), pp. 1223-1232.
- Baldwin, R. A. (2009) 'Use of maximum entropy modeling in wildlife research', *Entropy*, 11(4), pp. 854-866.
- Baxter, J. M., Boyd, I. L., Cox, M., Donald, A., Malcolm, S., Miles, H., Miller, B. and Moffat, C. (2011) 'Scotland's Marine Atlas: Information for the national marine plan'.
- Blake, C. and Maggs, C. A. (2003) 'Comparative growth rates and internal banding periodicity of maerl species (Corallinales, Rhodophyta) from northern Europe', *Phycologia*, 42(6), pp. 606-612.
- Bosence, D. and Wilson, J. (2003) 'Maerl growth, carbonate production rates and accumulation rates in the northeast Atlantic', *Aquatic conservation*, 13, pp. S21-S32.
- Broom, D. (1975) 'Aggregation behaviour of the brittle-star *Ophiothrix fragilis*', *Journal of the Marine Biological Association of the United Kingdom*, 55(1), pp. 191-197.
- Burrows, M., Hughes, D., Austin, W. E., Smeaton, C., Hicks, N., Howe, J., Allen, C., Taylor, P. and Vare, L. (2017) 'Assessment of Blue Carbon Resources in Scotland's Inshore Marine Protected Area Network: Commissioned Report No 957'.
- Burrows, M., Kamenos, N., Hughes, D., Stahl, H., Howe, J. and Tett, P. (2014) 'Assessment of carbon budgets and potential blue carbon stores in Scotland's coastal and marine environment'.
- Burrows, M., Tillin, H., Grundy, S., Smeaton, C., Austin, W. B. and O'Dell, A. (2024) 'The United Kingdom's Blue Carbon Inventory:: Assessment of Marine Carbon Storage and Sequestration Potential in the English Channel and Western Approaches Region (Including Within Marine Protected Areas)'.
- Bustamante, R. H. and Branch, G. M. (1996) 'The dependence of intertidal consumers on kelp-derived organic matter on the west coast of South Africa', *Journal of Experimental Marine Biology and Ecology*, 196(1-2), pp. 1-28.
- Coetsee, B. W., Robertson, M. P., Erasmus, B. F., Van Rensburg, B. J. and Thuiller, W. (2009) 'Ensemble models predict Important Bird Areas in southern Africa will become less effective for conserving endemic birds under climate change', *Global Ecology and Biogeography*, 18(6), pp. 701-710.
- Connor, D. W., Allen, J. H., Golding, N., Howell, K. L., Lieberknecht, L. M., Northen, K. O. and Reker, J. B. 2004. The Marine Habitat Classification for Britain and Ireland. Version 04.05. JNCC: Peterborough, UK.
- Cunningham, C. and Hunt, C. (2023) *Scottish blue carbon—a literature review of the current evidence for Scotland's blue carbon habitats*: NatureScot Research Report 1326. NatureScot, Inverness.
- Davies, A. J. and Guinotte, J. M. (2011) 'Global habitat suitability for framework-forming cold-water corals', *PloS one*, 6(4), pp. e18483.
- Duarte, C. M., Bruhn, A. and Krause-Jensen, D. (2022) 'A seaweed aquaculture imperative to meet global sustainability targets', *Nature Sustainability*, 5(3), pp. 185-193.
- Duggins, D. O., Simenstad, C. and Estes, J. A. (1989) 'Magnification of secondary production by kelp detritus in coastal marine ecosystems', *Science*, 245(4914), pp. 170-173.
- Esri Inc. (2024). ArcGIS Pro 3.2.1 [Software]. Redlands, CA: Esri Inc.
- Fourcade, Y., Engler, J. O., Rödder, D. and Secondi, J. (2014) 'Mapping species distributions with MAXENT using a geographically biased sample of presence data: a performance assessment of methods for correcting sampling bias', *PloS one*, 9(5), pp. e97122.
- Frankignoulle, M., Canon, C. and Gattuso, J. P. (1994) 'Marine calcification as a source of carbon dioxide: positive feedback of increasing atmospheric CO₂', *Limnology and Oceanography*, 39(2), pp. 458-462.
- Fraser, S., Ayres, S., McAllister, M., Thomason, L., Cubbon, K. and Angus, C. (2024) 'Survey report for the 2023 Fair Isle inshore fish survey'.

- Gama, M., Crespo, D., Dolbeth, M. and Anastácio, P. M. (2017) 'Ensemble forecasting of *Corbicula fluminea* worldwide distribution: Projections of the impact of climate change', *Aquatic Conservation: Marine and Freshwater Ecosystems*, 27(3), pp. 675-684.
- Giesler, R., Allan, K. and Shucksmith, R. (2025) *Searching for Shetland's lost seagrass: establishing the baseline distribution and abundance of seagrass in the Shetland Islands*.
- Green, A. E., Unsworth, R. K., Chadwick, M. A. and Jones, P. J. (2021) 'Historical analysis exposes catastrophic seagrass loss for the United Kingdom', *Frontiers in plant science*, 12, pp. 629962.
- Halliday, R. (2011) *Shetland Islands Wave and Tidal Resource. Report 805_NPC_SIC_004 prepared for Shetland Islands Council*.
- Hernandez, P. A., Graham, C. H., Master, L. L. and Albert, D. L. (2006) 'The effect of sample size and species characteristics on performance of different species distribution modeling methods', *Ecography*, 29(5), pp. 773-785.
- Hily, C. (1991) 'Is the activity of benthic suspension feeders a factor controlling water quality in the Bay of Brest?', *Marine ecology progress series. Oldendorf*, 69(1), pp. 179-188.
- Hughes, D. (1998) 'Subtidal brittlestar beds (volume IV)', *An overview of dynamics and sensitivity characteristics for conservation management of marine SACs. Scottish Association for Marine Science (UK Marine SACs Project)*.
- Jiménez-Valverde, A. (2012) 'Insights into the area under the receiver operating characteristic curve (AUC) as a discrimination measure in species distribution modelling', *Global Ecology and Biogeography*, 21(4), pp. 498-507.
- JNCC (2023) *Marine Habitat Classification for Britain and Ireland*.
- Kamenos, N. A. (2010) 'North Atlantic summers have warmed more than winters since 1353, and the response of marine zooplankton', *Proceedings of the National Academy of Sciences*, 107(52), pp. 22442-22447.
- Kamenos, N. A., Moore, P. G. and Hall-Spencer, J. M. (2004a) 'Nursery-area function of maerl grounds for juvenile queen scallops *Aequipecten opercularis* and other invertebrates', *Marine ecology progress series*, 274, pp. 183-189.
- Kamenos, N. A., Moore, P. G. and Hall-Spencer, J. M. (2004b) 'Small-scale distribution of juvenile gadoids in shallow inshore waters; what role does maerl play?', *ICES journal of marine science*, 61(3), pp. 422-429.
- Krause-Jensen, D. and Duarte, C. M. (2016) 'Substantial role of macroalgae in marine carbon sequestration', *Nature Geoscience*, 9(10), pp. 737-742.
- Krause-Jensen, D., Lavery, P., Serrano, O., Marbà, N., Masque, P. and Duarte, C. M. (2018) 'Sequestration of macroalgal carbon: the elephant in the Blue Carbon room', *Biology letters*, 14(6), pp. 20180236.
- Langmead, O., Mieszkowska, N., Ellis, R. & Hiscock, K. 2008. Rock and biogenic reef habitats: Review of indicators and identification of gaps. Report to the Joint Nature Conservation Committee from the Marine Biological Association. Plymouth, Marine Biological Association.
- Lebrato, M., Iglesias-Rodríguez, D., Feely, R. A., Greeley, D., Jones, D. O., Suarez-Bosche, N., Lampitt, R. S., Cartes, J. E., Green, D. R. and Alker, B. (2010) 'Global contribution of echinoderms to the marine carbon cycle: CaCO₃ budget and benthic compartments', *Ecological Monographs*, 80(3), pp. 441-467.
- Liu, C., Berry, P. M., Dawson, T. P. and Pearson, R. G. (2005) 'Selecting thresholds of occurrence in the prediction of species distributions', *Ecography*, 28(3), pp. 385-393.
- Mao, J., Burdett, H. L., McGill, R. A., Newton, J., Gulliver, P. and Kamenos, N. A. (2020) 'Carbon burial over the last four millennia is regulated by both climatic and land use change', *Global Change Biology*, 26(4), pp. 2496-2504.
- Mcleod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H. and Silliman, B. R. (2011) 'A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO₂', *Frontiers in Ecology and the Environment*, 9(10), pp. 552-560.

- Nellemann, C. and Corcoran, E. (2009) *Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment*. UNEP/Earthprint.
- Norris, C., Roberts, C., Epstein, G., Crockett, D., Natarajan, S., Barisa, K., Locke, S. (2021) 'Blue Carbon in the United Kingdom: Understanding and developing the opportunity.
- O'Dell, A. (2022) *Scotland's blue carbon: the contribution from seaweed detritus*. University of the Highlands and Islands.
- OSPAR (2009) *Background document for Zostera beds, Seagrass beds*. Available at: <http://www.ospar.org/documents?d=7190>.
- Parry, M. (2019) 'Guidance on assigning benthic biotopes using EUNIS or the marine habitat classification of Britain and Ireland (Revised 2019)', *JNCC report*, 54617.
- Pessarrodona, A., Moore, P. J., Sayer, M. D. and Smale, D. A. (2018) 'Carbon assimilation and transfer through kelp forests in the NE Atlantic is diminished under a warmer ocean climate', *Global Change Biology*, 24(9), pp. 4386-4398.
- Phillips, S. J., Anderson, R. P. and Schapire, R. E. (2006) 'Maximum entropy modeling of species geographic distributions', *Ecological modelling*, 190(3-4), pp. 231-259.
- Phillips, S. J. and Dudík, M. (2008) 'Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation', *Ecography*, 31(2), pp. 161-175.
- Poloczanska, E., Hughes, D. and Burrows, M. (2004) 'Underwater television observations of *Serpula vermicularis* (L.) reefs and associated mobile fauna in Loch Creran, Scotland', *Estuarine, Coastal and Shelf Science*, 61(3), pp. 425-435.
- Porter, J., Austin, W., Burrows, M., Clarke, D., Davies, G., Kamenos, N., Riegel, S., Smeaton, C., Page, C. and Want, A. (2020) 'Blue carbon audit of Orkney waters'.
- Riley, T., Giesler, R., Allan, K. and Shucksmith, R. (2025) *Guiding Marine Restoration and Enhancement in the Shetland Islands*. Shetland UHI report.
- Riley, T. G., Mouat, B. and Shucksmith, R. (2024) 'Real world data for real world problems: Importance of appropriate spatial resolution modelling to inform decision makers in marine management', *Ecological Modelling*, 498, pp. 110864.
- Riley, T. G. and Shucksmith, R. J. (2024) *Towards Net Zero: The role of marine habitats*. Shetland UHI report.
- Riley, T. G. and Shucksmith, R. J. (2025) *Shetland Islands Dominant Marine Biotope Map (2024 update)*. Shetland UHI report.
- Scott, W. and Palmer, R. (1987) *The flowering plants and ferns of the Shetland Islands*. Shetland Times.
- Sheehy, J., Bates, R., Bell, M. and Porter, J. (2024a) 'Sounding out horse mussel sediment thickness: an integrated data approach', *Frontiers in Marine Science*, 11, pp. 1321366.
- Sheehy, J., Bates, R., Bell, M. and Porter, J. (2024b) 'Sounding out maerl sediment thickness: an integrated data approach', *Scientific Reports*, 14(1), pp. 5220.
- Shelmerdine, R. L. and Mouat, B. (2020) 'Distribution of maerl and horse mussels (*Modiolus modiolus*) around Shetland: findings from a directed PMF survey'. NAFC Marine Centre UHI report. Pp. 57.
- Shelmerdine, R. L., Robinson, M., Johnson, A., Leslie, B., Stone, D. and Tait, L. (2013) 'Assessment of the appropriateness of areas closed to protect priority marine features from scallop dredging around Shetland'. NAFC Marine Centre.
- Smale, D. A., Burrows, M. T., Moore, P., O'Connor, N. and Hawkins, S. J. (2013) 'Threats and knowledge gaps for ecosystem services provided by kelp forests: a northeast Atlantic perspective', *Ecology and evolution*, 3(11), pp. 4016-4038.
- Smale, D. A., Pessarrodona, A., King, N., Burrows, M. T., Yunnice, A., Vance, T. and Moore, P. (2020) 'Environmental factors influencing primary productivity of the forest-forming kelp *Laminaria hyperborea* in the northeast Atlantic', *Scientific reports*, 10(1), pp. 12161.
- Smale, D. A., Pessarrodona, A., King, N. and Moore, P. J. (2022) 'Examining the production, export, and immediate fate of kelp detritus on open-coast subtidal reefs in the Northeast Atlantic', *Limnology and Oceanography*, 67, pp. S36-S49.

- Smeaton, C. and Austin, W. (2022) 'Understanding the role of terrestrial and marine carbon in the mid-latitude fjords of Scotland', *Global Biogeochemical Cycles*, 36(11), pp. e2022GB007434.
- Toochi, E. C. (2018) 'Carbon sequestration: how much can forestry sequester CO₂', *For. Res. Eng. Int. J*, 2(3), pp. 148-150.
- Turrell, W., Austin, W., Philbrick, S., Tilbrook, C. and Kennedy, H. (2023) 'Clarifying the role of inorganic carbon in blue carbon policy and practice', *Marine Policy*, 157, pp. 105873.
- Tyler-Walters, H., James, B., Carruthers, M., Wilding, C., Durkin, O., Lacey, C., Philpott, E., Adams, L., Chaniotis, P. and Wilkes, P. (2016) 'Descriptions of Scottish Priority Marine Features (PMFs)'.
- Young, N., Carter, L. and Evangelista, P. (2011) 'A MaxEnt model v3. 3.3 e tutorial (ArcGIS v10)', *Natural Resource Ecology Laboratory, Colorado State University and the National Institute of Invasive Species Science*.
- Zurell, D., Franklin, J., König, C., Bouchet, P. J., Dormann, C. F., Elith, J., Fandos, G., Feng, X., Guillerá-Arroita, G. and Guisan, A. (2020) 'A standard protocol for reporting species distribution models', *Ecography*, 43(9), pp. 1261-1277.

8 Acknowledgments

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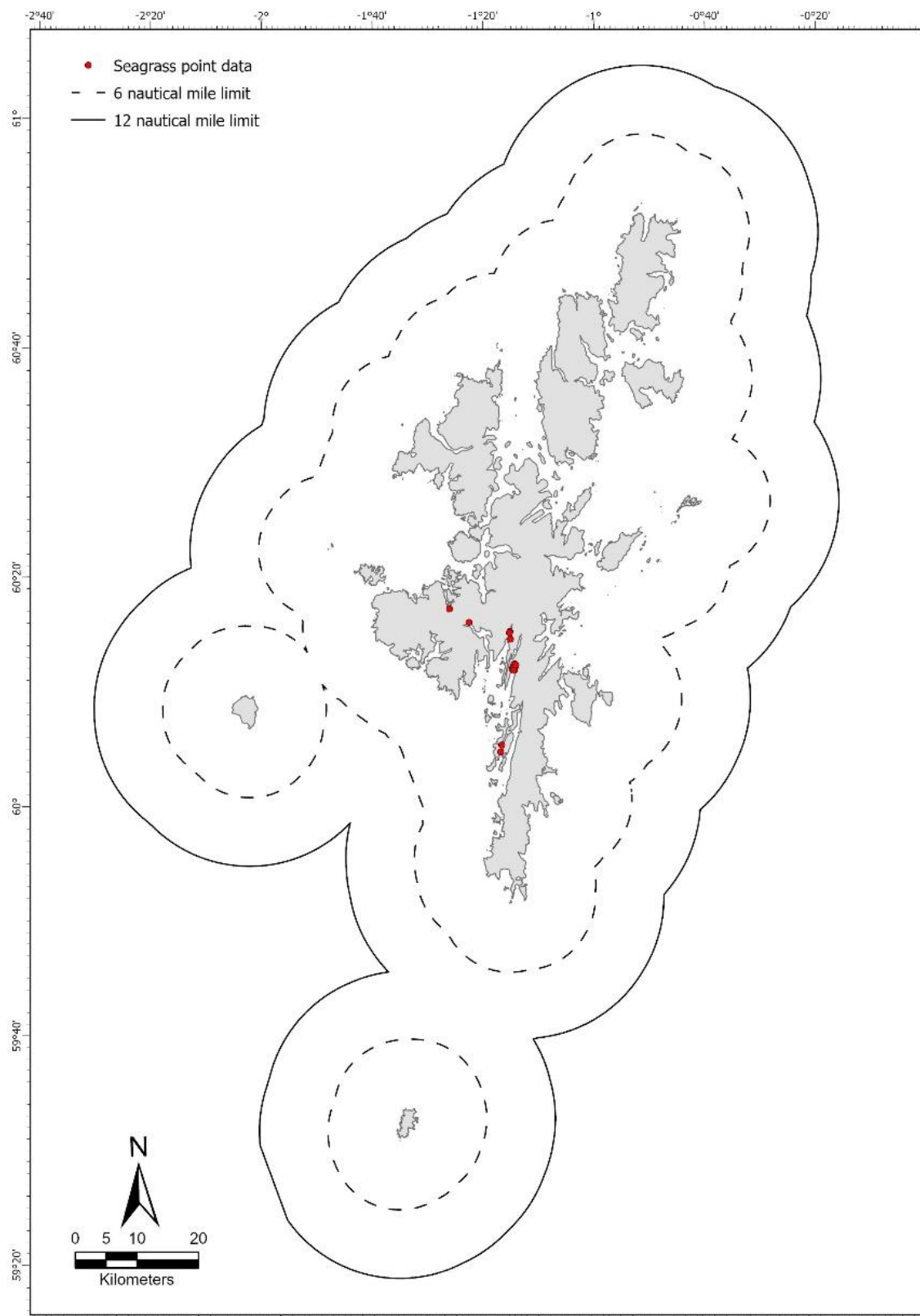
Appendix 1. Shetland Sublittoral Sediment Biotope Aggregation

<i>Sediment Class Assigned</i>	<i>Level 4 Biotope Name¹¹</i>
<i>Rock</i>	High energy circalittoral rock Low energy circalittoral rock Echinoderm and crustose communities Kelp with cushion fauna and/or foliose red seaweeds Sediment-affected or disturbed kelp and seaweed communities Silted kelp communities (sheltered infralittoral rock) Kelp and red seaweeds (moderate energy infralittoral rock) Kelp and seaweed communities in tide-swept sheltered conditions
<i>Coarse Sediment</i>	Circalittoral coarse sediment Infralittoral coarse sediment Offshore coarse sediment
<i>Mixed Sediment</i>	Circalittoral mixed sediment Infralittoral mixed sediment Offshore circalittoral mixed sediment
<i>Mud</i>	Circalittoral fine mud Circalittoral sandy mud Infralittoral fine mud Infralittoral sandy mud Offshore circalittoral mud
<i>Sand</i>	Circalittoral fine sand Circalittoral muddy sand Infralittoral fine sand Infralittoral muddy sand Offshore circalittoral sand
<i>Other Sediment Type</i>	Sublittoral mussel beds Kelp and seaweed communities on sublittoral sediment Maerl beds Seagrass

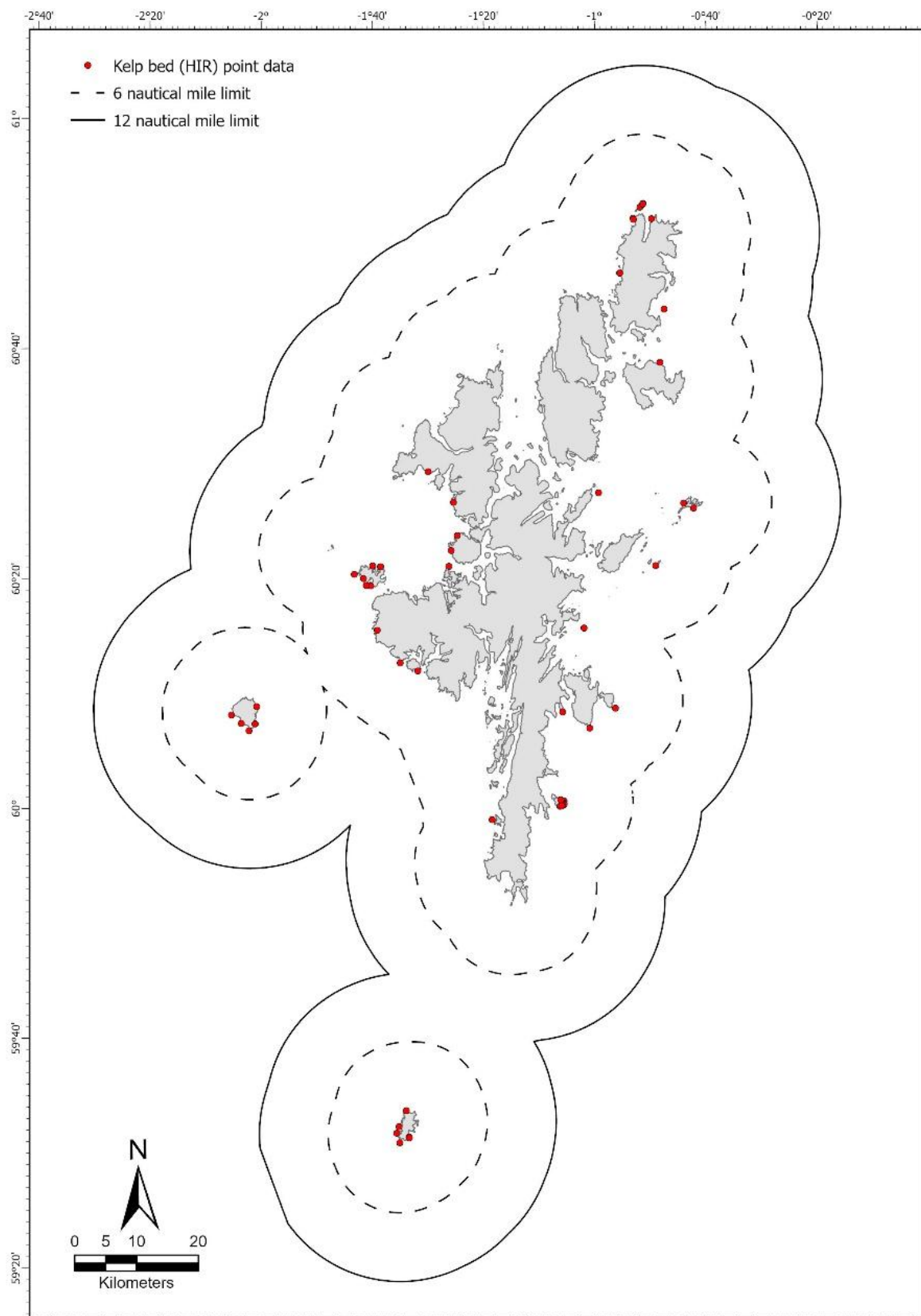
¹¹ JNCC (2023) *Marine Habitat Classification for Britain and Ireland*.

Appendix 2. Blue carbon habitat presence data in the Shetland Islands used in habitat suitability models

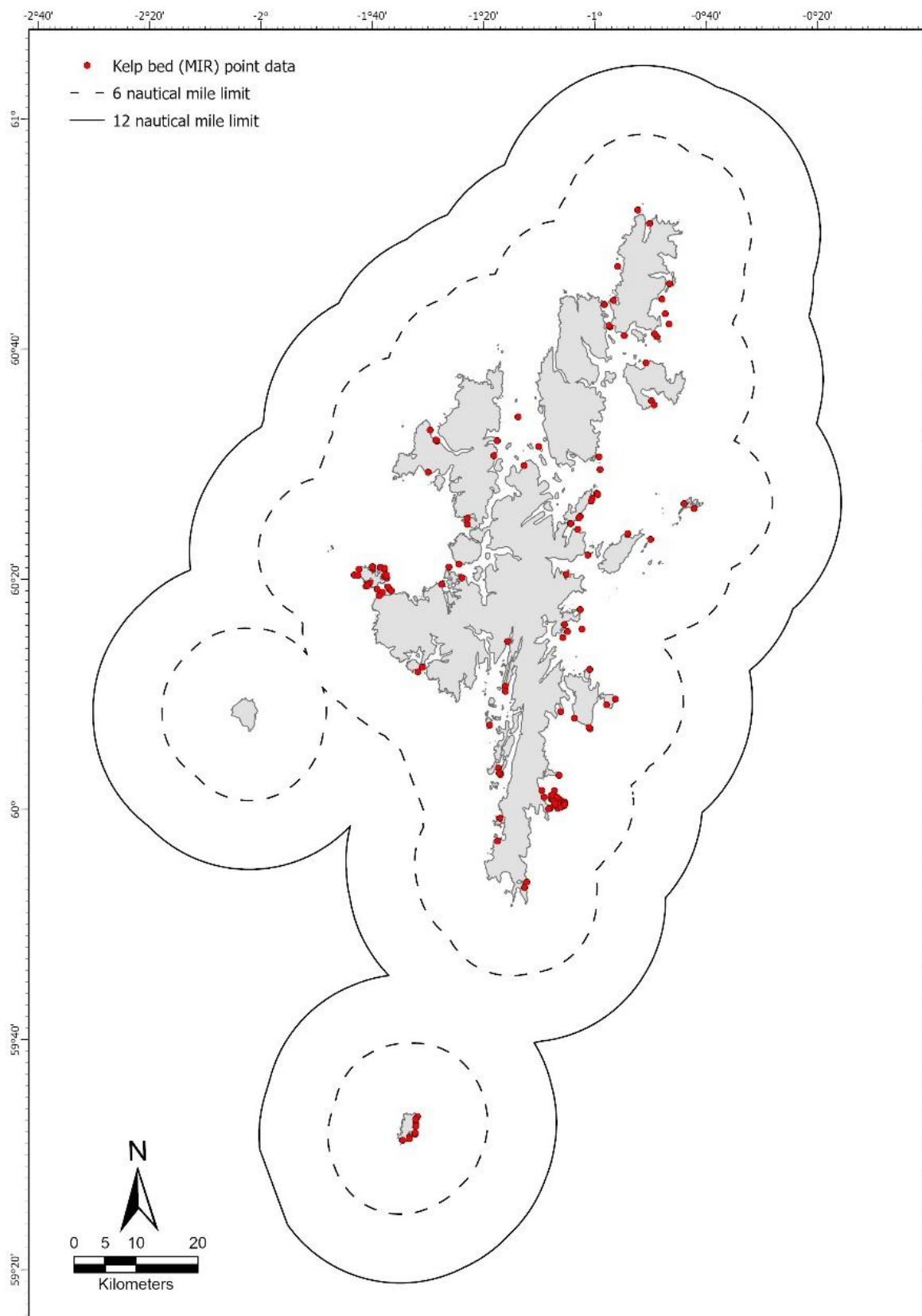
a. Seagrass meadows point data



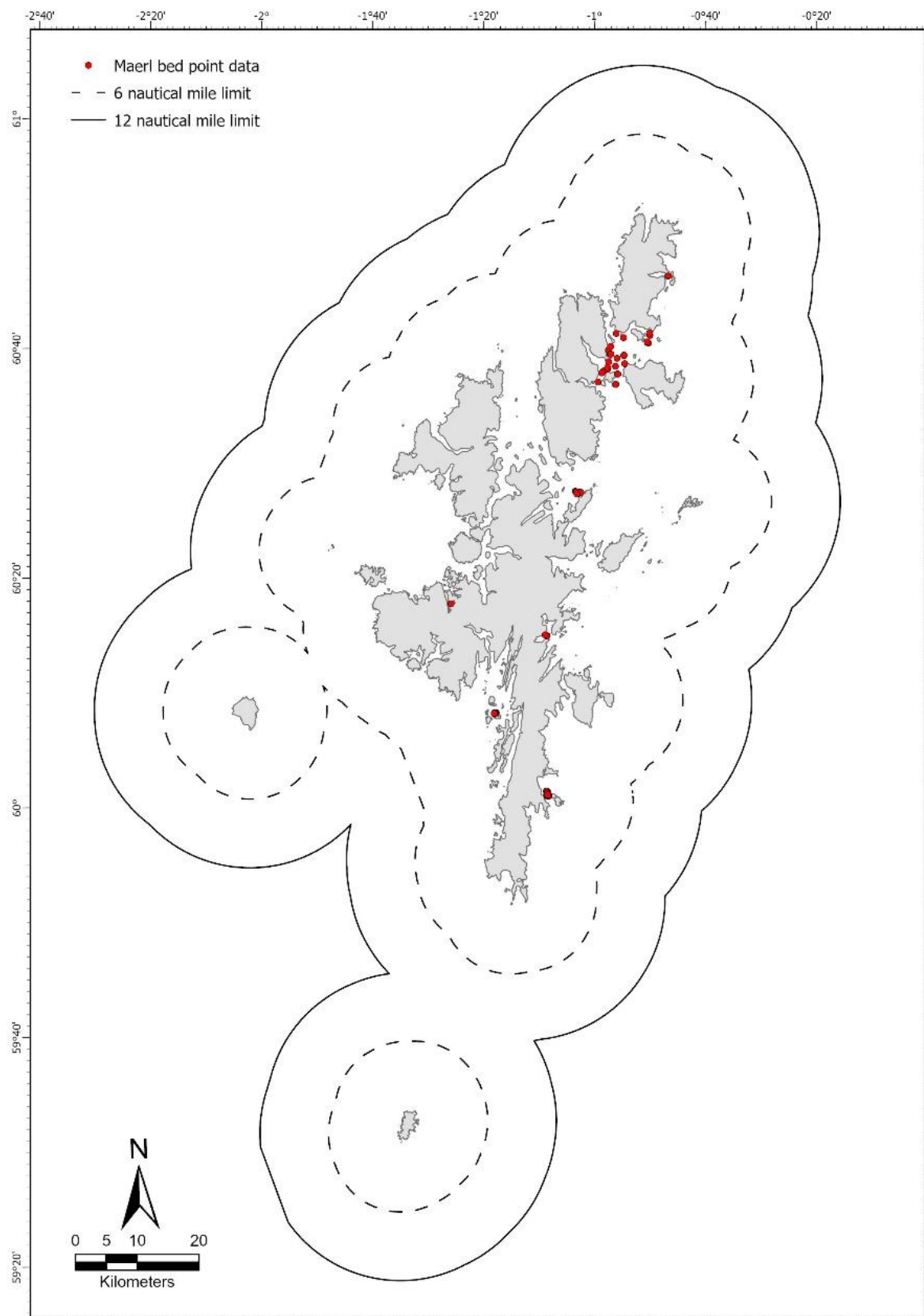
b. Kelp forest (high energy) point data



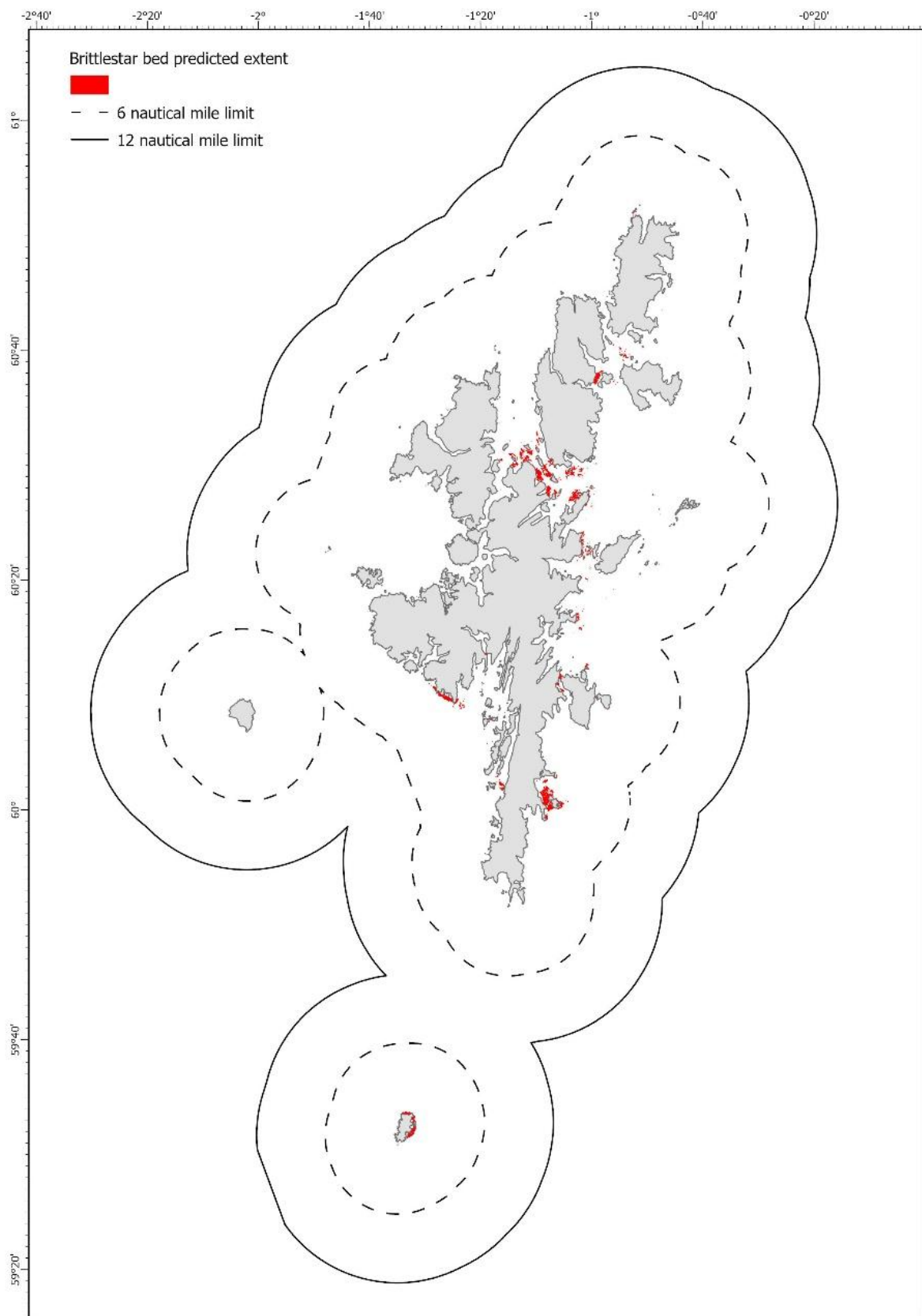
c. Kelp forest (medium energy) point data



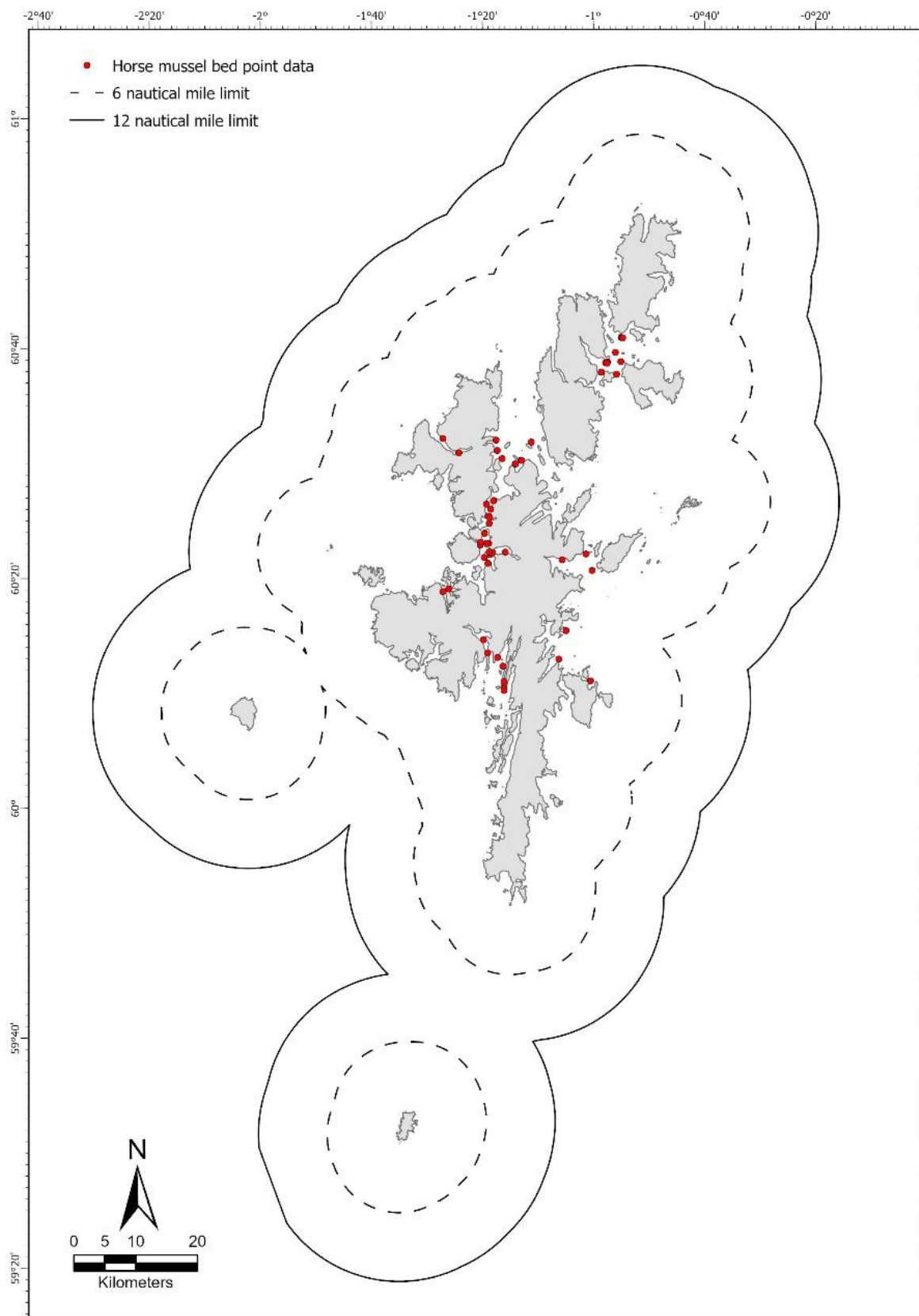
d. Maerl bed point data



e. Brittlestar bed point data



f. Horse mussel bed point data



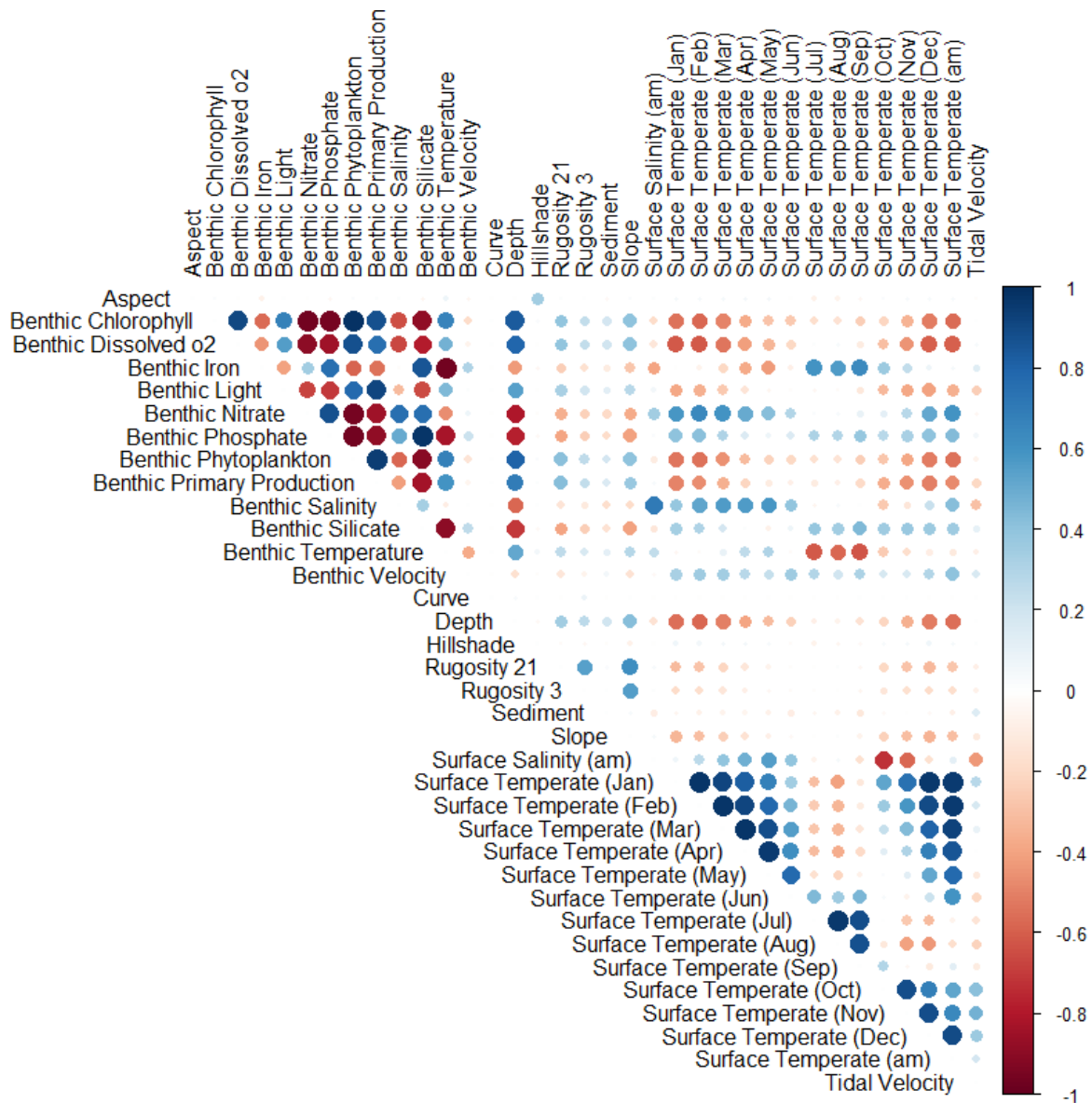
Appendix 3. ODMAP Standard Protocol

ODMAP element	Contents
OVERVIEW	
<u>Authorship</u>	Authors: Tanya G. Riley, Rachel Shucksmith Contact email: tanya.riley@uhi.ac.uk Title: Exploring Sublittoral Blue Carbon Habitat Suitability and Potential in the Shetland Islands Access: https://pure.uhi.ac.uk/en/persons/tanya-riley/
<u>Model objectives</u>	Objective: Mapping/interpolation. Target outputs: Maps of relative probability of presence
<u>Taxon</u>	• Brittlestar beds (<i>Ophiothrix fragilis</i>) • Kelp forests (<i>Laminaria hyperborea</i>) • Maerl beds (<i>Phymatolithon calcareum</i>, <i>Lithothamnion glaciale</i>) • Seagrass (<i>Zostera marina</i>) • Sublittoral mussel beds (<i>Modiolus modiolus</i>)
<u>Location</u>	Shetland Islands to the 12 nm extent
<u>Scale of analysis</u>	Spatial extent (Lon/Lat): 61°03' - 59°18' N and 2°31' - 0°00' W Spatial resolution: 50m Temporal extent/time period: 1968 -2024 Type of extent boundary: 12 nm
<u>Biodiversity data overview</u>	Observation type: Boat surveys, diver records Response/Data type: Presence-only
<u>Types of predictors</u>	Bathymetric, benthic oceanographic, sediment, sea surface temperature and tidal velocity.
<u>Conceptual model / hypothesis</u>	Assess the potential for blue carbon habitats within Shetland waters (12 nm).
<u>Assumptions</u>	We assumed that: • Relevant ecological drivers/proxies of habitat distributions are included. • Detectability does not change across transects or habitat gradients. • Habitats are at equilibrium with their environment.
<u>SDM Algorithms</u>	Algorithm: MaxEnt. Chosen due to competitive performance on small sample sizes and presence only data. Model complexity: MaxEnt models were built with linear, quadratic, product and hinge features. Model Averaging: 10-fold cross validate replicates.
<u>Model workflow</u>	Prior to model building, all predictor variables were standardised (as detailed in 'predictor variables') and correlation analysis conducted with

	variables omitted where a correlation coefficient exceeded 0.7 (Davies and Guinotte, 2011).
<u>Software</u>	Software: Analyses were conducted in ArcGIS Pro v2.3.1 and MaxEnt v3.4.4 (https://biodiversityinformatics.amnh.org/open_source/maxent/). Data availability: Data are available in an open, online, digital repository.
DATA	
<u>Biodiversity data</u>	Ecological level: Biotope Level 4 and Level 5 in accordance with JNCC Marine Habitat Classification for Britain and Ireland. Data source: Survey data taken from Geodatabase of Marine Features in Scotland (GeMS; accessed May 2025) spanning the years 1962 to 2024, and additional data from Fraser <i>et al.</i> (2024), Riley and Shucksmith (2025), (Giesler, Allan and Shucksmith, 2025). Sampling design: As the data was taken from a collated database this resulted in a range of sampling designs including opportunistic and targeted surveys, and a variety of sampling techniques; Drop-Down Videos, grabs, core samples and dive surveys. Sample size: The data contains 612 presence points across the differing blue carbon habitats. Regional mask: All data was clipped to the boundary of the study region. Data cleaning/filtering: Occurrences cited as “confirmed” were used. Errors and biases: Error rates deemed low as all records used in the study came from either physical dives or visual records (image and/or sample).
<u>Data partitioning</u>	Data Partitioning: 10-fold cross validation Model performance: 10 replicates
<u>Predictor variables</u>	• Predictor variables: • Bathymetric: aspect, curvature, depth, slope angle. • Benthic: light, salinity, temperature, velocity • Climate: sea surface temperature (monthly), sediment and tidal velocity. • Data sources: • Bathymetric: Compiled from: UK Hydrographic Office (https://www.admiralty.co.uk/access-data), Marine Scotland (Shetland Bathymetry 2012 marine.gov.scot), UHI Shetland and EMODnet Digital Bathymetry (DTM 2020) (https://emodnet.ec.europa.eu/en/bathymetry) • Benthic and sea surface temperature: Bio-ORACLE (https://www.bio-oracle.org/) • Tidal velocity: Natural Power • Spatial resolution and extant of raw data • Bathymetric: 2-115 m resolution. • Benthic: 0.05 degrees resolution. • Sediment: 100 m resolution. • Tidal velocity: 10m resolution. • Surface temperature: 1/12th degree resolution.

	• Geographic projection: WGS 1984 (EPSG:4326) • Temporal resolution of raw data: • Bathymetric: 1816-2020. • Benthic: 2010-2020. • Sediment: 2018. • Tidal velocity: 2001. • Surface temperature: 2010-2020. Data processing: layers are processed to a 50m grid resolution and clipped to the 12 nm limit of Shetland for use in the model. Predicted blue carbon extent was clip at probability of occurrence ≥ 0.9.
MODEL	
<u>Variable pre-selection</u>	Using an <i>a priori</i> approach based on available variables known or thought to influence benthic biotope distribution, including bathymetric variables, alongside sediment and benthic oceanographic variables.
<u>Multicollinearity</u>	Correlation analysis was conducted, and variables omitted where a correlation coefficient exceeded 0.7 (Davies & Guinotte, 2011).
<u>Model settings</u>	MaxEnt: (If italicised this has been changed from default) Log output, Feature set (Auto features: linear, quadratic, product and hinge features), Random seed (Yes), Remove duplicate presence records (Yes), Random test percentage (25), Regularization multiplier (1), Max number of background points (10000), Replications (10), Replicate run type (Crossvalidation), Maximum iteration (5000), Convergence threshold set (0.00001).
<u>Model estimates</u>	Covariate importance calculated with jackknife analyses of the regularised gain with training data, which accounts for dependencies between predictor variables by building two sorts of models: one involving a given predictor by itself, and the other involving all features except for the given predictor.
<u>Threshold selection</u>	To reduce overlapping locations among multiple models the "Highest Position" function was utilised in ArcGIS Pro. This function assessed multiple raster datasets on a cell-by-cell basis, returning the position of the raster with the highest value for each cell.
ASSESSMENT	
<u>Performance Statistics</u>	The averaged AUC and TSS scores were used as model predictive performance, following 10-fold crossvalidation with ten replicates
<u>Plausibility checks</u>	Expert judgement and comparison with known habitat extent.
PREDICTION	
<u>Prediction output</u>	The model output represents the predicted extent of blue carbon habitats in the Shetland Islands.

Appendix 4. Correlation matrix of the environmental layers developed for this study



Appendix 5. Environmental layers used for this study¹²

Variable	Units	Native Resolution	Source
Bathymetric Variables			
Aspect	N, NE, E, SE, S, SW, W, NW	2-115m	Compiled from the following sources: UK Hydrographic Office, Marine Scotland, UHI Shetland and EMODnet (EMODnet, 2018)
Curvature	Concave, Flat, Convex	2-115m	
Depth	M	2-115m	
Slope Angle	°	2-115m	
Benthic Variables			
Light	E/m ² /year	0.05 degrees	All benthic variables sourced from Bio-ORACLE (Assis <i>et al.</i> , 2018; Tyberghein <i>et al.</i> , 2018)
Salinity	PSS	0.05 degrees	
Temperature	°C	0.05 degrees	
Velocity	m/s	0.05 degrees	
Additional Variables			
Sediment	GSM, sand, rock, gravel, mud	100m	UK Sea Map 2018 (JNCC, 2018)
Surface Temperature	°C	1/12 th degree	Bio-ORACLE (Assis <i>et al.</i> , 2018; Tyberghein <i>et al.</i> , 2018)
Tidal Velocity	m/s	10m	Natural Power (Halliday, 2011)

¹² Riley, T. G., Mouat, B. & Shucksmith, R. (2024). Real world data for real world problems: Importance of data resolution appropriate modelling to inform decision makers in marine management. *Ecological Modelling*, 498, 110864 [Special Issue].

Appendix 6. ArcGIS Pro Python Code

a. Kelp forest highest position

```
import arcpy

from arcpy import env

# Set the workspace to your File Geodatabase
env.workspace = r"PATHWAY"

# Check out Spatial Analyst extension
arcpy.CheckOutExtension("Spatial")

# Define raster names
raster1 = "Kelp_bed_HIR_predicted_extent"
raster2 = "Kelp_bed_MIR_predicted_extent"

# Run HighestPosition
kelp_highest = HighestPosition([raster1, raster2])
```

b. All blue carbon habitats highest position

```
import arcpy

from arcpy import env

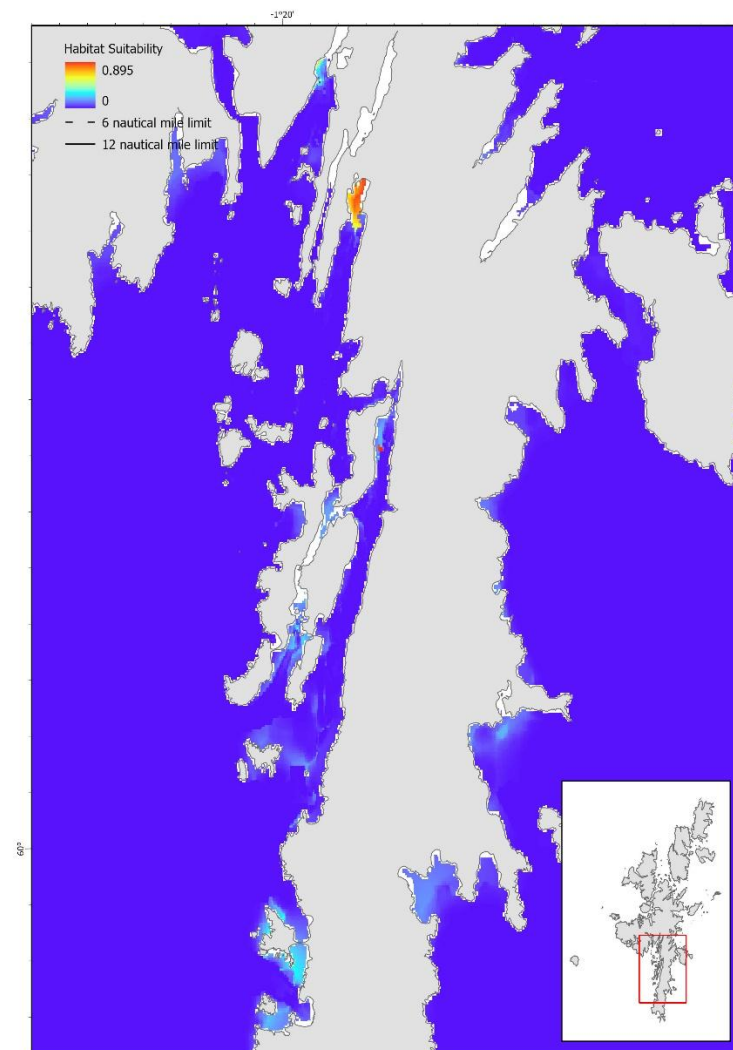
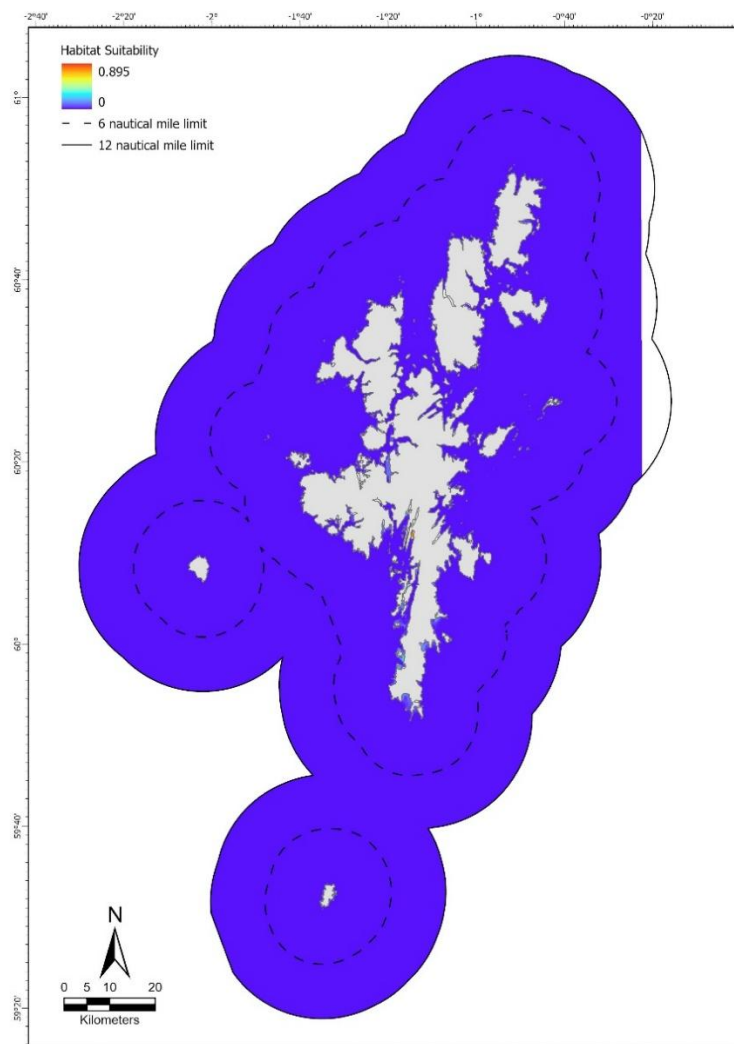
from arcpy.sa import *

# Set workspace to your File Geodatabase
env.workspace = r"PATHWAY"

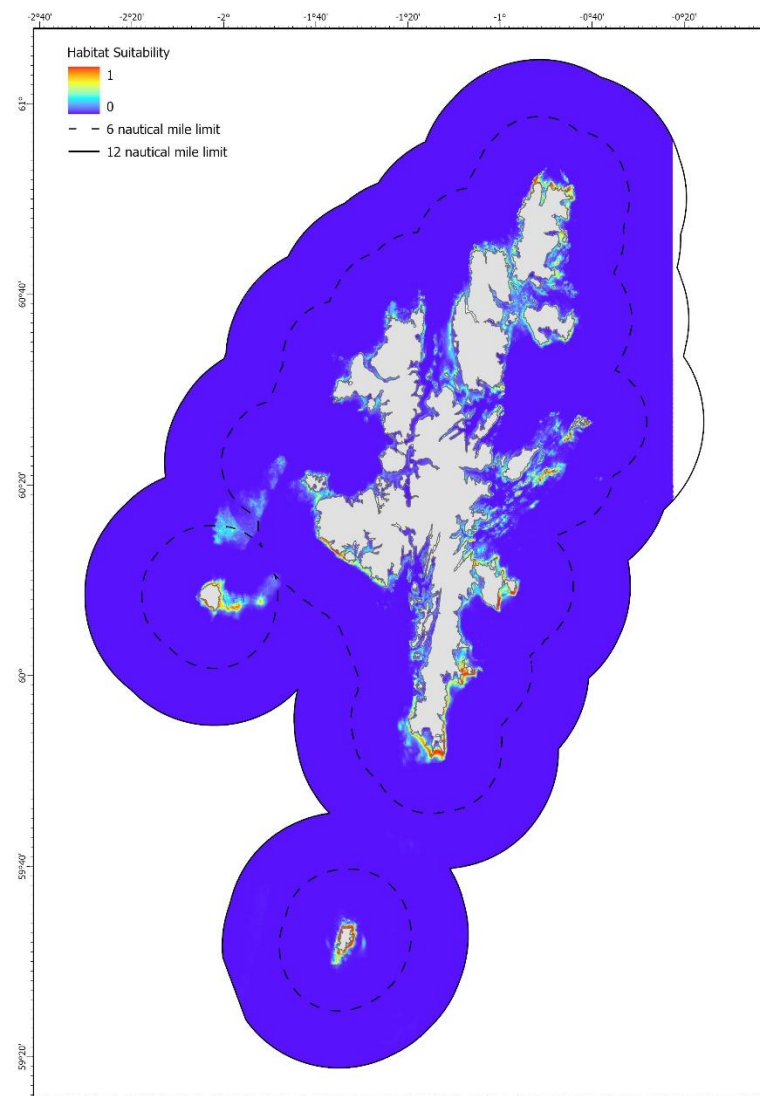
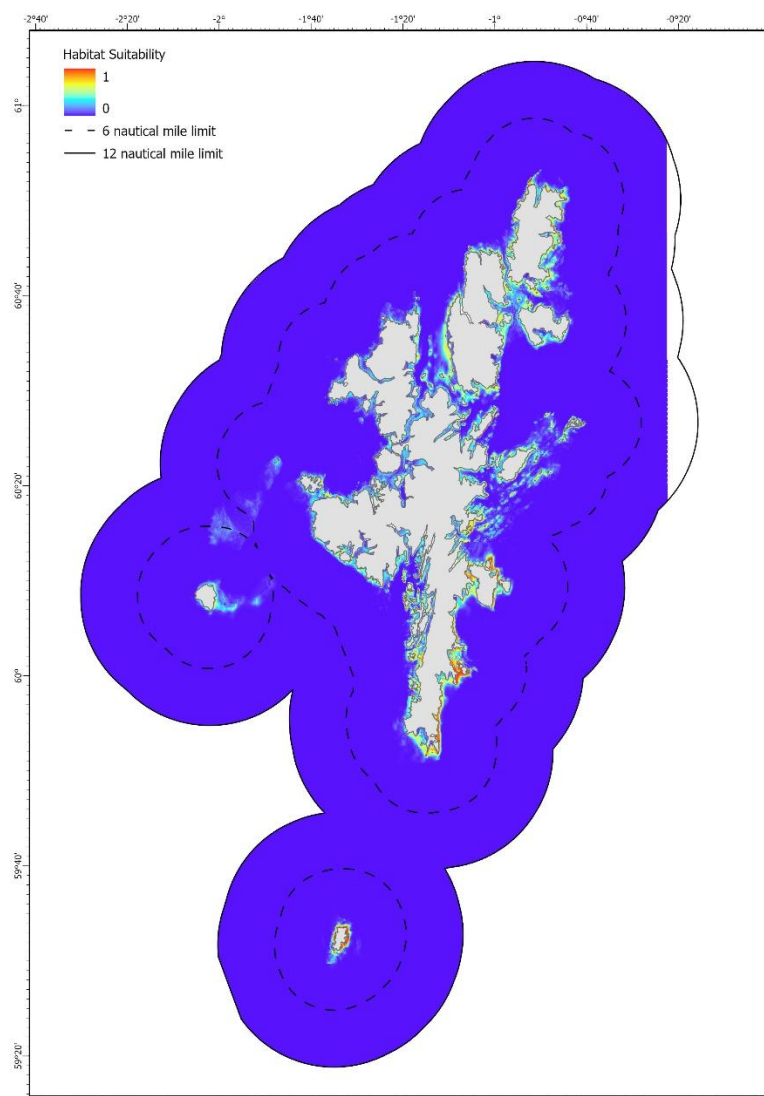
# Check out Spatial Analyst extension
arcpy.CheckOutExtension("Spatial")

# Define raster names
raster1 = "Kelp_bed_HIR_predicted_extent"
raster2 = "Kelp_bed_MIR_predicted_extent"
raster3 = "Maerl_bed_predicted_extent"
raster4 = "Brittlestar_bed_predicted_extent"
raster5 = "Horsemussel_bed_predicted_extent"

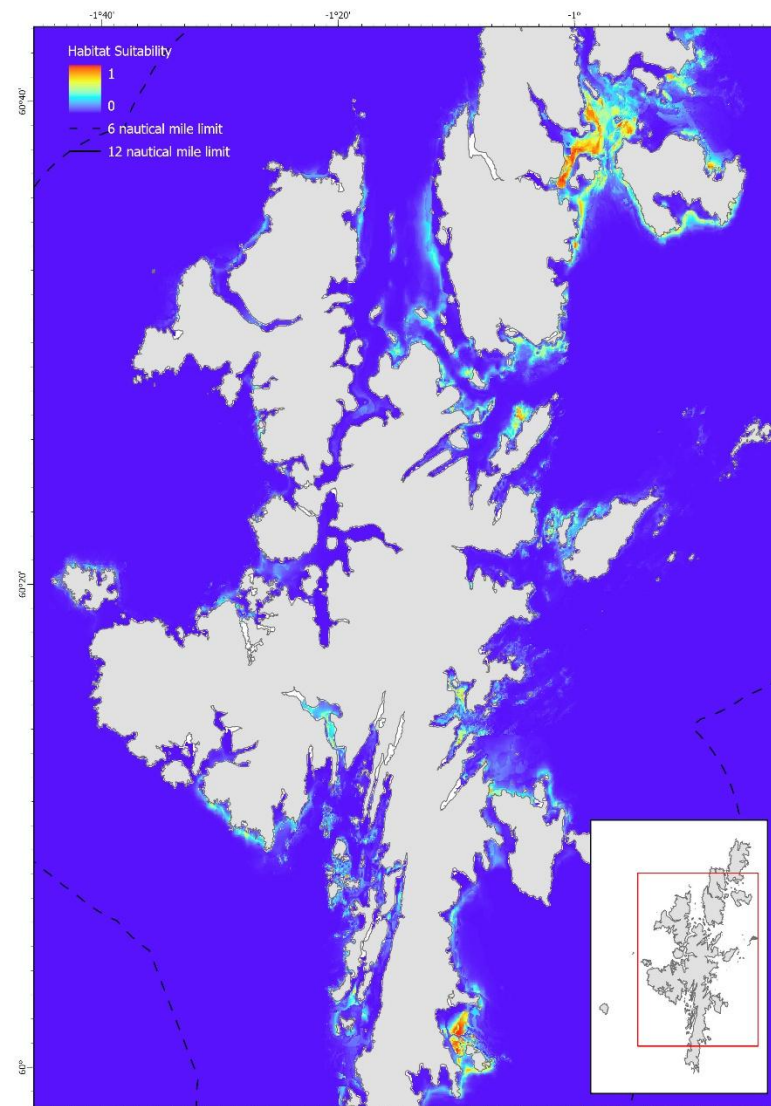
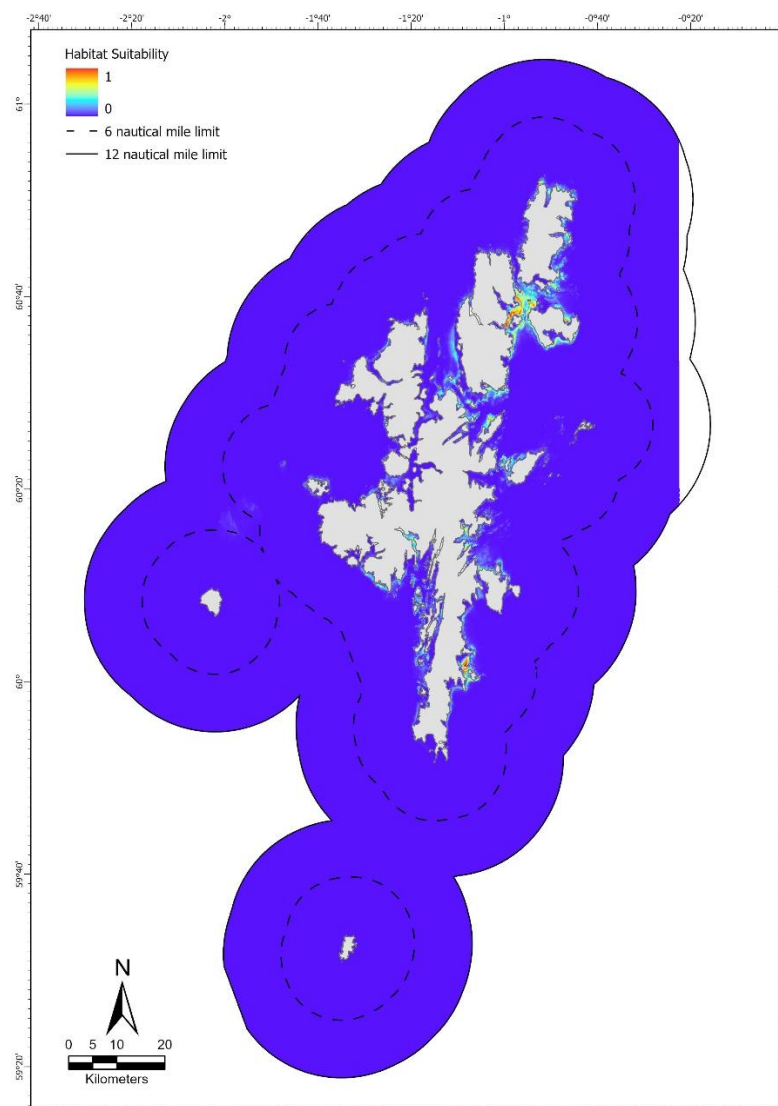
# Run HighestPosition
kelp_highest = HighestPosition([raster1, raster2, raster3, raster4, raster5])
```


Appendix 7. Blue carbon habitat suitability models***a. Seagrass meadow habitat suitability model - all Shetland (left) and zoomed to area of highest predicted (right)***

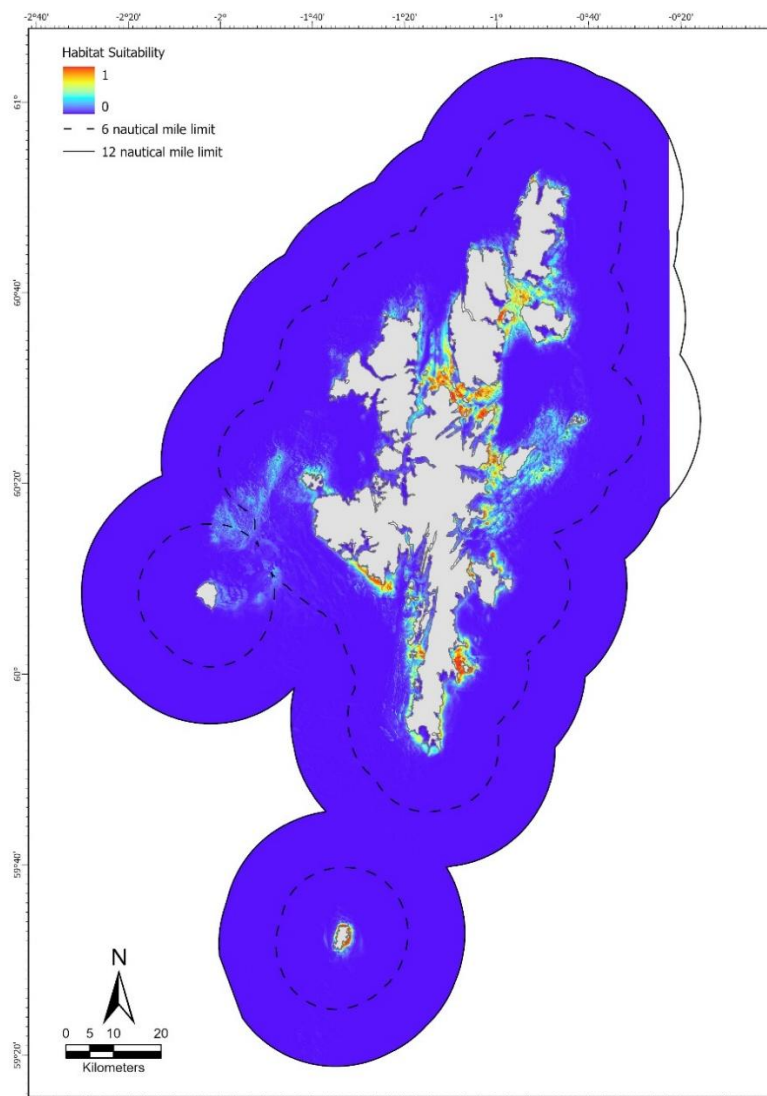
b. Kelp forest habitat suitability model - high energy (left) and medium energy (right)



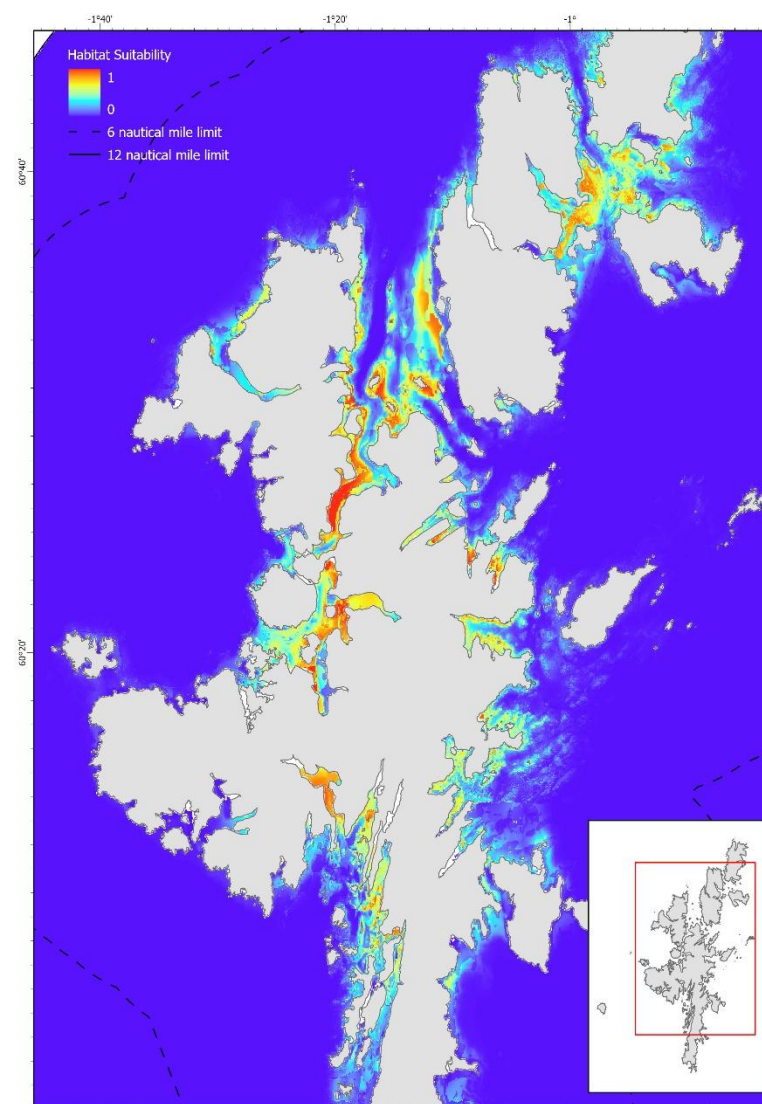
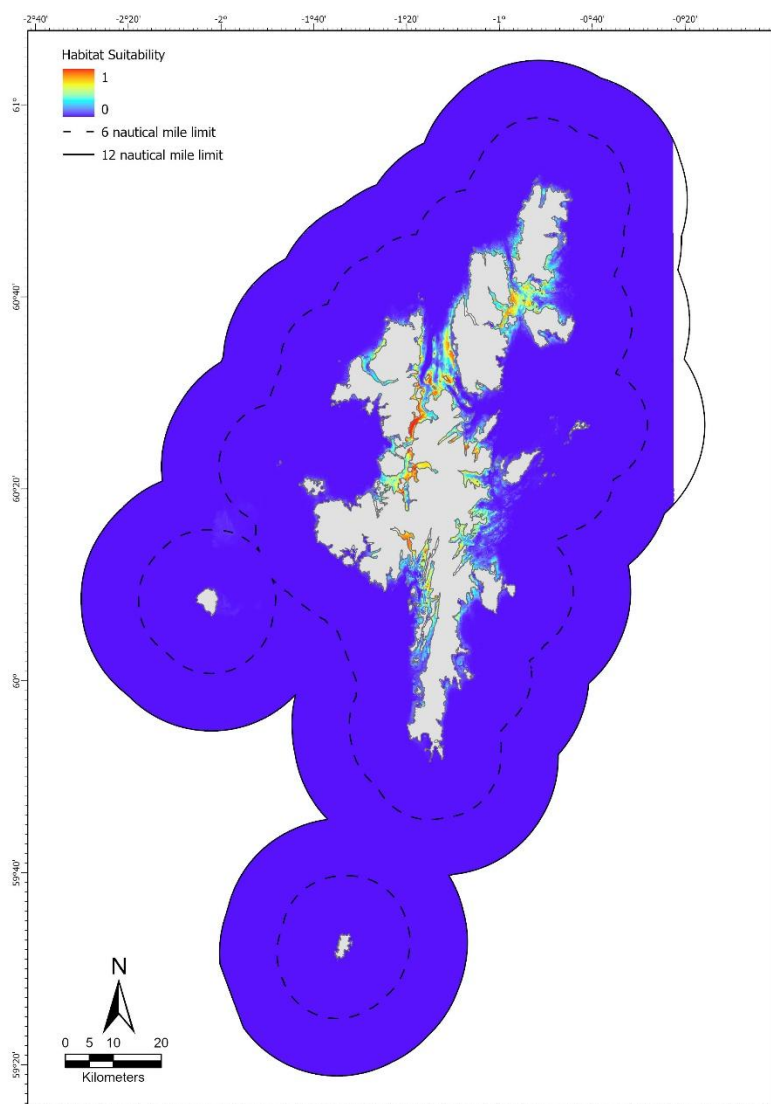
c. Maerl bed habitat suitability model - all Shetland (left) and zoomed to area of highest predicted (right)



d. Brittlestar habitat suitability model

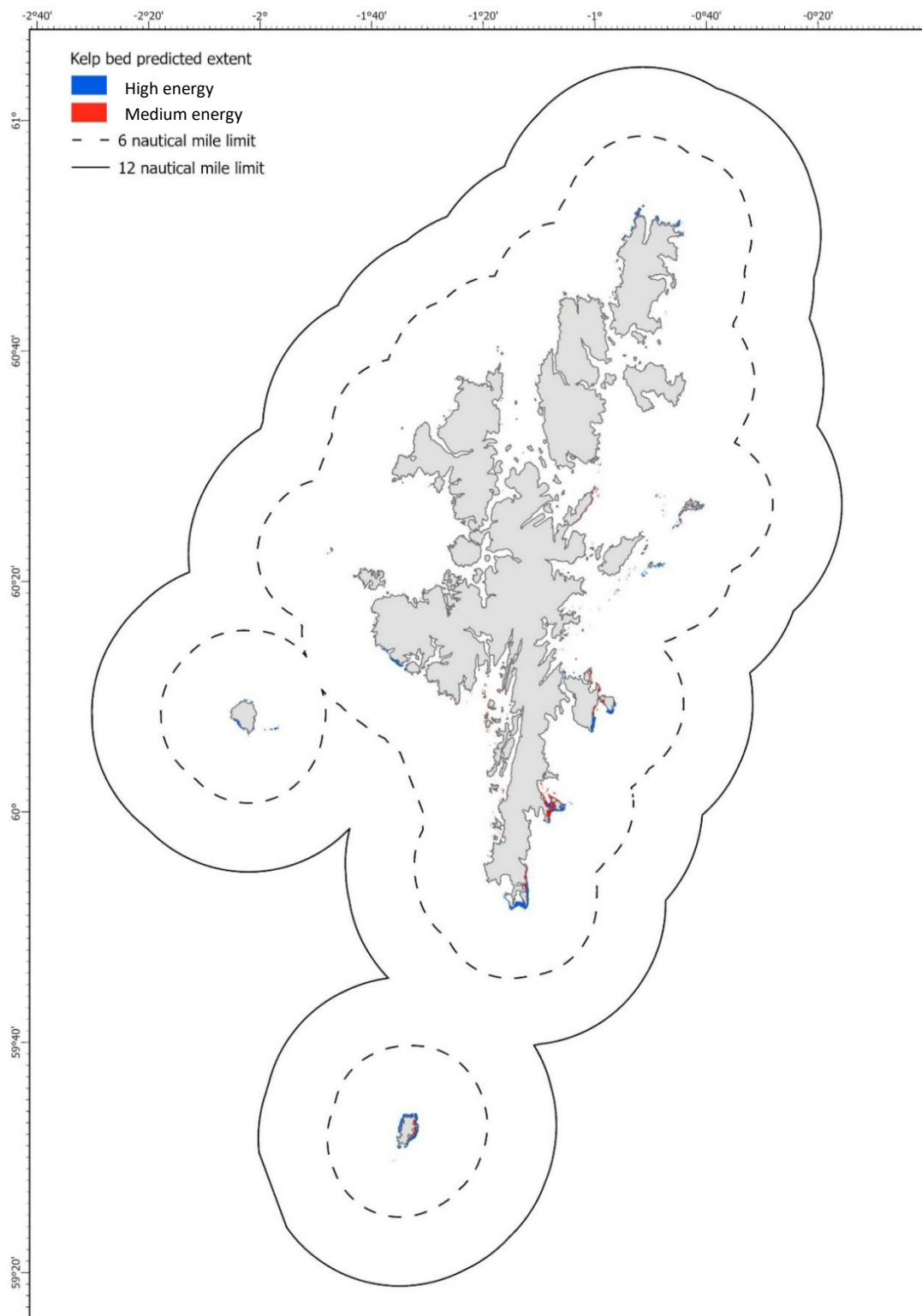


e. Horse mussel bed habitat suitability model - all Shetland (left) and zoomed to area of highest predicted (right)

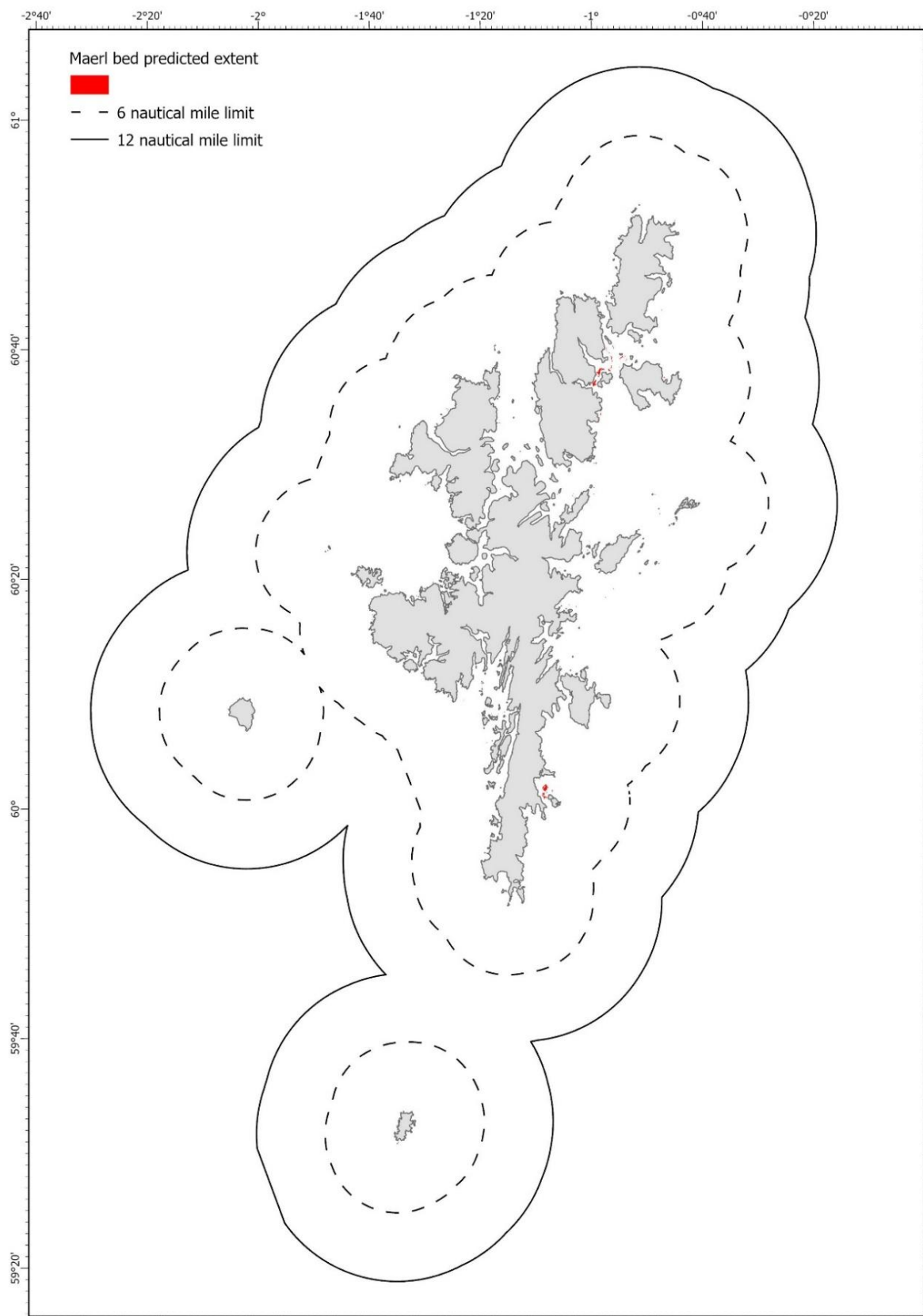


Appendix 8. Modelled distribution of blue carbon habitats in the Shetland Islands, showing areas with a predicted probability of occurrence ≥ 0.9

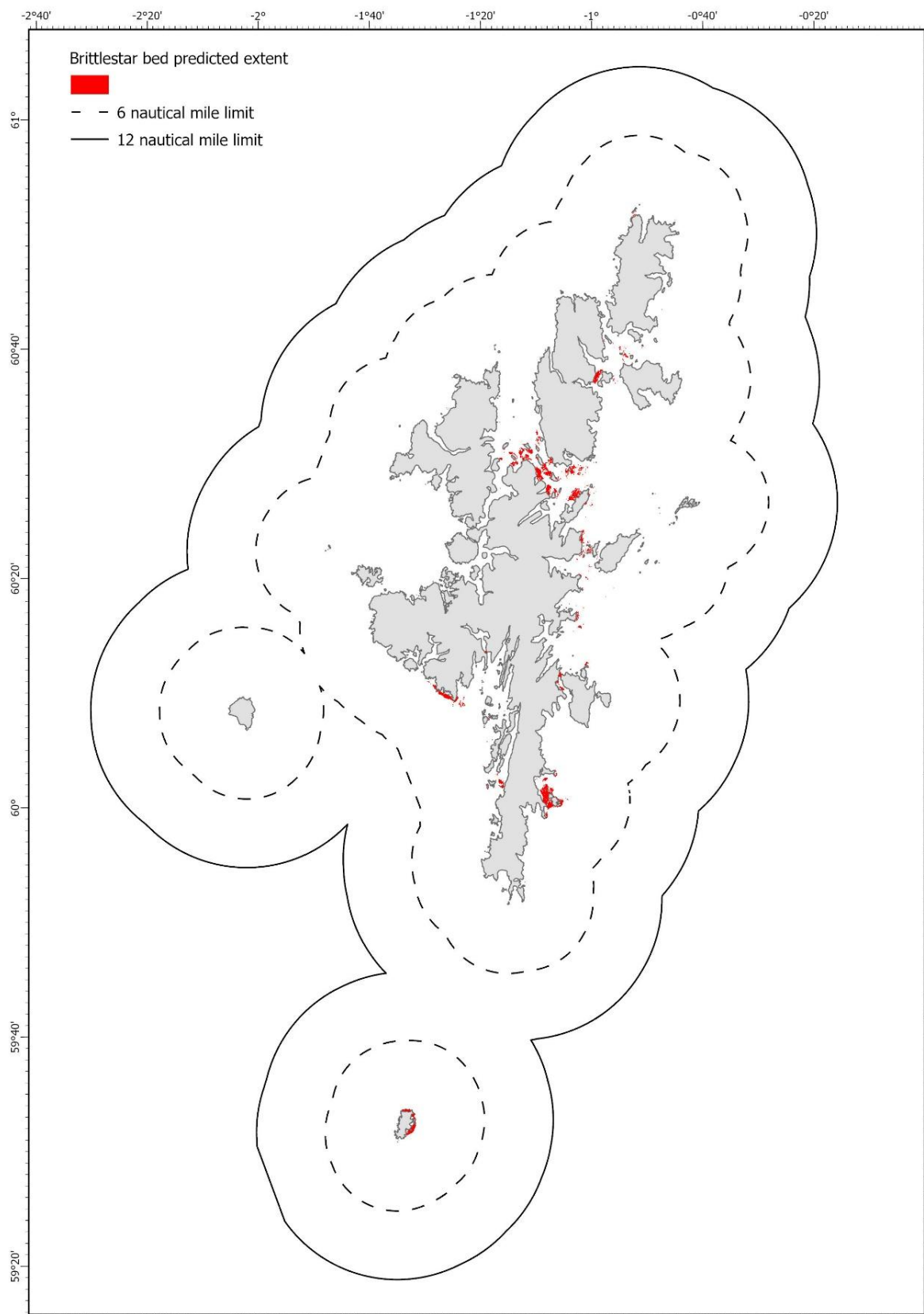
a. Predicted extent of kelp forests (high energy and medium energy), with overlapping areas assigned to the habitat with the highest predicted probability



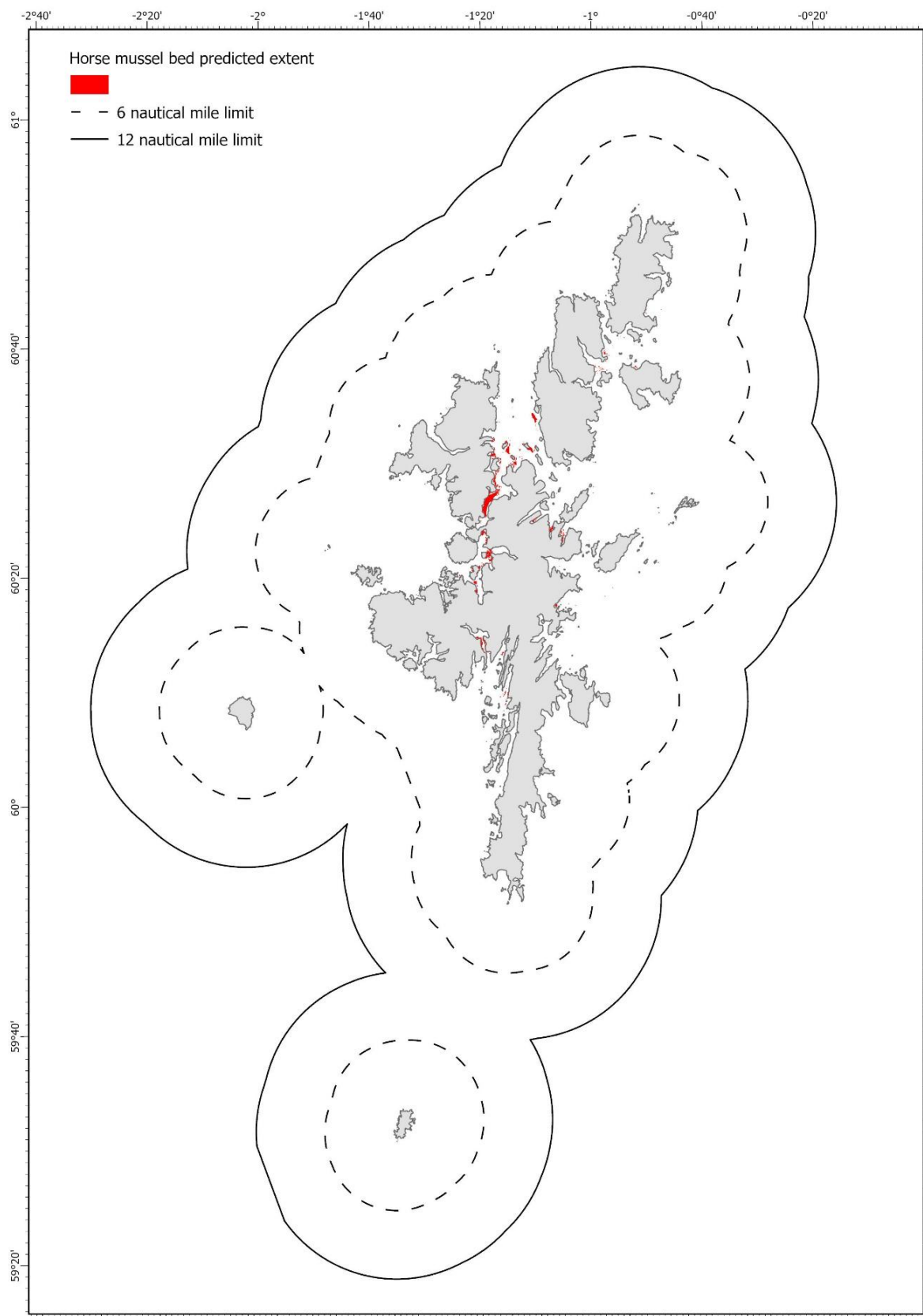
b. Predicted extent of maerl beds



c. Predicted extent of brittlestar beds



d. Predicted extent of horse mussel beds



Appendix 9. CO₂ equivalence (e)

Shetland per capita emissions (2022) = 5.1 t CO₂ eⁱ

Annual tree sequestration = 25 kg CO₂ eⁱⁱ

Car journey (1 mile) = 211.2 g CO₂ eⁱⁱⁱ

Cost = £64.90 t CO₂ e^{iv}

Northlink passenger (one-way) = 200kg CO₂ e^v

Return flight (Sumburgh to Aberdeen) = 50 kg CO₂ e^v

Household items^{vi}

Cup of tea = 40 g CO₂ e

1 internet search = 0.2 g CO₂ e

Mobile phone use (1 hour) = 172 g CO₂ e

Microwave use = 400 g CO₂ e

Washing machine = 275 g CO₂ e

Tumble dryer = 1kg CO₂ e

Lightbulb use (1 hour) = 43 g CO₂ e

Shower (10 minutes) = 2 kg CO₂ e

ⁱ [Carbon Emissions – Shetland Partnership](#)

ⁱⁱ [How Many Trees Would it take to Offset my Business?](#)

ⁱⁱⁱ [Average CO2 Emissions per Car in the UK | NimbleFins](#)

^{iv} [UK ETS: Carbon prices for use in civil penalties, 2024 - GOV.UK](#)

^v [Taking the plane turns out to be better for the climate | Shetland News](#)

^{vi} [Find out the Carbon Footprint of Common Items | Clever Carbon](#)