Title

Science-to-Policy Analysis of Seagrass and Macroalgae Habitats in Norway: Integrating Blue Carbon Ecosystems as Nature-Based Climate Solutions

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Integrating Blue Carbon Ecosystems as Nature-Based Climate Solutions

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Abstract

Blue carbon ecosystems (BCEs) are coastal vegetated habitats with a natural capacity to sequester and store vast amounts of carbon over long timescales. Given rising greenhouse gas concentrations and the subsequent increase in global efforts to reduce and offset emissions, BCEs are increasingly promoted as nature-based climate solutions. Their relevance to climate policy as a tool for climate change mitigation has garnered increasing attention, but heavily depends on ecosystem-specific evidence for carbon storage, sequestration permanence, monitoring feasibility, and governance compatibility. BCEs are also highly valued for providing many ecosystem services, biodiversity, and coastal resilience benefits. This study evaluates two prominent Norwegian BCEs: seagrass (*Zostera marina*) and macroalgal systems, primarily kelp forests and rockweed beds, as candidates for blue carbon policy and broader marine nature-based solutions. The analysis combines site-to-national carbon and ecosystem-service databases for seagrass and macroalgae, uncertainty analysis, spatial co-location screening from interactive mapping, and policy evaluation.

Seagrass occupies a comparatively small national area (modeled extent ≈ 90 km²) but is directly compatible with sediment-based blue carbon accounting. Its sediment carbon density varies strongly among regions — low in the Barents Sea, much higher in Oslofjord and Skagerrak — reflecting the influence of differing environmental controls such as sediment dry bulk density, hydrodynamic exposure, and water column depth. Macroalgae dominate Norway's vegetated coastal area (kelp ≈ 7,417 km², rockweed ≈ 3,090 km²) and hold far larger estimated biomass-carbon pools and annual production fluxes; however, their carbon is living biomass, so any long-term climate benefit depends on export, deposition, and burial outside the production habitat, creating significant attribution and permanence uncertainties for carbon accounting.

These differences imply different policy pathways. Norwegian seagrass is conceptually compatible with the Intergovernmental Panel of Climate Change (IPCC) Wetlands Supplement and could progress toward lower-tier inventory treatment as mapping, disturbance, and burial-rate data improve; its strongest near-term policy argument is the avoided degradation of existing sediment carbon. Macroalgae are better treated as an emerging blue carbon frontier and as high-priority biodiversity, fisheries, and coastal-resilience assets, entering policy through nature-based adaptation and co-benefits frameworks while export-driven accounting methods mature. The most defensible near-term pathway is therefore differentiated by habitat type: seagrass can begin IPCC Tier 1 accounting while developing capacity toward Tier 2 and Tier 3 readiness, whereas macroalgae should first be embedded into biodiversity and co-benefits frameworks while macroalgal carbon-fate research advances. Both ecosystems should be protected, monitored, and included into Nationally Determined Contributions immediately, with the differentiated pathway also phased so that each ecosystem is integrated further into formal carbon accounting and blue carbon governance as the underlying science matures.

1. Introduction

Rising atmospheric greenhouse gas concentrations drive increasingly severe climate impacts and intensify the need for a variety of mitigation strategies. The IPCC emphasizes that limiting warming requires rapid, deep, and sustained greenhouse gas emissions reductions across sectors, alongside protection and enhancement of land and ocean sinks where feasible (IPCC, 2022). Coastal vegetated ecosystems are recognized as potential nature-based climate solutions, contributing simultaneously to climate mitigation, biodiversity, and coastal resilience among other ecosystem services. The concept of "blue carbon" and the term blue carbon ecosystems (BCEs) have been used to highlight the outsized role coastal vegetated ecosystems play in global carbon sequestration, a function that has elevated these habitats to a position of international prominence in climate change strategy (Macreadie et al., 2019). While carbon sequestration is an urgent global priority, the policy relevance of BCEs extends beyond carbon alone. These ecosystems operate as multifunctional ecological infrastructure: they stabilize sediments, dampen hydrodynamic energy, improve water quality via nutrient cycling and particle retention, provide structurally complex habitat for fish and invertebrates, support food-web services and fisheries, and provide immense biodiversity value, all of which can generate extensive economic value (Boström et al., 2014; Krause-Jensen et al., 2022; Nordlund et al., 2016; Smale et al., 2019; Unsworth et al., 2019). BCE policy is often framed primarily around greenhouse gas mitigation, but recent blue carbon research priorities emphasize that these ecosystems should also be evaluated through the broader climate-biodiversity-coastal resilience nexus. This framing better captures the multi-benefit role of BCEs, including biodiversity support, coastal protection, community livelihoods, and ecosystem-service valuation in addition to carbon sequestration value (Macreadie et al., 2026).

The strongest existing framework for BCEs is provided by the IPCC Guidelines and the 2013 Wetlands Supplement, which established methods for estimating greenhouse gas emissions and removals from managed wetlands, including mangroves, salt marshes, and seagrasses (IPCC, 2014). These ecosystems have been prioritized because they accumulate organic carbon in soils and sediments that can persist over long timescales when undisturbed. Seagrasses remain less extensively studied and less consistently incorporated into BCE policy than mangroves or salt marshes, however, in part because they are more difficult to measure, more spatially dynamic, and highly variable across bioregions (Duarte et al., 2013; Fourqurean et al., 2012; IPCC, 2014; Macreadie et al., 2019). Macroalgae, including kelp forests and intertidal rockweed beds, are also recognized as blue carbon ecosystems due to their high productivity and capacity to export organic carbon to depositional sediments and the deep ocean. They are considered the largest and among the most productive coastal vegetated ecosystems globally, and may offer especially valuable mitigation opportunities in polar and temperate regions where conventional BCE mitigation pathways are less developed (Pessarrodona et al., 2023). However, only a small minority of countries presently incorporate macroalgae into BCE policies, largely because production and sequestration are often spatially decoupled, making carbon fate, attribution, and permanence difficult to quantify (Krause-Jensen & Duarte, 2016; Lovelock & Duarte, 2019).

Norway provides a prominent case study for evaluating how seagrass and macroalgae can be integrated into national BCE policy and carbon mitigation frameworks. Its coastal waters contain seagrass meadows, extensive kelp forests, intertidal rockweed beds, and offshore depositional environments, while its governance landscape already recognizes marine nature, biodiversity, ocean management, and blue-economy priorities given intense marine-sector activity (Frigstad et al., 2020; GRID-Arendal, 2021; Krause-Jensen et al., 2022). Seagrass and macroalgae present fundamentally different accounting challenges, and these differences are further shaped by Norway's regional environmental gradients, uneven evidence base, and ecosystem-specific management pressures. Norwegian seagrass is relatively limited in area and occurs across highly variable sedimentary and environmental conditions, but it has direct relevance to sediment carbon protection, making it more compatible with existing coastal wetland accounting logic. Macroalgae are far more extensive and productive, but their long-term climate contribution depends on complex dynamics, including carbon export, burial, remineralization losses, dissolved organic carbon persistence, and source attribution (d'Auriac et al., 2021; Frigstad et al., 2020; Krause-Jensen & Duarte, 2016). This dynamic setting makes Norway a highly relevant case for assessing data gaps, policy avenues and readiness, and differentiated pathways for blue carbon action.

The purpose of this report is to evaluate the current scientific evidence base, database-derived results, ecosystem-service implications, and policy readiness of Norwegian seagrass and macroalgae. The analysis asks four questions: (1) what is the current distribution, carbon evidence, and ecological context for Norwegian seagrass and macroalgae; (2) how do environmental drivers and human pressures shape their blue carbon potential; (3) how do the two ecosystem groups differ in scientific readiness for greenhouse gas accounting and policy integration; and (4) what monitoring and governance gaps currently impede defensible inclusion of seagrass and macroalgae in Norwegian climate policy?

A central premise of the analysis is that blue carbon policy should not treat all vegetated coastal ecosystems as interchangeable. Seagrass can be evaluated through a sediment-stock framework because long-term carbon storage occurs within the managed habitat. Macroalgae require an export-driven framework because carbon fixation occurs in kelp or rockweed habitats, while sequestration may occur elsewhere. This distinction changes the relevant evidence base: for seagrass, the key evidence needs are habitat extent, sediment carbon density, burial or accretion rates, disturbance-related carbon loss, and restoration or protection outcomes; for macroalgae, the key evidence needs are biomass production, detachment, transport, deposition, burial efficiency, dissolved organic carbon fate, and attribution of stored carbon to macroalgal sources (IPCC, 2014; Krause-Jensen & Duarte, 2016; Macreadie et al., 2019).

A second premise is that biodiversity, fisheries, nutrient cycling, coastal protection, and climate adaptation benefits can justify conservation even where greenhouse gas accounting remains uncertain (Boström et al., 2014; Nordlund et al., 2016; Smale et al., 2019; Unsworth et al., 2019). In Norway, both carbon sequestration evidence and co-benefit valuation remain incomplete, limiting the ability to translate existing ecological knowledge into strong governance action. However, the level of evidence required for national greenhouse gas inventory inclusion or carbon crediting is higher than the level of evidence required for biodiversity protection, ecosystem-service planning, or nature-based adaptation policy. This distinction and the arising data gaps are particularly important for Norway, where blue forest interest is growing but not yet organized into a unified domestic blue carbon strategy (GRID-Arendal, 2021).

2. Methods

2.1 Study design and analytical framework

This study used a comparative synthesis design to evaluate Norwegian seagrass and macroalgae across scientific, spatial, and policy dimensions. The analysis combined five components: (1) structured literature review; (2) construction of ecosystem-specific databases at site, regional, and national scales; (3) integration of human-pressure, protection, and environmental-context layers from EMODnet and Norwegian spatial datasets; (4) development of a reproducible geospatial workflow and interactive map to organize study sites, habitat polygons, carbon indicators, and pressure/protection context; and (5) quantitative analysis of carbon stocks, sequestration, and environmental drivers, incorporating non-parametric uncertainty estimation and bivariate regressions of drivers (Conti, 2026).

The analytical framework was organized around the information required for blue carbon policy assessment rather than carbon accounting alone. Variables were pre-selected based on the existing literature for their demonstrated importance to carbon stocks, carbon fluxes, environmental drivers, anthropogenic and climatic pressures, co-benefits, and uncertainty. This design was necessary because the evidence base is uneven: some carbon and environmental variables are available at individual sites, while many variables are available only from national or regional syntheses. Missingness was therefore treated as a result rather than as a data-cleaning problem. Variables were retained where they identified meaningful policy or accounting gaps, even if values could not yet be populated for Norway.

2.2 Seagrass database construction

A seagrass database was developed as a hierarchical synthesis database for Norwegian eelgrass (*Zostera marina*). It included a site-level raw sheet, a regional synthesis sheet, and a national synthesis row. This structure preserved the highest-resolution observations available while also producing summary values at scales relevant to management and policy. The site-level backbone was Gagnon et al. (2024), which provides the most comprehensive Norway-specific, multi-site eelgrass sediment carbon dataset identified in the review. That study includes carbon-stock data for eelgrass and unvegetated sites across Skagerrak, Oslofjord, the Norwegian Sea, and the Barents Sea, as well as a few variables describing environmental-drivers and sediment characteristics.

Rows in the raw site-level seagrass database represented site x depth x habitat combinations rather than named sites alone. This decision retained within-site variation where the same named location was sampled at multiple depths. This avoided premature averaging and retained important ecological gradients that are relevant to sediment carbon storage. Gagnon et al. (2024) identifies water depth, wave exposure, salinity, and sediment type as important environmental gradients affecting carbon stock variability, so collapsing multiple depth strata too early would have obscured meaningful variation. Sediment depth is specifically relevant because carbon stock estimates are highly sensitive to sampling depth and sediment accumulation profiles, which influence both comparability and long-term storage estimates (Lavery et al., 2013). The principal carbon metric was sediment organic carbon stock in the upper 50 cm, reported as g C m^{-2}, as Gagnon et al. (2024) standardized cross-site comparisons to that depth. Site metadata, region, year, water depth, habitat type, sediment type, wave exposure, salinity, temperature, mean dry bulk density, aboveground biomass, belowground biomass, and aboveground:belowground biomass ratio were transcribed or merged from the main article and supplementary tables.

Unvegetated rows were retained in the raw sheet for traceability and sensitivity analysis but were filtered out before aggregation of the regional synthesis. Where biomass or environmental variables were explicitly not measured in the source material, values were retained as missing rather than imputed.

A single supplemental row for the Norwegian Sea was backfilled using Röhr et al. 2018, following the standardization logic described by Gagnon et al. (2024) for previously published Røvik data. Because the available Gagnon et al. (2024) carbon file did not include Røvik, omitting the row would have removed the Norwegian Sea from downstream regional summaries. The 25 cm value reported in the source study was doubled to approximate a 50 cm-equivalent stock, following the procedure described by Gagnon et al. (2024). This value should therefore be interpreted as harmonized for comparability, not as a newly measured 50 cm core.

2.3 Seagrass regional and national aggregation

Regional synthesis was conducted in Python using pandas. Numeric fields were explicitly coerced to numeric types, eelgrass rows were filtered from the raw sheet, and observations were grouped by the four canonical regions used in the Gagnon-based structure: South West (Skagerrak), South East (Oslofjord), West (Norwegian Sea), and North (Barents Sea). The first-pass regional summary calculated the number of observations, number of unique sites, year range, mean, standard deviation, minimum, and maximum sediment carbon stock, and summary statistics for environmental and biomass variables. Regional carbon density statistics retain these four Gagnon-based canonical regions, whereas the analysis conducted for the figures collapsed Oslofjord into Skagerrak, reporting three regions: North, West, and South. The two schemes are intentional: the four-region split preserves the finest density resolution available and allows for compatibility with the Gagnon et al. (2024) study, while the three-region split matches the areal units used for stock scaling as the Oslofjord is an inlet within the Skagerrak strait.

The regional aggregation was row-weighted: each site-depth observation contributed equally. This choice was retained because depth strata represented real environmental variation rather than duplicate records, and because area weights were unavailable for the sampled sites. A site-weighted or area-weighted analysis would be preferable for national stock estimation, but applying such weighting without defensible regional extent data would introduce an arbitrary correction. Consequently, the regional and national summaries should be interpreted as evidence-based synthesis values rather than areally weighted national inventory estimates.

National values derived from the site-level database were calculated from the four regional means rather than directly from raw site-depth rows. This reduced dominance by the more heavily sampled southern regions and better aligned with the goal of comparing broad Norwegian eelgrass systems. Mean, minimum, and maximum values were calculated across regions. Standard deviation was reported for sediment carbon stock to characterize variability within regional observations and among regional means. National top-down values for seagrass extent, carbon stocks, production, and sequestration were incorporated separately from the Nordic Blue Carbon Project, because those estimates were not spatially resolved to the four Gagnon-based regions (Frigstad et al., 2020).

2.4 Macroalgae database construction

The macroalgae database used the same thematic categories as the seagrass database: extent, degradation/loss, restoration or intervention, carbon stocks, carbon fluxes, environmental drivers, human and climate pressures, co-benefits, and uncertainty; however, they were applied differently because macroalgae have different carbon dynamics and data availability. The database focused on dominant Norwegian macroalgal systems, including kelp forests dominated by *Laminaria hyperbore*a and *Saccharina latissima* and intertidal rockweed communities such as *Fucus spp.* and *Ascophyllum nodosum* (Frigstad et al., 2020; Gundersen et al., 2021).

Unlike eelgrass, macroalgae generally grow on hard substrate and do not usually accumulate long-term carbon within local sediments beneath the habitat itself (Frigstad et al., 2020; Krause-Jensen & Duarte, 2016). Recent evidence from seaweed aquaculture indicates that macroalgal systems can enhance organic carbon burial in underlying sediments when farms are located in depositional environments, with excess burial attributable to seaweed farms estimated using sediment cores and lead-210 isotope chronologies (Duarte et al., 2025). However, comparable evidence has not yet been resolved for natural Norwegian kelp forests or intertidal rockweed beds, making this an important research gap for future blue carbon assessment. In the existing Norwegian evidence base, macroalgal carbon cycling is still primarily understood through spatially decoupled processes of production, detachment, export, deposition, and sequestration. Site-level sediment carbon stocks and site-level sequestration rates were therefore not forced into the macroalgae database. Instead, macroalgae were treated using a synthesis-based approach: site-level data characterized ecological condition, species composition, standing stock, environmental gradients, and localized pressures; regional data described large-scale gradients and structural patterns; and national data provided modeled or synthesized carbon-relevant estimates such as extent, biomass carbon, net primary production, export, and sequestration (Frigstad et al., 2020; Krause-Jensen & Duarte, 2016).

This structure intentionally avoided aggregating site-level macroalgal observations into new national carbon estimates. For seagrass, the site-level Gagnon et al. (2024) dataset supported defensible aggregation of sediment carbon observations. For macroalgae, many carbon-relevant values are already produced through broader modeling frameworks that combine habitat extent, biomass estimates, productivity, and export assumptions. Re-aggregating individual site observations would have required unsupported assumptions about spatial representativeness, export efficiency, and burial. Values were therefore entered as reported unless a simple, explicitly documented sum was appropriate, such as a national row for all Norwegian macroalgae that combined kelp and rockweed values reported in compatible units. National macroalgal carbon is reported as standing living biomass carbon, and macroalgal climate relevance is expressed as export-contingent sequestration rather than as in-situ sediment stock; this allowed for distinction between autochthonous and allochthonous carbon. Autochthonous carbon is produced within the ecosystem where it is stored, while allochthonous carbon is produced elsewhere and later deposited or buried in a receiving environment. Because natural macroalgal carbon sequestration is often evaluated as allochthonous and export-driven, macroalgae records were not treated as local sediment-stock observations unless source attribution and burial evidence were explicitly reported (Houston et al., 2025). Macroalgal biomass carbon was never added to, or equated with, seagrass sediment carbon stocks.

2.5 Human-pressure and contextual geospatial datasets

National-scale human pressure and environmental context indicators were derived from EMODnet and complementary Norwegian spatial datasets. EMODnet layers included dredging, offshore oil and gas installations, maritime transport, sedimentation rates, coastal resilience/vulnerability, seabed erosion, Regional Sea Convention marine protected areas, and commercial fish habitat projections under climate change. Complementary Norwegian layers in the interactive-map workflow included Naturbase HB19 eelgrass and kelp habitat polygons, marine protected areas from Miljødirektoratet/Naturbase, aquaculture register sites from Fiskeridirektoratet/Barentswatch, MASSIMAL remote-sensing field sites, SeaBee aerial survey information, Fiskeridir ERS 2019–2023 fishing effort, NGU sediment organic carbon stock and accumulation products, and NINA Nature Index averages where available (Conti, 2026; EMODnet Biology, 2023; EMODnet Geology, 2026; EMODnet Human Activities, 2022, 2023, 2025; Fiskeridirektoratet, 2024).

Datasets were processed as pressure and context indicators, not as direct measures of ecosystem response. This distinction is critical: a dredging record, offshore platform, port-traffic metric, trawling cell, or aquaculture point identifies potential exposure or management relevance but does not by itself quantify eelgrass loss, kelp decline, carbon emissions impact, or restoration potential. When datasets lacked direct overlap with mapped habitat or when ecological response metrics were absent, values were treated as proxies and interpreted cautiously.

EMODnet datasets were heterogeneous in coordinate fields, geometry structure, temporal coverage, and attribute completeness. The processing workflow standardized column names, converted numeric fields, harmonized coordinate reference systems, filtered records to Norwegian waters, and summarized each dataset separately according to its structure. For point layers with latitude and longitude, coordinates were converted to geometries and spatially filtered. For datasets lacking coordinates but containing country or region attributes, filtering used standardized text matching. For descriptive datasets such as seabed erosion, categorical interpretation was used rather than forcing unsupported numerical aggregation.

2.6 Interactive map and reproducible geospatial workflow

The database and spatial-context layers were integrated into an interactive map using a reproducible Python workflow documented in the public Norway Blue Carbon Map GitHub repository. The repository describes a pipeline in which raw workbooks are normalized into processed CSVs, ecosystem-service tables are generated, Naturbase HB19 habitat layers and pressure/context layers are prepared, spatial co-location analysis is conducted, and a Folium-based interactive HTML map is generated. The map includes seagrass and kelp study sites, habitat polygons, marine protected areas, environmental drivers, carbon-stock and accumulation layers, and human-pressure layers (Conti, 2026).

The repository pipeline is organized into discrete scripts. The master inventory is built with build_master_inventory.py; carbon and ecosystem-service tables are generated with step2_ecosystem_services.py; HB19 habitat layers are prepared with prepare_hb19_map_layers.py; pressure and context layers are prepared with prepare_context_map_layers.py; pressure-protection co-location is analyzed with spatial_colocation_analysis.py; the interactive map is generated with build_norway_map.py; and a static co-location figure is produced with figure_colocation_topline_map.py (Conti, 2026). This script-based design improves reproducibility because input tables and spatial layers can be updated without manually rebuilding the map.

The co-location analysis classified mapped habitats according to pressure proximity and protection context. Classes included pressure nearby with less than 1% protected overlap, pressure nearby with at least 10% marine protected area overlap, protected habitat with at least 10% marine protected area overlap and no nearby pressure signal, a carbon study site within 5 km of mapped habitat, and mapped habitat or evidence gap where no strong pressure, protection, or study-site signal was identified. The spatial analysis used EPSG:32633 (UTM Zone 33N), and the repository explicitly identifies projection sensitivity as a caveat, recommending an equal-area sensitivity check (Conti, 2026).

2.7 Data analysis

Three distinct seagrass carbon density statistics are used in the Results and are defined here to avoid conflation: (i) the pooled mean of all eelgrass site-depth observations (4,094 g C m^{-2}), used for the site-level distribution (Figure 1); (ii) the mean of the nine site-level means (3,811 g C m^{-2}), used as the input to the bootstrap national estimate (Figure 3); and (iii) the paired eelgrass core mean vs unvegetated core mean (4,482 g C m^{-2}, n = 23 eelgrass cores vs. 17 unvegetated cores), used only for the vegetated-versus-unvegetated comparison (Figure 1). These differ because they pool at different levels and over different subsets; they are not interchangeable.

National seagrass carbon stock was estimated by scaling the site-mean density basis (3,811 g C m^{-2}) to mapped habitat extent. Two extent bases from the Nordic Blue Carbon Project (Frigstad et al., 2020) are reported and kept distinct throughout: a measured/mapped extent of ~60 km^2 (Naturbase HB19) and a modeled potential extent of 90 km^2. The modeled 90 km^2 extent is used for the headline bottom-up estimate to match the basis of the published national figures, with 60 km^2 carried as a conservative sensitivity bound.

Uncertainty in the bottom-up national stock was quantified with a non-parametric bootstrap: the nine site-level mean densities were resampled with replacement (10,000 iterations) and each resample scaled to the 90 km^2 extent, yielding a central estimate of 344 Gg C with a 95% confidence interval of [177–502] Gg C (±47%). This bottom-up estimate is reported alongside, and reconciled with, the Nordic Blue Carbon Project top-down value (245 Gg C; Frigstad et al., 2020) and the Gagnon et al. (2024) Nordic-weighted estimate (~250 Gg C). The ~100 Gg C offset between the bootstrap central value and the top-down references is driven by density rather than extent: the nine-site density basis is ~40% higher than Frigstad's Nordic-weighted density (~2,722 g C m^{-2}); the confidence interval overlaps both references. Across-site variability was summarized with the coefficient of variation (CV= standard deviation/mean of the nine site-level mean densities; CV≈ 77%).

Environmental drivers of sediment carbon were examined with bivariate ordinary-least-squares (OLS) regressions of carbon stock against each candidate predictor (dry bulk density, aboveground biomass, water depth, and mean temperature). These single-predictor models characterize the direction and strength of each association in the Norway-specific data and are reported with R^2, p-value, and sample size, which varies by predictor owing to uneven measurement coverage ($N = 20$ for dry bulk density and water depth; $N = 8$ for aboveground biomass; $N = 9$ for mean temperature). They are not intended to replace the multivariate partial-least-squares analysis of Gagnon et al. (2024); where the bivariate result diverges from their multivariate ranking, this is noted as a consequence of model structure and the smaller, Norway-restricted sample rather than a substantive contradiction.

Macroalgal sequestration was not derived from local sediment cores (as explained in §2.4) but estimated by applying published export-and-sequestration fractions (Krause-Jensen & Duarte, 2016) to national net primary production. A central export fraction (25.5%) gives ~1.7 Mt CO_2 yr^{-1}, with low and high fractions (23.2% and 61.6%) giving ~1.3 and ~4.1 Mt CO_2 yr^{-1} as a sensitivity range. These figures represent carbon potentially sequestered off-site following export and are reported separately from seagrass in-situ sediment stocks; the two pools are never summed.

Illustrative economic valuation was conducted by converting carbon masses to CO_2-equivalents using the stoichiometric factor 44/12 for comparability and valuation. The illustrative economic values were calculated under three price points: the EU Emissions Trading System price (€65 per t CO_2), the U.S. social cost of carbon (\$190 per t CO_2), and a representative voluntary-market price (\$20 per t CO_2) (European Environment Agency, 2025; Forest Trends' Ecosystem Marketplace, 2024; U.S. Environmental Protection Agency, 2023). These price points were used as order-of-magnitude policy context rather than as market valuations of creditable carbon. The EU ETS price represents a regulated compliance-market allowance price, the social cost of carbon represents an estimated marginal climate-damage value, and the voluntary blue carbon price represents an illustrative upper-end project-finance value rather than a verified average market price.

Management-priority classes were generated through the co-location analysis by combining relative pressure status and strict MPA overlap. Pressure status was classified as high or low using the within-dataset median pressure score, and protection status was classified using a ≥10% strict MPA overlap threshold. Habitat-region units were assigned to four screening classes: low pressure/≥10% MPA overlap, high pressure/<10% MPA overlap, low pressure/<10% MPA overlap, and high pressure/≥10% MPA overlap. These classes were used only as a screening framework and were not treated as formal policy designations or ecological impact categories.

All data analysis was conducted in Python; the workflow, CSVs, and scripts for all figures are available in the Norway Blue Carbon Map GitHub repository (Conti, 2026).

2.8 Treatment of uncertainty and missing data

Uncertainty was tracked in three forms: measurement uncertainty, representativeness uncertainty, and structural accounting uncertainty. Measurement uncertainty includes variability in reported carbon stocks, biomass values, environmental variables, and source-study methods. Representativeness uncertainty arises from uneven sampling across regions and from the absence of complete national habitat-condition and extent-change datasets. Structural uncertainty is particularly important for sequestration estimates, because national carbon-removal estimates depend on assumptions about productivity, export fractions, burial efficiency, and storage permanence that are not always empirically constrained in Norwegian systems (Frigstad et al., 2020; Macreadie et al., 2019). Measurement and representativeness uncertainty in the seagrass national estimate are quantified explicitly through the bootstrap confidence interval and coefficient of variation described in §2.7; the remaining structural uncertainties below are characterized qualitatively.

Missing values were intentionally left blank or coded as NaN when no defensible value was available. This approach preserved the distinction between absence of evidence and evidence of data gaps. Major data gaps identified through the database process included limited site-level seagrass carbon measurements outside southern Norway, lack of region-specific eelgrass extent estimates, limited direct sequestration or burial measurements, weak biodiversity and coastal protection data, limited anchoring and storm-disturbance data, and insufficient spatial linkage between human-pressure layers and observed ecosystem condition. For macroalgae, the major uncertainties were export fate, dissolved organic carbon persistence, attribution of stored carbon to macroalgal sources, and the lack of standardized co-located measurements of production, export, deposition, and burial.

3. Results

3.1 Ecosystem distribution and evidence base

Norwegian eelgrass is represented primarily by *Zostera marina*. National-scale synthesis estimates identify approximately 60 km^2 of measured seagrass extent across roughly 3,000 eelgrass meadows, with a modeled total extent of approximately 90 km^2 (Frigstad et al., 2020). Eelgrass has been documented from southern Norway near the Swedish border northward to the Barents Sea region, but the current carbon evidence base is spatially uneven (Gagnon et al., 2024; Krause-Jensen et al., 2022). In the compiled site-level carbon database, Southern Norway (the Skagerrak coast, including Oslofjord) contains the large majority of observations, while the west coast (Norwegian Sea) and Northern Norway (Barents Sea) are each represented by only one carbon observation. This uneven sampling means that the database is useful for identifying patterns and gaps, but is not yet sufficient for fully area-weighted national carbon accounting.

Macroalgae occupy a much larger area than eelgrass and dominate Norway's vegetated coastal habitat by orders of magnitude. The Nordic Blue Carbon Project estimated Norwegian kelp forest area at 7,417 km^2 (range 5,933-9,317 km^2), and Norwegian rockweed area at 3,090 km^2 (Frigstad et al., 2020). Kelp forests occur mainly on shallow subtidal hard-bottom habitats, while rockweed occurs in intertidal to shallow hard-bottom systems. The dominant kelp taxa in the database are *Laminaria hyperborea* and *Saccharina latissima*, while rockweed includes *Fucus spp*. and *Ascophyllum nodosum* (Frigstad et al., 2020; Gundersen et al., 2021).

The distributional contrast between seagrass and macroalgae is central to the policy analysis. Seagrass is spatially limited but occurs in soft-sediment environments where organic carbon accumulates beneath the meadow as a measurable, in-situ stock. Macroalgae are extensive and productive but grow largely on hard substrate, so their standing biomass and productivity must be connected to export and deposition processes elsewhere before they can be interpreted as long-term sequestration (Krause-Jensen & Duarte, 2016; Lovelock & Duarte, 2019). A large habitat area therefore does not automatically imply high inventory-ready climate mitigation, and a smaller habitat area does not imply low policy relevance if its carbon pools are persistent and vulnerable to disturbance.

Mapping readiness also differs between ecosystems. Kelp habitat modeling in Norway benefits from extensive observation datasets and spatially explicit environmental predictors; for example, the Nordic Blue Carbon Project used thousands of observations for tangle kelp and sugar kelp and produced 25 m-resolution modeled habitat products (Frigstad et al., 2020). By contrast, eelgrass mapping remains more fragmented, although emerging Norwegian work suggests that drone-borne topobathymetric LiDAR may substantially improve eelgrass monitoring by providing centimeter-scale, three-dimensional estimates of canopy structure, habitat volume, and aboveground carbon storage (Lavin et al., 2025, preprint). These diverging aspects of seagrass and macroalgae require different considerations for blue carbon evaluation (Table 1).

Metric	Seagrass	Macroalgae
Primary habitat	Soft-sediment eelgrass meadows dominated by *Zostera marina*	Hard-bottom kelp forests and intertidal rockweed beds
Estimated national extent	~60 km² measured; ~90 km² modeled	~7,417 km² kelp; ~3,090 km² rockweed
Dominant carbon pool	Sediment organic carbon beneath meadows	Living biomass carbon and exported organic carbon
Accounting fit	Direct conceptual fit with IPCC coastal wetlands guidance	Emerging export-driven accounting frontier
Main uncertainty	Extent, burial rates, disturbance-emission factors, regional representativeness	Export fractions, burial efficiency, DOC persistence, attribution, permanence

Table 1. Comparative evidence base and accounting logic for Norwegian eelgrass and macroalgae.

3.2 Seagrass carbon stocks and regional variability

Norwegian eelgrass stores measurable sediment carbon, but stocks vary strongly across regions. In the compiled regional synthesis, mean sediment carbon density ranges from approximately 112 g C m^{-2} in the North (Barents Sea) to approximately 4,990 g C m^{-2} in the South West (Skagerrak), with the South East (Oslofjord) at approximately 4,670 g C m^{-2} and the West (Norwegian Sea) at approximately 4,000 g C m^{-2} . The Barents Sea and Norwegian Sea values each rest on a single harmonized observation and therefore have limited regional representativeness. Within the most heavily sampled southern region, variability is high, with site values spanning approximately 374 to 9,420 g C m^{-2} in the Skagerrak region alone (Gagnon et al., 2024; Röhr et al., 2018).

The paired habitat comparison is one of the strongest findings for Norwegian seagrass. Across the harmonized Gagnon et al. (2024) cores, eelgrass sediments contained substantially higher mean carbon stocks than adjacent unvegetated sediments, approximately 4,482 g C m^{-2} (n=23) vs 2,999 g C m^{-2} (n=17), an enhancement of roughly 49% (Gagnon et al., 2024). This supports the interpretation that Norwegian eelgrass meadows enhance sediment carbon storage relative to nearby bare sediments, consistent with global seagrass blue carbon literature showing that vegetated meadows trap particles, add belowground organic matter, stabilize sediments, and promote long-term carbon accumulation (Duarte et al., 2013; Fourqurean et al., 2012; Lavery et al., 2013).

Carbon storage in Norwegian eelgrass meadows cannot be represented accurately by a single national value. The pooled mean across all site-depth observations is approximately 4,094 g C m^{-2}, while the mean of the nine site-level means is approximately 3,811 g C m^{-2}; both summaries conceal a wide underlying spread, from roughly 112 g C m^{-2} at low-carbon sandy and intertidal sites to nearly 7,800 g C m^{-2} at sheltered depositional sites. The comparison with unvegetated sediments confirms that eelgrass meadows function as blue carbon ecosystems, although the large overlap between groups also shows that local sedimentary and hydrodynamic context strongly mediates carbon storage, so inventory or restoration prioritization should be regionally differentiated (Figure 1).

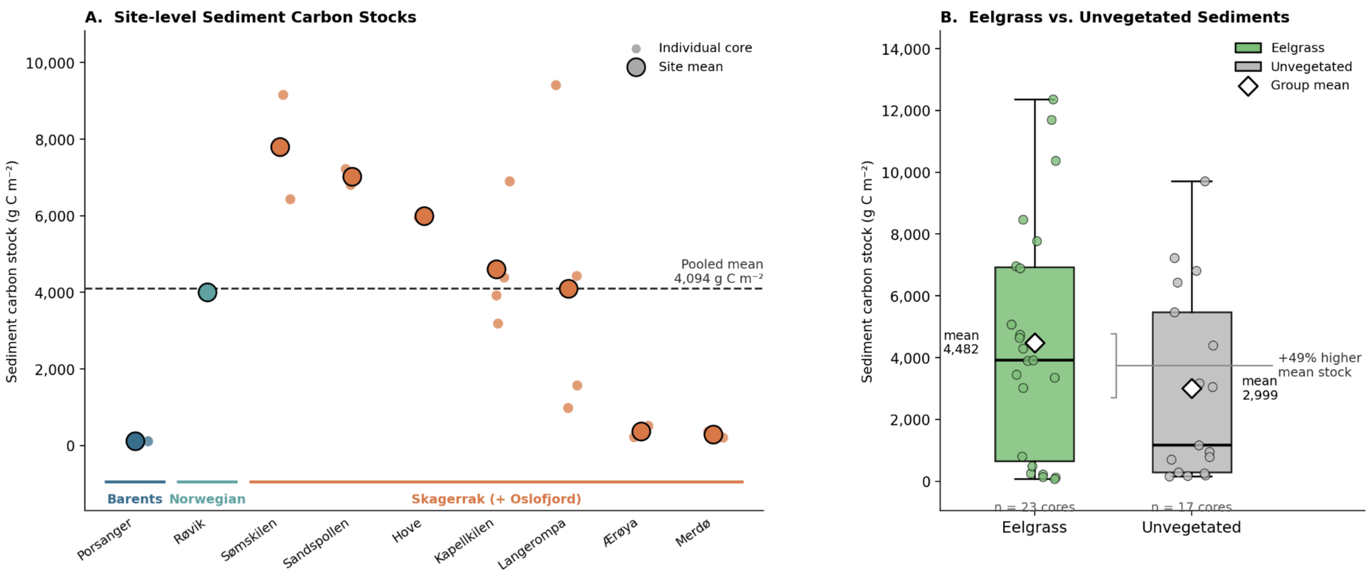

Figure 1. Norwegian eelgrass sediment carbon stocks across regions and a comparison of carbon stocks in vegetated vs unvegetated sediments.

Panel A: site-level stocks across 9 eelgrass sites (Gagnon et al. (2024); Röhr et al. (2018)); large markers = site means, small markers = individual cores, dashed lines = national pooled mean. Panel B: per-core comparison of eelgrass vs. unvegetated sediments (Gagnon et al. (2024)); ◆ = group mean.

The top-down national estimate from the Nordic Blue Carbon Project reports approximately 245 Gg organic carbon stored in Norwegian seagrass sediments, plus approximately 7 Gg C in living biomass (Frigstad et al., 2020). The relationship between Figure 1 and the bottom-up density estimates is instructive. Applied across the modeled area of 90 km², the 245 Gg C stock corresponds to an implied density of approximately 2,700 g C m^{-2}; applied across the 60 km² measured extent, it corresponds to approximately 4,083 g C m^{-2}. The bottom-up densities calculated in this analysis (≈ 3,811-4,094 g C m^{-2}) align closely with the measured-extent estimates but exceed the modeled-extent estimate by roughly 40%. The two approaches are therefore broadly consistent, and the apparent discrepancy is driven by differences in spatial assumptions and aggregation logic rather than by disagreement over how much carbon eelgrass sediments hold.

Carbon-stock variability is itself a policy-relevant result. Within-region standard deviation in sediment carbon density ranged from approximately 1,966 g C m^{-2} in the South East (Oslofjord) to approximately 3,994 g C m^{-2} in the South West (Skagerrak). This variability indicates that a single national factor would obscure major regional differences in sediment conditions, hydrodynamic exposure, meadow structure, and carbon vulnerability. For greenhouse gas inventory development, these results support a phased approach in which national estimates are improved by regionally differentiated carbon factors and condition classes rather than relying only on global defaults or modeled estimates (IPCC, 2014; Macreadie et al., 2019).

3.3 Macroalgal carbon values, productivity, and sequestration estimates

The Nordic Blue Carbon Project estimated Norwegian kelp forests to contain approximately 4,969 Gg C in living biomass and Norwegian rockweed beds to contain approximately 927 Gg C in living biomass (Frigstad et al., 2020). While these figures indicate that macroalgae hold substantial living-biomass carbon pools, this carbon is fundamentally different in kind and must not be equated directly with seagrass sediment stock. Macroalgal biomass is continuously turned over through growth, grazing, detachment, decomposition, harvesting, export, and remineralization, so its climate relevance depends on the fraction that is ultimately sequestered long-term (Krause-Jensen & Duarte, 2016; Lovelock & Duarte, 2019). Recent seaweed aquaculture evidence suggests that macroalgae can enhance sedimentary carbon burial under farm conditions in depositional environments, but comparable evidence has not yet been resolved for natural kelp forests or rockweed beds (Duarte et al., 2025).

As seagrass represents in-situ, primarily autochthonous sediment carbon, in contrast to macroalgal living biomass, the two values are distinct carbon pools that should not be summed. Autochthonous carbon is produced within the ecosystem where it is stored, whereas allochthonous carbon is produced elsewhere and later deposited or buried in a receiving environment. Seagrass sediment stocks may include both eelgrass-derived material and trapped allochthonous organic matter, but the carbon pool is measured directly within the meadow sediment and is more directly compatible with standard in-situ sediment-based accounting. Macroalgal carbon storage is primarily export-driven: its long-term sequestration potential depends on whether macroalgae-derived allochthonous carbon can be attributed to source habitats and shown to be durably stored elsewhere. Allochthonous carbon can provide genuine climate mitigation when storage is additional, attributable, and persistent, but these conditions are not yet resolved for national-scale Norwegian macroalgal accounting (Houston et al., 2025).

Macroalgal sequestration estimates are also much larger than those for seagrass but more structurally uncertain. The Nordic Blue Carbon Project estimated Norwegian kelp sequestration at approximately 503 Gg C yr^{-1}, roughly 1.8 million tonnes CO_2 yr^{-1}, and rockweed sequestration at approximately 117 Gg C yr^{-1}, roughly 0.4 million tonnes CO_2 yr^{-1} (Frigstad et al., 2020). These estimates depend on the export of particulate and dissolved organic carbon from coastal production areas to shelf sediments, fjord basins, or deep-ocean reservoirs where carbon may be buried or stored over climatically relevant timescales (Krause-Jensen & Duarte, 2016). The principal uncertainty is therefore what fraction of that production escapes rapid remineralization and can be attributed to long-term storage, which is presently unknown.

Empirical evidence from the Nordic Blue Carbon Project provides important but still spatially limited support for macroalgal carbon burial. Sediment-core analyses in Frohavet, Trøndelag used stable isotopes, dating, and species-specific eDNA/qPCR methods to detect kelp-derived carbon in offshore sediments. Kelp DNA from *Laminaria hyperborea* and *Saccharina latissima* was detected through sediment cores down to approximately 23 cm depth, representing roughly 120 years of accumulation (d'Auriac et al., 2021; Frigstad et al., 2020). The analyses estimated total sediment carbon sequestration rates of approximately 15-50 g C m^{-2} yr^{-1}, with kelp-derived material contributing approximately 10-32% of sediment organic carbon and a kelp-specific sequestration rate of roughly 13 g C m^{-2} yr^{-1} (Frigstad et al., 2020).

A second distinct approach to macroalgal sequestration rates is reported in this analysis and should not be conflated with the Nordic Blue Carbon Project's estimate (kelp + rockweed: 620 Gg C yr^{-1}, and ~2.3 Mt CO_2 yr^{-1}; Frigstad et al., 2020). An independent estimate was derived by applying published export and sequestration fractions to national net primary production, finding a range from 1.3-4.1 Mt CO_2 yr^{-1}, with the central estimate of 1.7 Mt CO_2 yr^{-1} (Krause-Jensen & Duarte, 2016). The Frigstad et al. (2020) value is cited where national totals are discussed, while the export-fraction estimate from Krause-Jensen & Duarte (2016) is used in order to conduct subsequent uncertainty analyses (Figures 2 and 3).

These findings show that kelp-derived carbon can reach depositional environments and persist in sediments. However, this evidence still does not yet resolve national-scale accounting. To translate macroalgal production into greenhouse gas inventory-grade removals, Norway would need repeated spatial validation of source attribution, export pathways, burial efficiency, sediment accumulation rates, dissolved organic carbon persistence, and long-term permanence across multiple depositional settings. The current evidence therefore supports macroalgae as a major carbon-cycling and ecosystem-service asset, but not yet as a high-certainty inventory category equivalent to sediment-based seagrass (IPCC, 2014; Krause-Jensen & Duarte, 2016; Macreadie et al., 2019).

3.4 Comparative carbon balance and uncertainty

The compiled carbon evidence indicates that macroalgae dominate the national blue carbon balance in mapped area, standing biomass carbon, and potential annual sequestration, while seagrass contributes a smaller but more directly sediment-associated and inventory-ready carbon pool. Published national estimates place Norwegian seagrass sediment carbon stock at approximately 245 Gg C (Frigstad et al., 2020), compared with approximately 5,896 Gg C of macroalgal living-biomass carbon; although more conservative approach using Gundersen et al. (2021) standing-stock densities and Krause-Jensen & Duarte (2016) yields approximately 2,600 Gg C of macroalgal living-biomass carbon. Given either estimate, macroalgae exceeds seagrass by roughly one to one-and-a-half orders of magnitude in national stored carbon, and by approximately two orders of magnitude in estimated annual CO_2 sequestration. These are different carbon pools that cannot be conflated: seagrass carbon figures represent a centuries-built sediment stock, whereas macroalgae is annually-cycling living biomass whose climate value is contingent on export and burial (Figure 2).

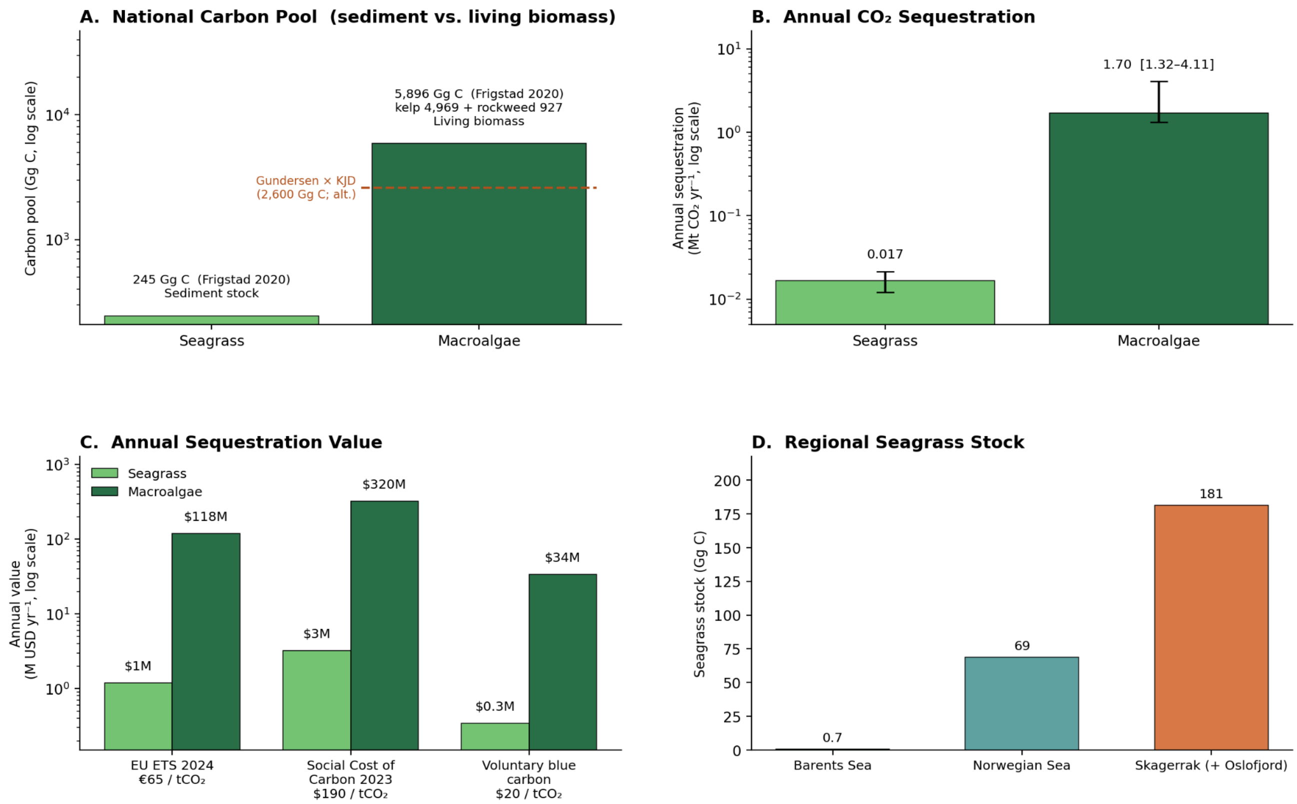

Figure 2. Norwegian seagrass and macroalgae carbon balance sheet: carbon pool, annual sequestration, indicative carbon value, and regional seagrass stock.

Panel A: bars show national carbon pools for seagrass and macroalgae; carbon types are different and not directly comparable: seagrass = sediment stock and macroalgae = living biomass carbon (Frigstad et al. (2020) Table 8). Gundersen x KJD areal alternative (2,600 Gg C) shown as dashed red line for additional context. Panel B: annual sequestration values for seagrass (TemaNord (2020)) and macroalgal export-fraction 23-62% (Krause-Jensen & Duarte (2016)). Panel C: annual sequestration x carbon prices; EU ETS 2024 (€65/tCO_2); U.S. social cost of carbon 2023 ($190/$tCO_2$); high-end voluntary blue carbon price ($20/$tCO_2$). Panel D: regional mean sediment carbon density for seagrass (Gagnon et al. (2024); Röhr et al. (2018)) x HB19 mapped area; need not sum to the national total. Barents and Norwegian Seas estimates each represent a single site.

The indicative economic valuation of annual CO_2 sequestration illustrates the difference in scale between the two ecosystem groups, but should be read as a coarse example rather than a market-ready estimate. Applying three illustrative carbon prices, the 2024 EU ETS price of €65 tCO_2^{-1}, the 2023 U.S. social cost of carbon of US$190 tCO_2^{-1}, and a voluntary blue carbon price of US$20 tCO_2^{-1}, produces annual values of approximately: US$1 million, US$3 million, and US$0.3 million for seagrass; against approximately US$118 million, US$320 million, and US$34 million for macroalgae (Figure 2). These estimates reflect only the value of the potential CO_2 sequestration and exclude the unresolved export, burial, permanence, and attribution assumptions that condition the macroalgal numbers; the seagrass values are more directly attributable to sediment carbon, though they too omit valuation of uncertainty and co-benefits.

Regional seagrass stock estimates also show that the national carbon pool is spatially uneven. Combining regional mean sediment density with mapped (HB19) eelgrass area, the southern Skagerrak region (including Oslofjord) accounts for the largest estimated regional seagrass carbon stock at approximately 181 Gg C, followed by the Norwegian Sea at approximately 69 Gg C, while the Barents Sea contributes under 1 Gg C; the Norwegian Sea and Barents Sea estimates each rest on a single site (Figure 2, Panel D). These regional stocks sum to approximately 251 Gg C, closely matching the Frigstad national estimate of 245 Gg C. Macroalgal carbon pools are not resolved at the regional level and cannot yet be interpreted spatially.

The two ecosystems differ in the kind of uncertainty attached to their estimates, which shapes how each should be interpreted. For seagrass, uncertainty in this analysis is primarily sampling-driven. A non-parametric bootstrap (10,000 resamples) of the nine site-level eelgrass sediment carbon-density estimates, applied to the 90 km^2 modeled national extent, produced a national stock estimate of approximately 344 Gg C with a 95% confidence interval of 177-502 Gg C (Figure 3 Panel A). This interval overlaps the published Frigstad (2020) estimate of 245 Gg C and the Gagnon et al. (2024) Nordic-weighted estimate (~250 Gg C), but its central value sits above both. The gap is driven by density, not extent: the nine-site pooled mean from this analysis (~3,811 g C m^{-2}) is roughly 40% higher than Frigstad's Nordic-weighted density (~2,722 g C m^{-2} implied at 90 km^2). The underlying site densities span 112 to 7,805 g C m^{-2} with a coefficient of variation of approximately 77%, confirming that seagrass stock uncertainty is governed less by whether eelgrass stores sediment carbon and more by how representative the available sites are of national conditions.

For macroalgae, uncertainty is dominated by the transfer functions used to estimate sequestration. The national macroalgal stock is comparatively well constrained, but annual sequestration varies widely because it depends on the assumed fraction of production that is exported, deposited, and buried over climatically relevant timescales. Applying the published macroalgal export/sequestration fraction range of 23-62%, with a central estimate of 25.5%, produces annual sequestration of approximately 1.3 to 4.1 Mt CO_2 yr^{-1}, centered near 1.7 Mt CO_2 yr^{-1} (Figure 3 Panel C; Frigstad et al., 2020; Krause-Jensen & Duarte, 2016). By contrast, estimated seagrass sequestration is much smaller, approximately 0.017 Mt CO_2 yr^{-1} (95% bounds ≈ 0.008-0.026), with uncertainty set by the published sequestration-rate standard deviation (Frigstad et al., 2020).

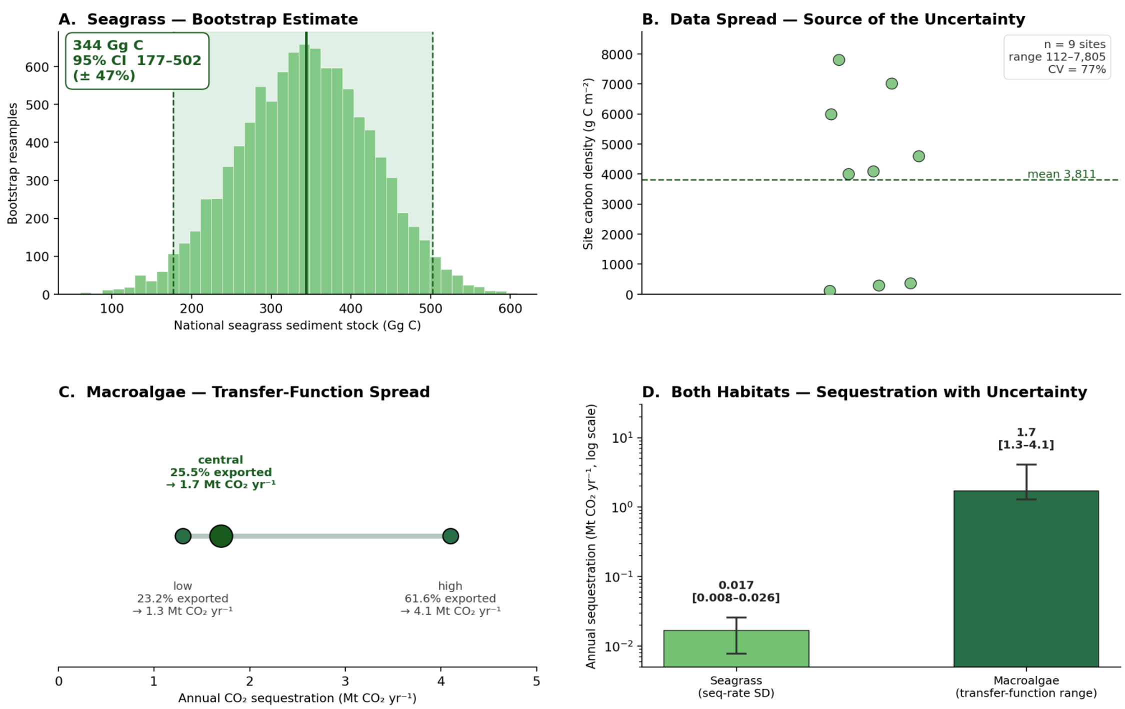

Figure 3. Seagrass and macroalgae carbon uncertainty structures.

Panel A: non-parametric bootstrap (10,000 resamples) of 9 site sediment-stock measurements (Gagnon et al. (2024); Röhr et al. (2018)) x national modeled extent of 90 km² (Frigstad et al. (2020)). Panel B: seagrass site data spread driving the bootstrap confidence interval. Panel C: macroalgae sequestration uncertainty governed export fraction transfer-function spread (23-62%, central 25.5%) (Krause-Jensen & Duarte (2016)); the living-biomass carbon pool itself is source-dependent (Frigstad et al. (2020): 5,896 Gg C; Gundersen x KJD: 2,600 Gg C). Panel D: annual sequestration with the two uncertainty types side-by-side: seagrass ±1.96 SD of the TemaNord (2020) rate; macroalgae the transfer function range.

3.5 Environmental drivers of carbon storage and ecosystem function

Seagrass

Sediment dry bulk density

Seagrass carbon storage in Norway is associated most strongly with sediment properties, with hydrodynamic and light context as supporting controls. In the compiled seagrass database, simple bivariate regressions identify sediment dry bulk density as the only statistically significant correlate of sediment carbon ($R^2 = 0.62$, $p < 0.001$, $N = 20$), with a negative relationship: lower dry bulk density indicates finer, muddier, more depositional sediments that retain organic matter, consistent with the strong non-linear relationship and peak carbon densities near 0.5 g cm^{-3} reported by Gagnon et al. (2024) (Figure 4 Panel A). Aboveground biomass showed a positive but non-significant association ($R^2 = 0.38$, $p = 0.101$, $N = 8$), water depth was effectively flat ($R^2 = 0.01$, $p = 0.688$, $N = 20$), and mean temperature was weakly positive but non-significant ($R^2 = 0.14$, $p = 0.322$, $N = 9$) (Figure 4 Panels B-D). The regional pattern reinforces the sediment signal: the South East (Oslofjord) combined high mean carbon stock with low mean dry bulk density, while the North (Barents Sea) had low carbon stock and high dry bulk density.

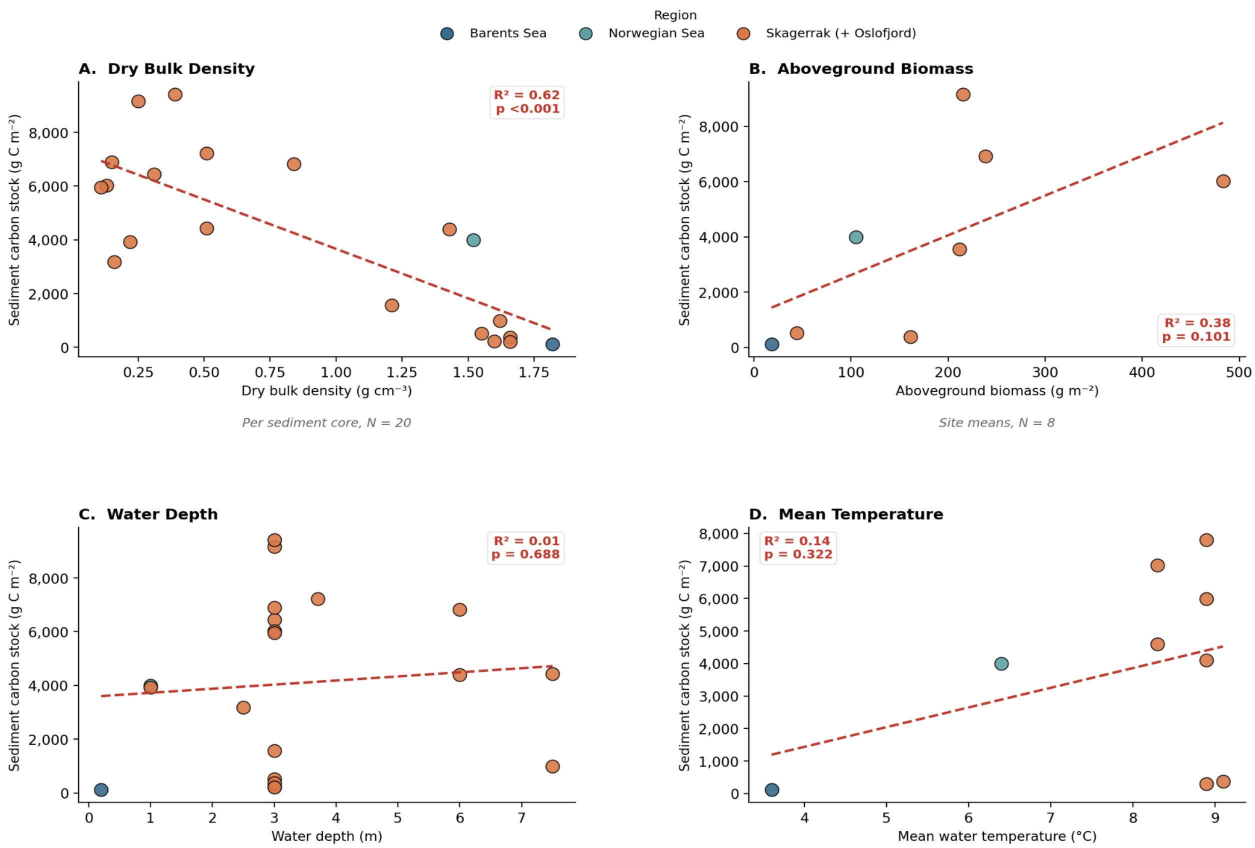

Figure 4. Four bivariate environmental drivers of eelgrass carbon storage.

Sediment carbon stock (g C m^{-2}) against four bivariate environmental drivers: dry bulk density (Panel A), aboveground biomass (Panel B), water depth (Panel C), and mean water temperature (Panel D). Points colored by region. Panel A and C use per-core data; panels B and D use site means. Dashed line = OLS regression; R^2 and p-value shown per panel (Gagnon et al. (2024); Röhr et al. (2018)).

It is important to interpret these bivariate results alongside the multivariate analysis of Gagnon et al. (2024), which used partial least squares regression and ranked water depth as the leading predictor across their full model. The two findings are not contradictory: in a multivariate model, water depth co-varies with exposure, light, and sediment structure and absorbs much of their shared signal, whereas in the smaller harmonized bivariate dataset analyzed here, depth alone explains little of the variance and dry bulk density emerges as the dominant single correlate. The difference reflects analytical structure and sample size rather than disagreement, and it underscores that the present driver analysis is best read as exploratory given the limited, spatially imbalanced sample. Further studies on environmental drivers specific to Norwegian eelgrass meadows would be useful for examining inventory-grade readiness of carbon storage capacity.

Hydrodynamics
Wave exposure provides a second control consistent with the sediment result: sheltered, low-energy environments favor fine-sediment deposition and organic-matter retention, whereas high-energy environments promote erosion, resuspension, and coarser sediments. Wave exposure, wind exposure, and sediment type jointly influence meadow resilience and carbon storage (Boström et al., 2014; de Smit et al., 2022).

Light/ Photosynthetically Active Radiation (PAR)
Light availability and depth set distributional limits. Eelgrass requires sufficient light for photosynthesis (photosynthetically active radiation), and reduced light availability from depth, turbidity, eutrophication, suspended sediment, or epiphyte loading can reduce growth, biomass, and meadow persistence (Burkholder et al., 2007; Dennison et al., 1993; Orth et al., 2006). In high-latitude systems, seasonal light constraints may further shape productivity and carbon metabolism; Arctic and sub-Arctic *Zostera marina* may require strong seasonal acclimatization to maintain carbon capture across extreme light regimes (Jueterbock et al., 2021).

Temperature and Salinity
Temperature and salinity appear to operate more as broad regional gradients than as simple local predictors of sediment carbon. Mean temperature across regions ranges from approximately 3.6°C in the Barents Sea to approximately 8.9°C in the Skagerrak coast, and salinity from approximately 25.5 to 33.4 PSU. Temperature can regulate eelgrass respiration, photosynthesis, stress tolerance, and disease vulnerability, but the limited Norwegian site-level dataset cannot separate temperature effects from correlated regional differences in sediment type, exposure, salinity, depth, and productivity (Gagnon et al., 2024; Waycott et al., 2009).

Macroalgae
Macroalgal systems respond to a different configuration of drivers than eelgrass. Kelp forests require hard substrate for attachment, sufficient light, appropriate depth ranges, and hydrodynamic conditions that support nutrient exchange without exceeding attachment or survival thresholds. In a Norwegian spatial distribution model for *Laminaria hyperborea*, depth, slope, terrain curvature, wave exposure, and light exposure were the most important geophysical predictors of kelp distribution (Bekkby et al., 2009). Unlike eelgrass, which stores the most carbon in sheltered depositional settings, *L. hyperborea* can reach high biomass and secondary production in more wave-exposed habitats (Gundersen et al., 2021; Norderhaug & Christie, 2011). Wave exposure enhances water movement and nutrient exchange, hard substrate provides attachment, and depth and light set lower distributional limits, with turbidity or coastal darkening compressing vertical extent (Bekkby et al., 2009; Frigstad et al., 2020).
Temperature affects macroalgae through species distributions, productivity, and carbon transfer. In northeast Atlantic kelp forests, warmer regimes have been associated with lower carbon assimilation and lower particulate carbon transfer, suggesting that warming may reduce the carbon-cycling role of kelp even before habitat is completely lost (Pessarrodona et al., 2018). Biological interactions are also central, especially sea urchin grazing in northern Norway, where kelp forests have historically shifted to urchin barrens causing lower biomass, lower habitat

complexity, and reduced carbon export potential (Norderhaug & Christie, 2009). Understanding the drivers for both seagrass and macroalgae is necessary for future carbon accounting because carbon production and carbon fate are governed by complex, interacting ecological processes.

3.6 Human pressures and protection context

Dredging

Human-pressure indicators show that Norwegian blue carbon ecosystems sit within a complex coastal and offshore activity landscape. EMODnet-derived dredging data indicate sustained physical disturbance in Norwegian waters, with the roadmap database summarizing approximately 9.33 dredging events per year during 2017-2023, including approximately 5.5 capital dredging events per year and approximately 453,372 tonnes of extracted material per year (EMODnet Human Activities, 2025). Dredging can affect seagrass through direct substrate removal, increased turbidity, sediment deposition, altered bathymetry, and reduced light availability, although the ecological consequence of each dredging record depends on its spatial and temporal overlap with eelgrass meadows (Erftemeijer & Lewis, 2006).

Vessel traffic & offshore infrastructure

Maritime transport and offshore infrastructure create additional human pressure pathways. The database summarized approximately 69,934 vessels per year across approximately 40 Norwegian ports and identified 542 active offshore installations from EMODnet-derived layers (EMODnet Human Activities, 2022, 2025). These indicators suggest substantial marine industrial and transport activity. For eelgrass, the most relevant mechanisms include anchoring, mooring scars, propeller wash, dredging, coastal construction, sediment resuspension, and water-quality degradation. For macroalgae, relevant mechanisms include kelp harvesting, aquaculture interaction, coastal construction, trawling in adjacent areas, sedimentation, and cumulative changes in water quality and light (Christie et al., 1998; Frigstad et al., 2020; HELCOM, 2019).

Protected Areas

Protection context is present but incomplete: the mapping workflow identified 27 marine protected areas covering approximately 6,173 km^2, but the overlap between protected areas and eelgrass meadows is not fully quantified, and protection status does not guarantee reduced exposure to eutrophication, turbidity, anchoring, or climate-related stress (Conti, 2026).

Case Studies

A case study in Northern Norway demonstrates the importance of co-location analysis clearly. In Balsfjord, two Ramsar-protected eelgrass sites diverged: Sørkjosleira lost 28.7% of eelgrass area since 2009 while Kobbevågen increased 2.8-fold (Kristiansen, 2024). The likely mechanism was nutrient-related stress, with Sørkjosleira sitting closer to river outlets and agricultural infrastructure and exhibiting higher nitrate concentrations, higher epiphyte load, shorter shoots, and reduced meadow condition (Figure 5; Kristiansen, 2024). Figure 5 compares environmental and biological indicators at Sørkjosleira relative to Kobbevågen, with Kobbevågen treated as the reference baseline. It provides a strong local example of why protection status alone is insufficient for eelgrass conservation, and demonstrates the significant impact of eutrophication on eelgrass health. Further studies linking eutrophication and other pressures directly to impact on carbon storage and sequestration is necessary to track inventories and protection strategies.

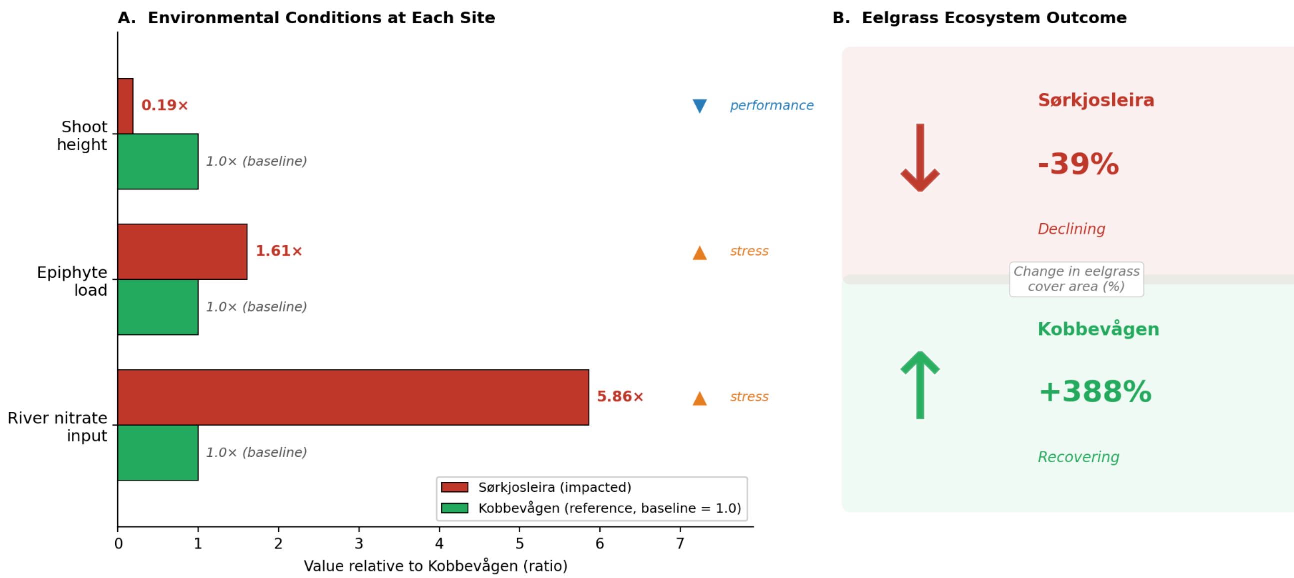

Figure 5. Balsfjord Case Study: Divergent Eelgrass Responses Under Different Eutrophication Regimes at Two Ramsar-Protected Sites in Northern Norway.
Panel A: environmental indicators at Sørkjosleira (high stress) relative to Kobbevågen (low stress, baseline – 1.0x); upward arrow– greater stressor, downward arrow – lower performance. Panel B: change in eelgrass cover area over the monitoring period at each site. Legal protection alone does not ensure recovery – environmental quality is the prerequisite (Kristiansen, 2024).

Another case study in Oslofjord illustrates cumulative pressure and heterogeneous recovery dynamics. Oslofjord has favorable sediment conditions for carbon storage, including high regional mean carbon stock and low dry bulk density, but it is also one of Norway's most heavily impacted coastal systems by human pressures. Re-mapping of eelgrass meadows indicated reduced lower growth limits, filamentous algae problems, alien species occurrence, and spatially variable persistence and recovery compared with earlier baselines (Rinde et al., 2021). This result highlights the crucial distinction between carbon capacity and realized ecosystem function, with persistent human pressures threatening the health and long-term effectiveness of otherwise carbon-rich environments.

3.7 Spatial co-location analysis

Co-location as a screening tool for protection vs. pressures vs. carbon

The interactive map operationalizes the ability to co-locate habitat polygons, study sites, pressure layers, marine protected areas, carbon indicators, and evidence gaps. The co-location categories create a transparent screening framework for identifying where more detailed field assessment, monitoring, or management review may be warranted. The most important methodological caveat is that spatial proximity should not be treated as ecological effect without field validation, especially because many pressure layers differ in temporal coverage, spatial precision, reporting intensity, and ecological relevance (Conti, 2026).

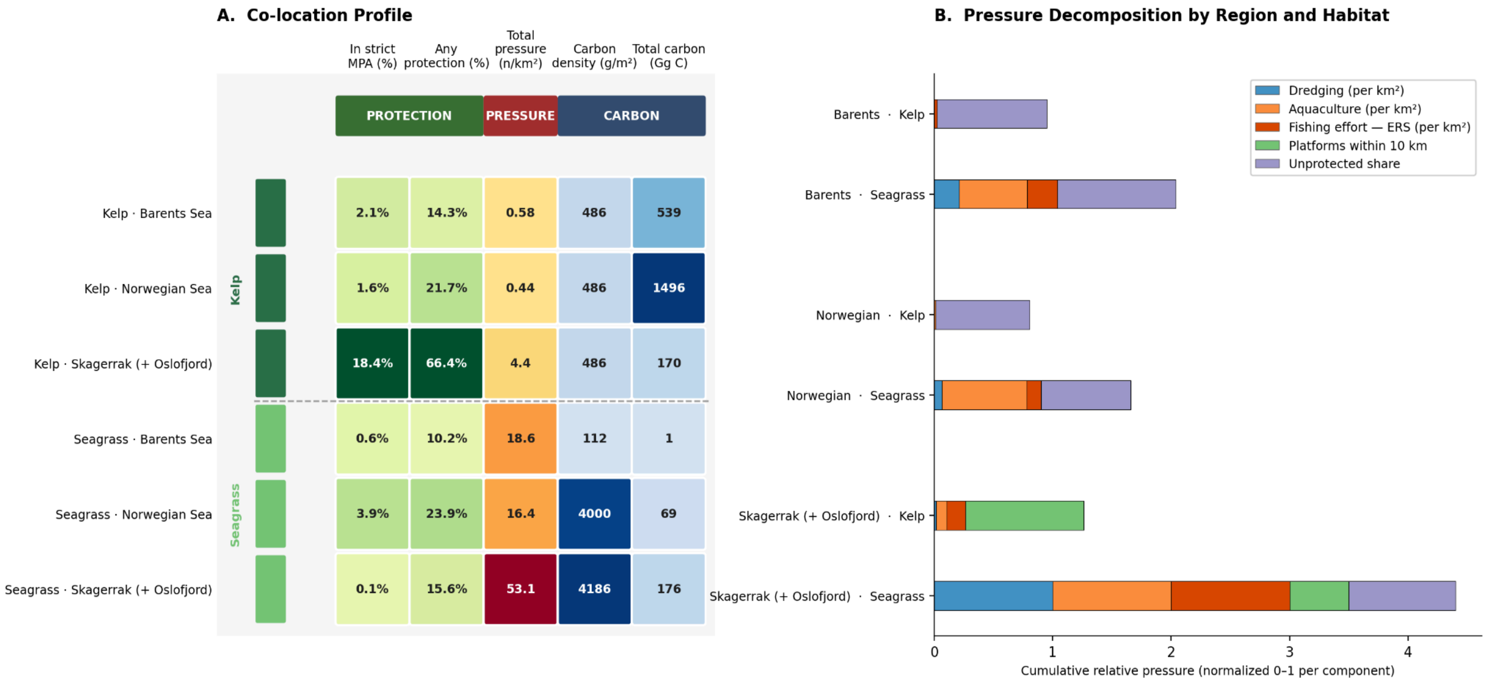

Figure 6. Co-location Profiles and Pressure Decomposition of Norwegian Seagrass and Macroalgae. Panel A: Co-location profiles. Cells are a min-max normalized within each indicator column; raw values are annotated. Protection (green): % habitat in strict MPA, % under any protection designation. Pressure (red): total anthropogenic pressure per km² of habitat – sum of dredging, aquaculture, ERS fishing effort, and offshore platforms within 5 km, divided by habitat area. Carbon (blue): mean stock density (g C m^{-2}) and total stock (Gg C). Panel B: Pressure decomposition. Each component is normalized 0-1 across all region-habitat units (0=lowest observed, 1= highest). Bars show cumulative relative pressure; longer bars indicate more intense cumulative pressure relative to the rest of the dataset. Fishing effort from Fiskeridir ERS 2019-2023 (DCA catch messages). Unprotected share = 1 – (% habitat under any protection).

The results of the spatial mapping were translated into a screening tool by co-locating protection, pressures, and carbon (Figure 6). Protection indicators include the percentage of mapped habitat within strict marine protected areas and within any protected designation. Pressure is expressed as total anthropogenic pressure per km² of habitat, calculated from dredging, aquaculture, fishing effort, offshore facilities, and wind farms within a 5 km radius, normalized by habitat area. Carbon density and total carbon are shown using habitat-specific values from the compiled database. The co-location analysis reveals that eelgrass in Southern Norway (Skagerrak and Oslofjord) shows a combination of high pressure, very low strict-MPA overlap, and substantial carbon density, making it a priority region for further investigation and potential intervention (Figure 6 Panel A).

Panel B decomposes cumulative relative pressure into component pressure layers and includes the unprotected habitat share. Values are normalized within components and should be interpreted as relative screening indicators rather than direct ecological response estimates. The pressure decomposition shows that different habitats and regions are exposed to different pressure mixtures, implying that a single national management intervention would likely be ineffective and that Norway needs spatially explicit blue carbon planning rather than generic national-level recognition (Figure 6 Panel B).

Using the interactive mapping co-location analysis to identify management-priorities

The existing literature in Norway does not link pressures or protection of macroalgae or seagrass habitats directly with ecosystem or carbon outcomes, which serves as a significant data gap. However, while spatial analysis alone cannot directly establish ecological effect, it can serve as a useful management tool to visualize habitats with the most carbon relevance and their levels of urgency regarding anthropogenic pressures and protection priorities — especially if combined with further field studies (Figure 7).

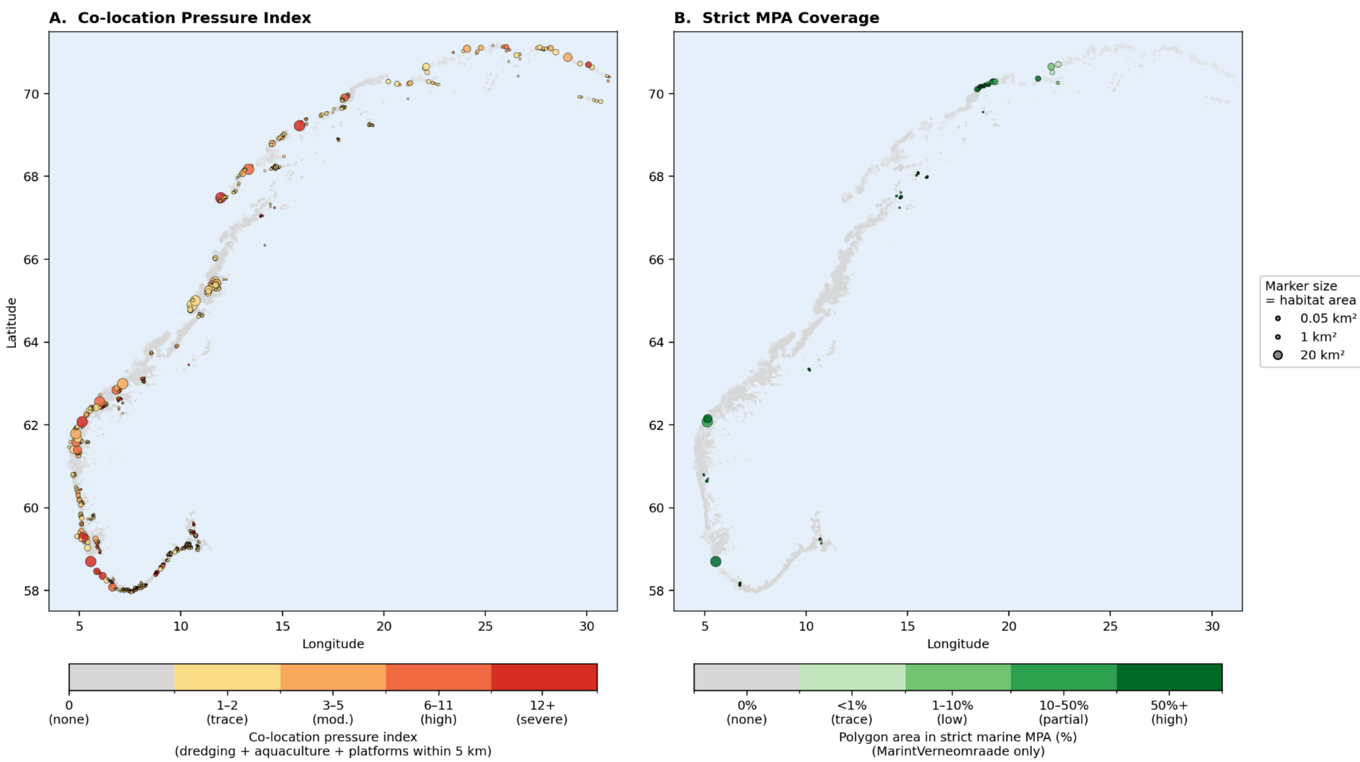

Figure 7. Spatial co-location of mapped eelgrass and kelp habitat polygons with anthropogenic pressures and strict marine protected area coverage in Norway.

Panel A: co-location pressure index (dredging + aquaculture + platforms within 5 km). Panel B: fraction of each polygon's area within a strict marine MPA (MarintVemeomraade only). Each point is the centroid of one mapped habitat polygon (4,343 eelgrass + 7,243 kelp; HB19 Naturbase), sized by habitat area; grey= no signal.

The interactive mapping allows for the creation of visualization tools of co-location relationships in geographic space, such as mapping where carbon-relevant seagrass and macroalgae habitats fall relative to anthropogenic pressure vs. marine protected areas. Mapped seagrass and macroalgae habitat polygons illustrate a side-by-side visual comparison of these zones, with marker size proportional to the habitat-polygon area and colored by strength of human pressures (Figure 7 Panel A) and MPA coverage (Figure 7 Panel B). The purpose is to move from regional screening toward a spatially explicit view of management context.

It reveals that mapped habitats are unevenly distributed relative to both anthropogenic pressure and protection. Pressure signals are more concentrated in southern and more heavily inhabited coastal areas, while protection overlap is less frequent than pressures and spatially disconnected from the highest-pressure habitat polygons.

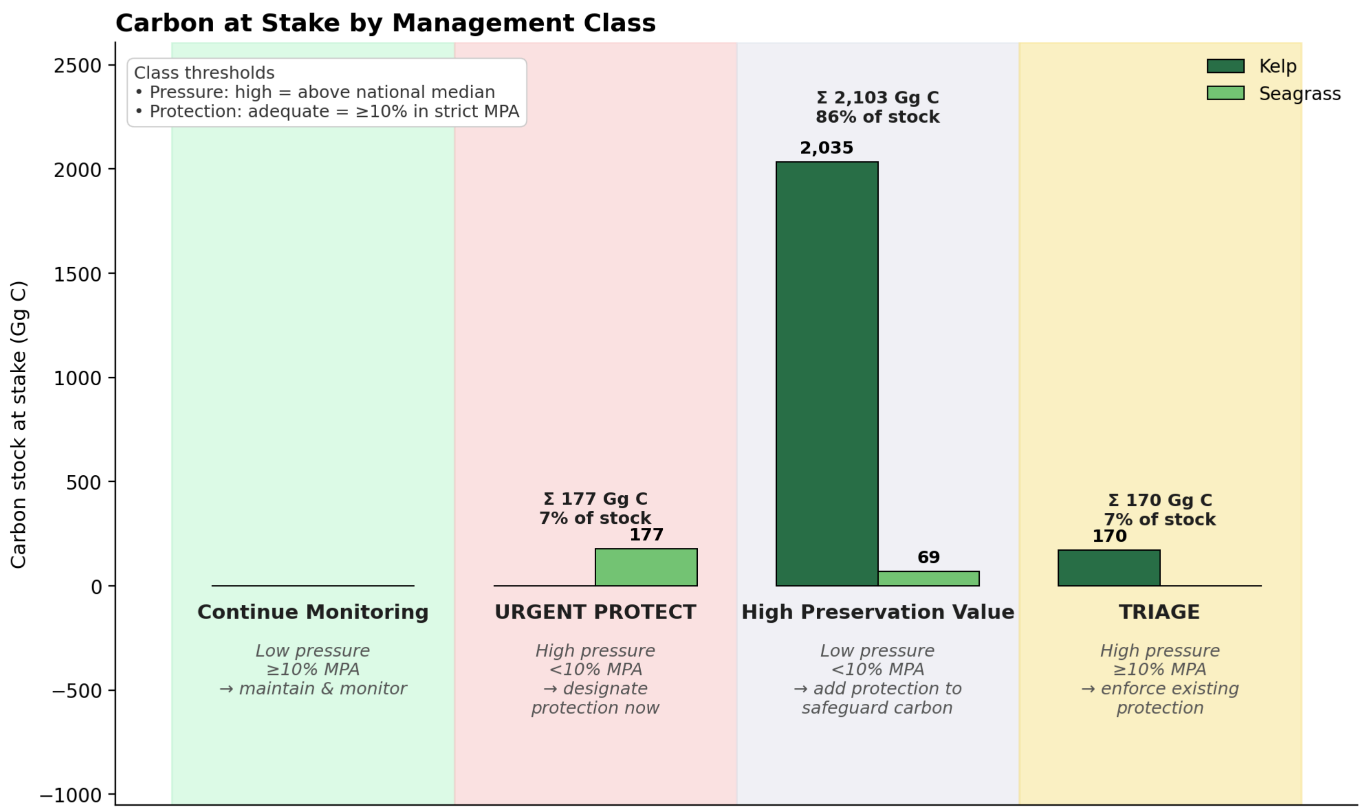

Figure 8. Carbon-at-stake by protection and pressure management-priority screening classes. Each region-habitat unit (kelp and seagrass x Barents Sea, Norwegian Sea, Skagerrak + Oslofjord) is assigned to a management class based on two thresholds: anthropogenic pressure (high if above the national median) and protection (adequate if ≥ 10% of habitat area lies in a strict marine protected area). Bars show carbon pools (Gg C) in each class. Kelp applies a national mean density (Gundersen et al. (2021)) to mapped regional areas; seagrass uses regional field measurements (Gagnon et al. (2024)).

Developed alongside the co-location profile by region (Figure 6) and the national-scale map (Figure 7), management-priority screening classes were established by grouping estimated carbon at stake with pressure and protection thresholds (Figure 8). Four management designations were created: low pressure with ≥10% MPA coverage is classified as “continue monitoring”; high pressure with <10% MPA coverage is classified as “urgent protect”; low pressure with <10% MPA coverage is classified as “high preservation value”; and lastly, high pressure with ≥10% MPA coverage is classified as “triage,” meaning enforce existing protection. These classes are intended as an example screening framework for prioritization, they are not formal policy designations.

The largest share of carbon at stake falls in the lowest protection class (<10% MPA coverage), though it also coincides with low pressures mapped nearby. The second and third largest shares of carbon at stake, however, are within high-pressure co-location zones. There are no carbon pools that were found to be co-located with high MPA coverage and low pressure.

The management-classes illustrate how existing spatial data and subsequent co-location analysis can be used to screen blue carbon ecosystems according to pressure and protection statuses. Results indicate that a significant amount of carbon occurs in areas with low protection, and in some cases where pressure indicators are also elevated. These outputs identify that carbon-rich habitats may warrant monitoring, protection, or targeted pressure reduction. However, the results are limited by a lack of data on quantified ecosystem responses and ecological conditions. The analysis is based on the spatial proximity between mapped habitats and pressure layers or protection status, rather than empirical responses to those elements.

3.8 Ecosystem services and co-benefits

Biodiversity and co-benefits

Both ecosystem groups provide substantial co-benefits beyond carbon, and these benefits are central to a defensible Norwegian policy pathway. Eelgrass meadows function as nursery habitat, enhance infaunal and fish communities, contribute to trophic subsidies, stabilize sediments and support coastal resilience, and improve water quality through particle trapping and nutrient cycling (Boström et al., 2014; Fredriksen et al., 2010; Nordlund et al., 2016; Unsworth et al., 2019). Norwegian infaunal studies confirm that eelgrass meadows support higher faunal abundance than adjacent unvegetated sediments, consistent with broader findings that seagrass structure supports biodiversity and fisheries production (Fredriksen et al., 2010; Unsworth et al., 2019).

Macroalgal ecosystems also provide major ecosystem-service co-benefits. Kelp forests create three-dimensional habitats that support fish, crustaceans, mollusks, epifauna, and epiphytes, and their structural complexity influences secondary production, food-web dynamics, and biodiversity at local to regional scales (Norderhaug & Christie, 2011; Smale et al., 2019). Macroalgae also assimilate dissolved nutrients, contribute detritus to coastal and offshore food webs, and may attenuate hydrodynamic energy in rocky coastal systems.

Coastal Resilience

Coastal protection and shoreline resilience are particularly important but under-quantified services that seagrass provides. Seagrass can attenuate waves, reduce near-bed flow, trap particles, stabilize sediments through roots and rhizomes, and limit resuspension (Christianen et al., 2013; Fonseca & Cahalan, 1992; Ondiviela et al., 2014). In Norway, direct measurements of eelgrass-mediated wave attenuation or shoreline-protection value were not found, but the observed association between high carbon stocks and low dry bulk density in depositional sediments is consistent with the mechanistic role of eelgrass in stabilizing fine sediment (Boström et al., 2014; Gagnon et al., 2024). The absence of Norway-specific coastal-protection valuation should be treated as a major ecosystem-service data gap rather than as evidence that the service is unimportant.

Macroalgae contribute to coastal resilience through a different mechanism. Dense kelp canopies and stipes can modify local hydrodynamics, reduce nearshore wave energy, and alter water movement in rocky coastal systems, with effects that depend on canopy density, water depth, exposure, morphology, and storm conditions (Løvås & Tørum, 2001; Mork, 1996). As with eelgrass, the lack of systematic Norway-specific valuation represents a research gap for ecosystem-service accounting and coastal adaptation planning.

3.9 Policy and governance evaluation

Policy analysis of blue carbon integration for seagrass and macroalgae was organized around three components: (1) characterization of Norway's existing governance landscape; (2) assessment of ecosystem-specific compatibility with available policy and accounting frameworks; and (3) evaluation of policy and evidence gaps. The analysis indicates that both ecosystems are relevant to near-term conservation and management frameworks because degradation can reduce carbon stocks, weaken ecosystem-service function, and undermine biodiversity and coastal resilience. However, the policy frameworks and accounting timelines applicable to each habitat diverge substantially because the underlying carbon science differs.

The governance landscape and identified gaps

Several policy avenues are relevant to Norwegian blue carbon integration, biodiversity protection, and climate resilience. At the international accounting level, the 2006 IPCC Guidelines and 2013 Wetlands Supplement provide the main methodological framework for greenhouse gas inventory reporting, with the Wetlands Supplement explicitly extending guidance for coastal wetlands (IPCC, 2006; IPCC, 2014). At the national climate-policy level, blue carbon ecosystems may be incorporated into nationally determined contributions (NDCs) under the UNFCCC and Paris Agreement either quantitatively, through reported emissions and removals, or qualitatively, through conservation, restoration, and adaptation commitments (High Level Ambition Group on Blue Carbon [HILAG], 2024; Herr & Landis, 2016). Blue carbon ecosystems also intersect with the UN's Sustainable Development Goals (SDGs), particularly through biodiversity, fisheries, climate adaptation, and sustainable ocean-management objectives.

Norway's greenhouse gas inventory already operates under the 2006 IPCC Guidelines and the 2013 Wetlands Supplement, as documented in the country's first Biennial Transparency Report (Norwegian Ministry of Climate and Environment, 2024). Norway applies IPCC methodologies across major sectors, including energy, agriculture, waste, land use, land-use change, and forestry (Miljødirektoratet, 2018). Although coastal blue carbon habitats are not yet operationalized as distinct inventory categories, this establishes a direct institutional link between existing national reporting infrastructure and the IPCC methods under which seagrass could be accounted. Macroalgae are not yet covered by the Wetlands Supplement in the same direct way as seagrass meadows and would therefore require a more novel methodological pathway.

Both seagrass and macroalgae are already visible within Norwegian biodiversity, conservation, and resource-management systems. Eelgrass meadows are included in Norwegian marine biodiversity mapping as "ålegrasenger og andre undervannsenger," a marine "nature type" recognized for high productivity, associated species richness, fish nursery function, sediment binding, and erosion reduction (Directorate for Nature Management, 2007; Miljødirektoratet, n.d.). Kelp forests and eelgrass meadows are also identified in Norway's integrated marine conservation planning as coastal habitat types with high species diversity and biological production, as habitats affected by nutrient inputs, climate change, turbidity, and other pressures in regions such as the Oslofjord (Norwegian Ministry of Climate and Environment, 2021). Macroalgae are additionally present in ocean-industry and resource-management policy, with government documents identifying seaweed as a long-standing harvested resource and promising aquaculture sector; kelp harvesting is governed through regional harvesting regulation and rotation systems (Norwegian Ministry of Trade, Industry, and Fisheries, 2021; Greenhill et al., 2021; Steen et al., 2016). Further Norwegian regulations and governance systems relevant to seagrass and macroalgae include marine protected areas, the Nature Diversity Act, ocean management plans, municipal and regional coastal planning, fisheries policy, energy policy, tourism policy, blue economy development, and climate adaptation. This breadth of policy relevance and infrastructure creates opportunities for multiple points of integration, but it also creates coordination challenges because no single instrument currently captures the full governance domain needed for coordinated blue carbon integration.

The Norwegian Blue Forests Network landscape assessment found growing interest in blue forests and government support for domestic and international blue forest initiatives, but also found that these efforts had not yet been consolidated into a single national blue forests strategy (GRID-Arendal, 2021). This indicates that Norway's policy environment is supportive of blue carbon governance, while also confirming the current lack of a unified domestic framework that integrates carbon accounting, biodiversity, spatial planning, and ecosystem-service valuation. This gap is consistent with recent blue carbon research priorities, which emphasize that scalable and credible BCE governance requires not only improved GHG flux estimates, but also stronger understanding of human-pressure impacts, co-benefit valuation, natural capital accounting, and monitoring systems that can link carbon outcomes with biodiversity and coastal-resilience benefits (Macreadie et al., 2026).

Across both ecosystem groups, the main policy and evidence gaps are the absence of a unified national blue carbon strategy; lack of distinct blue carbon categories in Norway's greenhouse gas inventory; incomplete national habitat mapping and change detection; limited empirical data linking pressures to carbon loss or ecosystem-service decline; and ecosystem-specific accounting gaps. For seagrass, these gaps are primarily associated with operational data readiness, while for macroalgae they are primarily associated with unresolved carbon-fate, attribution, and permanence methods.

Analysis of seagrass policy readiness

Norwegian seagrass has a clear conceptual fit with established IPCC coastal wetland accounting. The IPCC Wetlands Supplement explicitly includes seagrass meadows within coastal wetland guidance, creating a methodological entry point for estimating emissions and removals from managed seagrass systems (IPCC, 2014). The primary barrier is therefore not conceptual eligibility, but operational data readiness.

The evidence needed for inventory compatibility differs from the evidence needed to show that eelgrass stores carbon. Existing studies demonstrate that Norwegian eelgrass sediments store organic carbon and that sediment carbon stocks vary strongly across regions and environmental gradients (Gagnon et al., 2024; Frigstad et al., 2020). However, national greenhouse gas inventories require repeatable estimates of emissions and removals over time rather than standing stock estimates alone.

IPCC inventory tiers describe increasing methodological complexity and data specificity for carbon accounting: Tier 1 uses basic methods and IPCC default emission and removal factors; Tier 2 uses country or region-specific data and factors; and Tier 3 uses the most detailed approaches, such as higher-resolution measurements, models, or inventory systems, with accuracy and precision generally expected to improve from Tier 1 to Tier 3 when adequate data are available (IPCC, 2006; IPCC, 2019). The current Norwegian seagrass evidence base is most consistent with Tier 1 and early Tier 2 readiness, but not yet Tier 3. A Tier 1 or coarse Tier 2 approach could combine national extent estimates, published stock values, and conservative emission/removal factors, but such estimates would remain highly uncertain. Tier 3 treatment would require spatially explicit national monitoring, site-specific process data, direct burial or accretion-rate measurements, and model-data integration.

To progress toward higher-tier accounting, Norway would specifically need: (1) repeated national seagrass mapping and change detection; (2) region-specific sediment carbon density factors; (3) direct burial or accretion rate measurements such as lead-210 isotope dating; (4) disturbance-emission factors; and (5) methods for separating anthropogenic and natural change (IPCC, 2014; IPCC, 2019; Macreadie et al., 2019). These requirements represent defined research and monitoring gaps rather than fundamental methodological obstacles. The distinction between tier readiness matters because premature high-confidence accounting could create overclaiming and credibility risks, while delaying action until definitive Tier 2 or Tier 3 data are available could leave existing carbon stocks and ecosystem services vulnerable to degradation.

Analysis of macroalgae policy readiness

Norwegian kelp forests and rockweed beds are nationally extensive, ecologically important, and estimated to have large biomass and sequestration-related fluxes (Frigstad et al., 2020; Krause-Jensen et al., 2022). However, their climate relevance cannot be inferred directly from standing biomass alone, and their sequestration pathway is more complex than that of sediment-associated blue carbon ecosystems. Kelp and rockweed carbon becomes a long-term climate benefit only if a fraction of production is exported, deposited, buried, or otherwise stored over climatically relevant time scales (Krause-Jensen & Duarte, 2016; Lovelock & Duarte, 2019). Consequently, applying a seagrass-style sediment-stock framework to macroalgae would be methodologically inappropriate. IPCC greenhouse gas inventory methodologies do not currently include macroalgae in the same direct way as seagrass, creating an accounting and governance gap for advancing macroalgae into blue carbon policy.

The Nordic Blue Carbon Project represents one of the strongest regional efforts to address macroalgal blue carbon because it combines habitat modeling, biomass and production estimates, export assumptions, climate simulations, sediment-core analysis, and eDNA-based source attribution (d'Auriac et al., 2021; Frigstad et al., 2020). National estimates suggest that Norwegian macroalgae systems may contribute approximately 620 Gg C per year in sequestration-related fluxes, making them highly relevant to blue carbon policy discussions (Frigstad et al., 2020). However, the estimates are not yet inventory-ready removals because they remain insufficiently resolved across space, species, and carbon-fate pathways. Many estimates depend on generalized transfer functions rather than direct, Norway-wide measurements of export, deposition, burial, and long-term retention.

Uncertainty in macroalgal accounting is both parametric and structural. Parametric uncertainty concerns input values such as extent, biomass, productivity, export fractions, and burial efficiency (Frigstad et al., 2020; Krause-Jensen & Duarte, 2016). Structural uncertainty concerns the accounting model itself, including how exported particulate and dissolved organic carbon are assigned to long-term sequestration, how source attribution is established, and how permanence is defined if production and sequestration occur in different places (d'Auriac et al., 2021; Krause-Jensen & Duarte, 2016; Lovelock & Duarte, 2019). Some assumptions in current Norwegian estimates are drawn from wider literature and comparable Nordic systems, such as Danish studies, rather than fully resolved measurements across Norwegian fjords, shelves, depths, species, and hydrodynamic regimes (Frigstad et al., 2020). Unlike higher-confidence sediment accumulation studies, national estimates are not based on repeated direct burial measurements across representative Norwegian depositional settings with methods such as lead-210 isotope dating (Frigstad et al., 2020; IPCC, 2014; Macreadie et al., 2019). Current estimates therefore should be interpreted as lower-tier, uncertainty-bounded estimates rather than inventory-ready annual removals. Even though macroalgae dominate Norway's marine vegetated habitat and exceed seagrass in estimated biomass carbon and potential carbon fluxes, they currently present greater methodological and governance challenges for greenhouse gas accounting.

4. Discussion

The Results established that Norwegian seagrass and macroalgae share a similar governance landscape but differ fundamentally in carbon mechanism, evidence maturity, and accounting readiness (§3.9). This Discussion translates that diagnosis into recommendations for a differentiated, phased policy strategy. It sets out distinct but parallel pathways for the two ecosystems, situates them within Norway's existing governance and financing architecture, and identifies the monitoring and research priorities needed to move each ecosystem towards policy, inventory, and market readiness.

4.1 A differentiated, phased policy roadmap for Norwegian blue carbon

The central recommendation of this analysis is that both ecosystems warrant immediate protection, expanded monitoring, and integration into national marine policy, as the loss of either would cause cascading ecological and climate consequences. However, a single undifferentiated blue carbon policy would overgeneralize across two ecosystems with very different carbon mechanisms and would weaken the scientific credibility of any resulting claims. The recommended implementation strategy therefore recognizes that seagrass and macroalgae should enter Norwegian climate and marine policy through different but equally defensible entry points, matched to the readiness of the underlying carbon science. A phased, differentiated roadmap is a recommended strategy for policy integration (Figure 9).

The roadmap synthesizes the scientific and policy findings of this analysis into a staged pathway for blue carbon integration in Norway. It begins by identifying existing international and national governance frameworks that could support blue carbon action, including the IPCC 2013 Wetlands Supplement, reporting and financing under the UNFCCC, Nationally Determined Contributions (NDCs), the UN Sustainable Development Goals (SDGs), and Norwegian marine and biodiversity regulations identified in §3.9. The two ecosystem groups then diverge according to their levels of scientific and accounting readiness. For seagrass, the pathway emphasizes near-term recognition in Norway's NDCs and preliminary greenhouse gas accounting framed around avoided degradation and protection of existing carbon stocks. The next stages focus on generating progressively more robust and spatially explicit carbon and monitoring data to support higher-confidence greenhouse gas accounting, with subsequent expansion into SDGs, biodiversity, and marine-policy instruments that broaden protection and financing. For macroalgae, the pathway begins with SDGs 14 and 15, NDC commitments framed around nature-based adaptation and co-benefits, and existing marine-management instruments, while carbon-fate science develops toward a defensible future accounting method. The roadmap highlights how differences in the carbon dynamics, accounting feasibility, evidence gaps, and co-benefit profiles necessitate distinct governance approaches and reinforce the need for integrated carbon, biodiversity, and coastal resilience policy rather than a single, blanket blue carbon framework. Ultimately, the roadmap illustrates how multiple policy instruments can be applied over time to support conservation, financing, monitoring, and carbon accounting as the evidence base expands (Figure 9).

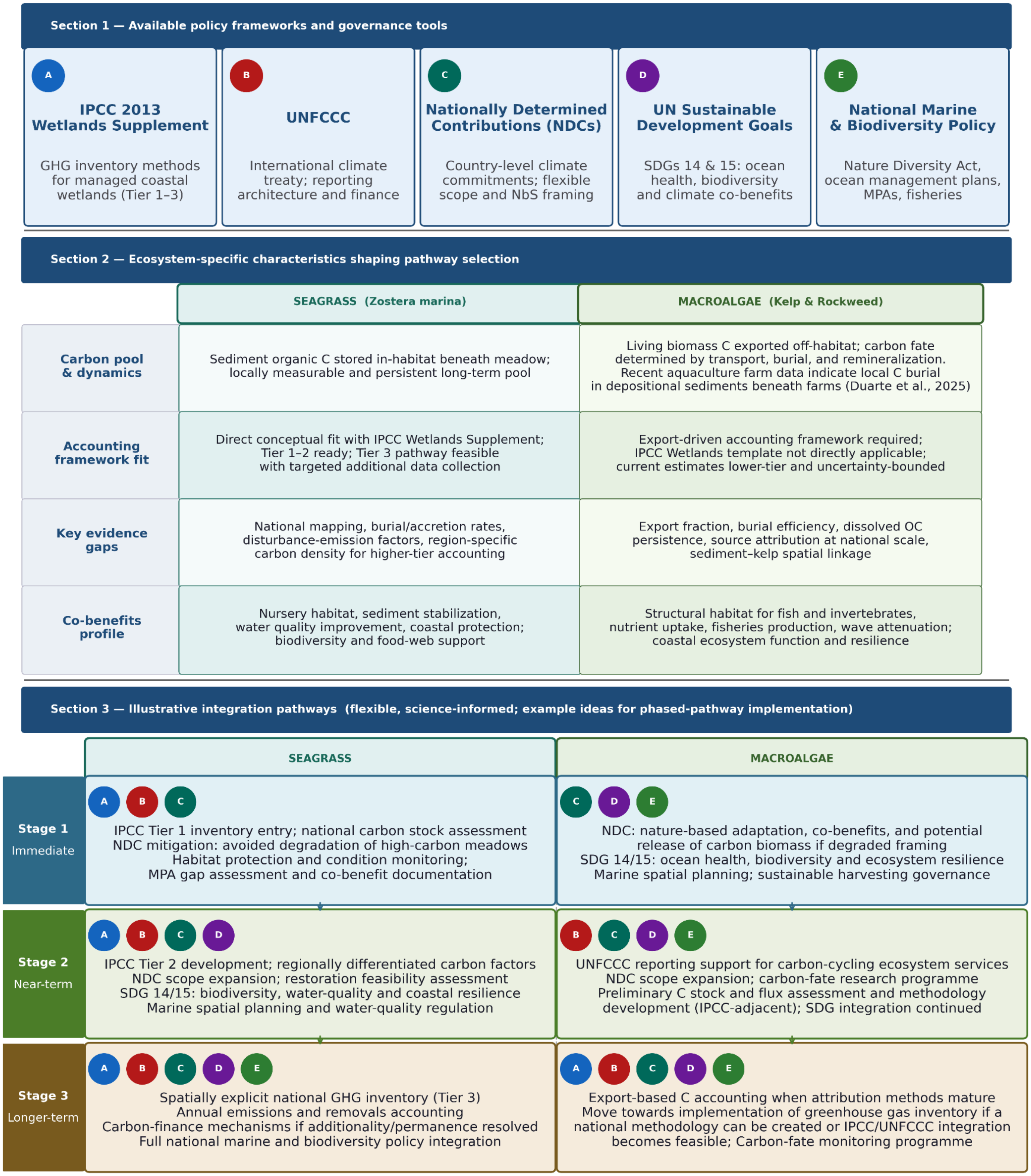

Figure 9. Policy framework design for Norwegian blue carbon governance: differentiated entry points by ecosystem type and carbon science readiness.

4.1.1 Seagrass strategy: protect existing carbon stocks while building inventory readiness

The strongest near-term carbon argument for Norwegian seagrass is the avoided degradation of existing sediment carbon stocks. Disturbance can reduce seagrass sediment carbon, and because the recovery of vegetation does not necessarily restore lost sediment carbon on policy-relevant timescales, these losses are effectively irreversible within the horizons that matter for climate policy (Macreadie et al., 2015). This risk-of-loss logic is most acute where high sediment-carbon density coincides with strong anthropogenic pressure and incomplete protection. The Results show that the highest-density regions, particularly Oslofjord and Skagerrak in southern Norway, overlap with elevated human pressure and incomplete marine protected area (MPA) coverage, making targeted protection of these meadows the highest-priority near-term action.

A measurable carbon stock, the current evidence base, is necessary but not sufficient alone for this suggested pathway. Avoided-degradation crediting is defined against a counterfactual: the rate at which sediment carbon would be lost in the absence of protection. Quantifying that benefit therefore requires not only the stock itself but a credible national baseline rate of seagrass loss (how much the meadow area is degraded or lost per year, and where), against which protection can be shown to reduce emissions. Norway currently has a defensible first-order national stock estimate but lacks the corresponding national extent-change and habitat-condition time series. The available loss evidence is limited, such as the 28.7% decline at Sørkjosleira (Kristiansen, 2024) and the heterogeneous recovery documented in the Oslofjord (Rinde et al., 2021), rather than systematic. The binding constraint on seagrass crediting is thus not the stock estimate, which is the comparatively mature component despite high regional variability, but the absence of a national loss-rate baseline. Establishing recurring, standardized national monitoring of seagrass extent and condition is thus the single highest-value near-term investment for inventory and crediting readiness.

This avoided-degradation framing also aligns with emerging carbon-finance methodologies. The French Label Bas-Carbone method for *Posidonia oceanica* institutionalizes seagrass conservation by valuing avoided losses from anchoring degradation rather than relying solely on active-restoration gains, demonstrating that an avoided-loss accounting model is workable in a European governance context (Comte et al., 2024; French Ministry for Ecological Transition, 2023).

The recommended pathway for Norwegian seagrass is therefore to enter UNFCCC reporting under IPCC inventory treatment, initially using Tier 1 while building Tier 2 readiness, combined with NDC commitments framed around avoided degradation and the protection of valuable carbon stocks and ecosystem services. The phased pathway can then expand to higher-tier inventory accounting, as well as scaling policies to include seagrass in SDGs, biodiversity goals, and other national marine policy, building durable funding avenues and long-term integration.

4.1.2 Macroalgae strategy: protect and manage via alternative pathways while researching and building carbon accounting capacity

For macroalgae, the appropriate entry point is not the greenhouse-gas inventory pathway, as applying a seagrass-style sediment-stock framework would be methodologically inappropriate and sequestration estimates should not be presented with the same confidence as seagrass sediment stocks. At the same time, macroalgae should not be dismissed from policy simply because accounting is difficult.

The recommended pathway is therefore to integrate macroalgae immediately into the frameworks where its value is already defensible: NDCs framed around nature-based adaptation, co-benefits, and protection of living carbon biomass; biodiversity targets under SDGs 14 and 15; and Norway's existing marine-management architecture which already encompasses ocean management plans, the Nature Diversity Act, marine spatial planning, and fisheries and harvesting regulation directly applicable to kelp and rockweed habitats (Norwegian Ministry of Climate and Environment, 2021; Norwegian Ministry of Trade, Industry, and Fisheries, 2021).

The autochthonous-allochthonous distinction complicates how blue carbon responsibility is assigned. A strict source-based view would privilege carbon produced and stored within the same habitat, making seagrass appear more straightforward than macroalgae. However, allochthonous organic carbon can still represent genuine climate mitigation when monitored and accounted for properly (Houston et al., 2025). This shifts the accounting question from carbon origin alone to the ecosystem process that creates durable retention. For macroalgae, production occurs in kelp or rockweed habitats, while durable storage may occur elsewhere. A defensible framework should therefore avoid treating all allochthonous carbon as invalid, while also avoiding premature attribution of exported macroalgal carbon as a creditable removal.

Japan's recent incorporation of seaweed-bed carbon removals and absorption into national greenhouse gas inventory reporting demonstrates that macroalgae-related accounting methods can be developed and implemented nationally. However, Japan's policies should be treated as methodological precedent rather than a directly transferable template for Norway, because species composition, coastal geomorphology, kelp forest dynamics, management boundaries, and carbon-fate pathways differ from Japan's systems (National Institute for Environmental Studies, 2024; Reuters, 2024). For Norway, the relevance of Japan is therefore not that its method can be adopted directly, but that macroalgae accounting can become policy-relevant when national methods explicitly address attribution, monitoring boundaries, and carbon-fate assumptions.

Carbon accounting for macroalgae should remain explicitly developmental as these challenges are addressed. A scientifically credible approach treats it as an emerging accounting frontier supported by targeted investment in export tracking, sediment attribution, eDNA/qPCR validation, dissolved-organic-carbon (DOC) fate, and depositional-environment mapping. If that science matures, Norway could establish its own crediting method and eventually pursue inventory inclusion; until then, macroalgae are best governed as a high-priority ecosystem-service asset rather than a carbon-accounting unit

4.2 Governance integration and financing mechanisms under uncertainty

Norway's central challenge is not a lack of policy relevance or scientific interest, but a mismatch between fragmented existing governance tools and an evidence base that is maturing at different speeds for the two ecosystems. The question is therefore less whether seagrass and macroalgae can be named in climate or biodiversity policy than whether policymakers can integrate the instruments that already apply to them while developing more carbon-specific policy; the ultimate objective being to build a unified framework for the carbon-biodiversity-coastal-resilience nexus rather than treating carbon sequestration as an isolated objective. This distinction is important because blue carbon governance increasingly depends upon integrating mitigation with biodiversity protection, coastal resilience, human-pressure management, and natural capital accounting (Macreadie et al., 2026).

The Montreal Protocol offers a useful governance precedent: it demonstrates that environmental policy can proceed successfully under scientific uncertainty when designed from the outset to be adaptive, evidence-responsive, and capable of becoming more ambitious as knowledge and technological capacity improve (Dugoua, 2021; UNEP, n.d.). The lesson for Norway is that blue carbon governance need not wait for carbon-accounting uncertainty to be fully resolved. Policy can protect existing BCEs now, incorporate ecosystem services and co-benefits, and establish the monitoring, research, and accounting pathways that allow the carbon science to mature.

Financing should follow scientific and governance readiness. The Blue Carbon Finance Toolbox developed under the High-Level Ambition Group on Blue Carbon emphasizes that finance can combine government funding, blended finance, payments for ecosystem services, blue bonds, carbon-market approaches, and support for monitoring, reporting, and verification (MRV) systems (HILAG, 2024). For Norway, finance should be linked first to mapping, monitoring, restoration feasibility, water-quality improvement, and ecosystem-service protection. Carbon-market finance should be approached cautiously until additionality, permanence, leakage, baseline, monitoring, and double-counting risks are resolved – concerns that are especially acute for export-driven macroalgae (HILAG, 2024).

International examples of recent blue carbon success are instructive but must also be interpreted cautiously: Australia has built operational crediting infrastructure through a tidal-restoration method and the Blue Carbon Accounting Model, but that method is designed around reintroducing tidal flow to coastal wetlands and does not resolve seagrass or macroalgae accounting in Norway (Clean Energy Regulator, 2024; Lovelock et al., 2022); France's Posidonia method is seagrass-specific but differs in species, habitat, and governance context (Comte et al., 2024; French Ministry for Ecological Transition, 2023); and Japan's kelp reporting requires careful methodological comparison before any transfer (National Institute for Environmental Studies, 2024; Reuters, 2024).

4.3 Monitoring and research priorities

Advancing either ecosystem along its pathway depends on closing specific evidence gaps. For seagrass, Norway needs repeated national eelgrass mapping, region-specific extent estimates, standardized sediment-carbon sampling in underrepresented regions, direct burial or accretion measurements such as lead-210 isotope dating, disturbance-emission factors, anchoring- and dredging-overlap analysis, and long-term monitoring of meadow condition, depth limits, epiphyte load, and post-disturbance recovery. Among monitoring gaps, the most consequential is the absence of a national seagrass extent-change baseline: without it, even a well-quantified sediment carbon stock cannot support avoided-degradation accounting. These data would support the transition toward rigorous annual emissions-and-removals accounting (IPCC, 2014; Macreadie et al., 2019). For macroalgae, the highest priorities are carbon-fate related: broader validation of kelp-derived carbon in depositional sediments, export-pathway modeling, DOC-persistence studies, species-specific productivity and detachment estimates, spatial matching between kelp source areas and sediment sinks, and repeated assessment of urchin barrens, kelp recovery, harvesting effects, and warming-driven shifts. The eDNA/qPCR approach developed in Norwegian research is especially promising for attributing buried carbon to macroalgal sources but must be validated across more sites and sedimentary settings before it can support national accounting (d'Auriac et al., 2021; Frigstad et al., 2020).

These priorities align closely with the most recent decadal agenda for blue carbon science. The foundational 2019 roadmap for blue carbon science set out an original set of ten priority questions for the field (Macreadie et al., 2019); seven years on, a panel of global experts revisited and recalibrated that agenda, refining a new set of priority questions through a structured horizon-scanning process (Macreadie et al., 2026). Half of the new questions concern the precision, comparability, and scalability of carbon data, which Norway still lacks for both ecosystems. Two new questions map directly onto the gaps identified here: forecasting the future greenhouse-gas balance of blue carbon ecosystems under global change, for which process-based models remain underdeveloped for submerged aquatic vegetation and for the lateral carbon transport that governs macroalgal sequestration; and improving estimates of how human pressures and management affect carbon cycling. The study emphasizes natural-capital accounting that captures co-benefits and trade-offs, and on scalable tools such as remote sensing, machine learning, eDNA, standardized field protocols, and findable, accessible, interoperable, and reusable (FAIR) data-sharing platforms (Macreadie et al., 2026).

Another study frames temperate coastal habitats, including seagrass and macroalgal beds, as delivering both carbon sequestration and nutrient bioremediation, and argues that the uncertainty currently surrounding these processes precludes their credible integration into nature-based solutions and market-based instruments until "decision-grade" data are generated (Watson et al., 2026). For Norway this reinforces two points. First, carbon monitoring should be co-designed with nutrient and water-quality monitoring, as the same eutrophication and land-based nutrient pressures that degrade Oslofjord and Balsfjord meadows also determine their carbon permanence and bioremediation value. Second, the bar for policy claims should be set explicitly at decision-grade evidence, meaning conservative, uncertainty-bounded, and reproducible, rather than headlining premature sequestration figures. Crucially, this standard does not call for delay; it applies to the claims that carry quantitative risk, such as carbon credits and inventory removals rather than to conservation itself. Policy can and should act now utilizing the evidence that is already sound: protecting existing seagrass sediment stocks and managing both ecosystems for their well-established biodiversity, water-quality, and coastal-protection benefits, while reserving carbon-accounting and crediting claims for the components that meet the decision-grade threshold and allowing unknowns to be resolved over time through targeted research. In this framing, scientific rigor and near-term action are complementary, as action where the science is strong builds the institutional capacity and monitoring infrastructure through which remaining uncertainties can be closed.

The pressure analysis conducted in this study demonstrates why national averages alone are insufficient for blue carbon policy. Dredging, vessel traffic, offshore infrastructure, trawling, aquaculture, eutrophication, sedimentation, and coastal development vary spatially, and their ecological effects depend on overlap with habitat, timing, intensity, and local vulnerability. A national total of dredging events or offshore installations is a useful pressure indicator but does not identify which meadows or kelp forests are at risk; spatially explicit co-location analysis is therefore a valuable screening step, though it cannot replace field validation (Conti, 2026; EMODnet Human Activities, 2025). The Oslofjord and Balsfjord case studies make the same point at the site scale. In Balsfjord, divergent trajectories between nearby protected sites indicate that local nutrient loading and epiphyte pressure can override protected-area status (Kristiansen, 2024); in Oslofjord, high carbon-stock potential coexists with cumulative water-quality and disturbance pressures, producing heterogeneous loss and recovery (Rinde et al., 2021). Together these cases support a management principle central to blue carbon policy: protection and restoration should be evaluated not only by whether habitat exists, but by whether the environmental conditions required for long-term function and carbon permanence are maintained.

The most important cross-cutting need is integration. Carbon, biodiversity, and coastal resilience metrics are often collected separately, yet a credible blue carbon framework requires co-located, repeatable, quality-controlled information with transparent uncertainty reporting. The interactive map developed in this study provides a foundation for that integration by making evidence gaps visible, showing where study sites, habitat polygons, pressure layers, protected areas, and carbon indicators do and do not overlap. This is particularly valuable for Norway, where interest in blue forests is high but data are scattered across research papers, national reports, EMODnet portals, environmental agencies, and sectoral datasets. The map should be treated as a decision-support and hypothesis-generating tool rather than a final impact model, and the next step is to link its layers to repeatable monitoring protocols and standardized metadata.

4.4 Limitations

Several limitations bound the interpretation of these results. The seagrass carbon synthesis rests on a limited and spatially uneven sample of nine site-level means, with the Norwegian Sea and Barents Sea each anchored by a single harmonized observation. Regional contrasts outside southern Norway should be read as indicative rather than representative. The bivariate driver regressions are also based on limited and uneven coverage (N= 8–20 depending on predictor), and they characterize single-predictor associates only; they are not a substitute for multivariate analysis. Regional aggregation was row-weighted rather than area-weighted because defensible regional extent data were unavailable, so national summaries are evidence-based synthesis values rather than areally weighted inventory estimates. The macroalgal sequestration estimates depend on published export, deposition, and burial transfer functions rather than direct Norway-wide measurement, and therefore carry structural as well as parametric uncertainty. Finally, the co-location and pressure analyses rest on spatial proximity between mapped habitat and pressure or protection layers, not on measured ecological response. Proximity can be used as a screening signal, but it is not evidence of impact. The layers themselves differ in spatial precision, temporal coverage, and reporting intensity. These constraints reflect the current state of the Norwegian evidence base and define the monitoring priorities identified in §4.3.

5. Conclusions

This evaluation set out to characterize the distribution, carbon evidence, and ecological context of Norwegian seagrass and macroalgae; to assess how environmental drivers and human pressures shape their blue carbon potential; to determine how the two ecosystem groups differ in scientific readiness for greenhouse-gas accounting and policy integration; and to identify the monitoring and governance gaps that impede their defensible inclusion in Norwegian climate and marine policy. The results support the overarching finding that both ecosystems belong in national blue carbon and marine nature-based solution policy, including Norway's NDC, but they are not interchangeable, and treating them as a single category would weaken the credibility of any resulting climate claim.

On distribution, carbon pool estimates, and ecological context, there is substantial national-level data, but significant evidence gaps emerge at the regional and local levels. This study took the only site-level carbon data for seagrass from the existing literature and estimated a site-scaled, bottom-up figure of ≈ 344 Gg C (95% CI 177-502), which is consistent with the national top-down estimate of ≈ 245 Gg C. Seagrass sediment carbon density is highly regionally variable, with the lowest values found in Northern Norway (Barents Sea) to much higher values in Southern Norway (Skagerrak, including Oslofjord). Despite the variability, vegetated eelgrass cores hold roughly 49% more carbon than adjacent unvegetated sediments, confirming a measurable habitat effect. Macroalgae, by contrast, dominate Norway's vegetated coastal area and hold far larger estimated biomass-carbon pools and annual production fluxes, but grow on hard substrate as living biomass whose carbon is decoupled from the sediment beneath the habitat.

Analysis of environmental drivers and human pressures similarly revealed important data gaps, especially the lack of explicit carbon and ecosystem-service response to drivers, but there was enough evidence to show that blue carbon potential is highly impacted by these drivers. Among measured variables, sediment dry bulk density was the dominant control on seagrass carbon density (the strongest and only statistically robust bivariate relationship). Critically, the highest-density seagrass regions in southern Norway coincide with elevated human pressure and incomplete marine protected area coverage, and the Oslofjord and Balsfjord cases demonstrate that formal protection and favorable physical conditions are not sufficient when cumulative water-quality and nutrient pressures override them. National pressure averages obscure these nuances; spatially explicit co-location screening is needed to identify which meadows and kelp forests are actually at risk, and carbon permanence depends on maintaining the environmental conditions that sustain the habitat.

Scientific and policy readiness analysis revealed key differences between the two ecosystems. Seagrass is conceptually compatible with the IPCC Wetlands Supplement and sits at Tier 1 to early Tier 2 readiness, with the remaining barriers being operational data rather than methodological eligibility. Macroalgae are not covered by the Wetlands Supplement in the same direct way; their climate benefit depends on export, deposition, burial, and source attribution occurring away from the production habitat, which does not yet have a standard international methodology. Additionally, their sequestration estimates carry both parametric and structural uncertainty, with emerging scientific techniques critical for developing a national methodology. This in-situ-stock-versus-export-contingent-biomass distinction is what drives the differentiated, phased policy framework that is this study's central contribution (Figure 9): seagrass entering policy through avoided-degradation and lower-tier inventory pathways, macroalgae through biodiversity, fisheries, and other marine policy instruments while carbon-fate science matures.

Identified monitoring and governance gaps reveal that defensible inclusion is currently impeded on two fronts. Scientifically, Norway lacks necessary evidence for both seagrass and macroalgae: repeated national mapping and region-specific extent estimates, standardized sediment sampling, direct burial-rate measurement (lead-210 dating) and disturbance-emission factors for seagrass; and carbon-fate evidence via export pathways, DOC persistence, and validated eDNA source attribution for macroalgae. The broader conclusion is that blue carbon readiness is not a binary property. Ecosystems can be policy-relevant before they are inventory-ready, and conservation can be justified by ecosystem services even when carbon accounting remains uncertain; and while differentiated pathways for implementation are recommended, both ecosystems can already be considered for national blue carbon policy. Establishing a unified policy framework which integrates the carbon-biodiversity-coastal-resilience nexus is the connective step that would move Norway from fragmented, ecosystem-by-ecosystem interest toward a coherent national blue carbon strategy.

6. Data and code availability

The interactive map and reproducible geospatial workflow are available in the public GitHub repository Norway-blue-carbon-interactive-map. The repository includes the raw databases, processed CSVs, committed map layers, scripts for building the master inventory, ecosystem-service tables, spatial co-location analysis, the Folium-based interactive map, and the scripts for the static figures. Raw Excel workbooks and certain oversized or licensed datasets are not committed to the repository; the README identifies relevant data sources and download procedures (Conti, 2026).

7. References

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