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Richard Bulmer, Zhanchao Shao, Orlando Lam-Gordillo

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Richard Bulmer[1], Zhanchao Shao[1], Orlando Lam-Gordillo[2], Phoebe Stewart-Sinclair[2]

Georgina Flowers[1]

[1]Tidal Research Limited

[2]National Institute of Water and Atmospheric Research, NIWA

Environmental Evaluation and Monitoring Unit, EEMU

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Executive summary

This study uses satellite imagery paired with machine learning to quantify the extent of saltmarsh, mangrove, and seagrass ecosystems in the Auckland region and carbon sequestration rates measured primarily from New Zealand to estimate associated carbon sequestration rates. In addition, the extent and carbon sequestration by unvegetated habitats was estimated and the hypothetic extent of kelp habitat and associated carbon sequestration rate was quantified based on two scenarios (kelp cover occupying 10 per cent and 50 per cent of rocky reefs). This is the first study to create a regional layer of blue carbon ecosystem extent that uses data acquired from one time period (from 12 June 2023 to 11 January 2024) and uses Australasia sourced carbon sequestration measures (including samples from the Auckland region) to estimate associated carbon sequestration rates.

Saltmarsh occupied 3587 ha, mangroves 8181 ha, and seagrass 10,995 ha, with the west coast of Auckland containing over twice the extent of these habitats than the east coast (16,180 ha vs 6582 ha). Adjusted for their habitat extents, saltmarsh sequestered 3192 tC yr^{-1}, mangroves 5236 tC yr^{-1} and seagrass 3518 tC yr^{-1} throughout the Auckland region with a combined carbon sequestration of 11,946 tC yr^{-1}. Carbon sequestration by kelp was estimated at 160 and 798 tC yr^{-1}, based on kelp occupying 10 per cent and 50 per cent of all rocky reef habitats throughout the Auckland region, respectively. Rates of water-column phytoplankton net primary production (depth-integrated) in New Zealand range from approximately 0.4 to 17.8 tC ha^{-1} yr^{-1}, however, estimates of sediment carbon sequestration of phytoplankton carbon were not obtained. Unvegetated habitats had the lowest carbon sequestration rate per unit area of all habitat types. However, unvegetated habitats occupied an estimated 993,806 ha within the Auckland Region Coastal Marine Area, with an associated area adjusted carbon sequestration rate of 258,389 tC yr^{-1}, approximately 21-fold the combined rate of sequestration by other vegetated blue carbon ecosystems throughout the region.

The regional scale estimates of blue carbon ecosystem extent and sequestration quantified in this study illustrate their potential contribution to regional scale carbon abatement (in addition to the other important services provided by marine ecosystems), and highlight the importance of protecting and enhancing these ecosystems.

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1 Key definitions

Blue carbon ecosystem (BCE) – i.e., mangroves, saltmarshes, seagrasses, unvegetated habitats with high capacity to sequester and store carbon.

Blue carbon sequestration – Carbon which accumulates and is stored for extended periods of time (e.g. hundreds of years) in anoxic (low oxygen) and waterlogged marine sediment.

Carbon stock – Carbon (organic matter) located in the sediment and the living biomass of BCE and other habitats.

Primary production – The production of organic matter by photosynthetic processes. Within BCEs, a proportion of the organic material produced during primary production is either cycled through marine food webs or contributes to carbon stocks and sequestration within BCEs.

2 Background

2.1 Introduction

Blue carbon ecosystems (BCE; i.e., mangroves, saltmarshes, seagrasses, unvegetated sediments) have high capacity to absorb and store carbon (referred to here collectively as carbon sequestration) (Kelleway et al. 2016, Arias-Ortiz et al. 2018, Ewers Lewis et al. 2018, Alongi 2020, Bulmer et al. 2020, Bulmer et al. 2024b). In many locations carbon sequestration from vegetated BCE greatly exceeds the rate of carbon sequestration from terrestrial ecosystems (McLeod et al. 2011). BCE store carbon through a variety of different pathways, including being taken up by primary producers to fuel photosynthesis, accumulated into above- and below-ground biomass, and/or stored in the sediment. A large amount of carbon that is sequestered is stored below ground in low oxygen environments and can stay captured in the sediment for long time periods (sometimes thousands of years), contributing to BCE by acting as carbon sinks (Duarte et al. 2013). Carbon that is stored in the sediment can be sourced from the ecosystem (i.e. autochthonous) or from surrounding estuarine/coastal areas or transported from the land (i.e. allochthonous (e.g. plant detritus)). Meanwhile, carbon that is sequestered and stored in above-ground biomass of primary producers will accumulate as new plant material until the plants reach maturity. Therefore, carbon stored in plant biomass does not accumulate over time in plant communities that have already reached maturity.

Overall, the resulting carbon sequestration rates in coastal environments can be large, and the carbon cycling behaviour differs by habitat type and condition (Kelleway et al. 2016, Arias-Ortiz et al. 2018, Ewers Lewis et al. 2018, Alongi 2020, Bulmer et al. 2020). Shifts in the proportions of different habitat types within an estuary or region could therefore lead to large shifts in overall carbon sequestration, and associated reduction in net greenhouse gas emissions (Doughty et al. 2015, Kelleway et al. 2016, Bulmer et al. 2020). Other relatively common coastal habitats may also be highly productive, yet not have the carbon sequestration potential of mangroves, saltmarshes and seagrass habitats. For example, kelp forests on rocky reefs are unable to directly bury carbon into the sediment, and therefore the carbon sequestered by kelp is difficult to quantify. However, kelp forest habitats can maintain high rates of productivity (Blain et al. 2021) and a proportion of carbon that they produce is known to be transported and then stored in adjacent soft sediment ecosystems (Krause-Jensen and Duarte 2016).

The potential for long-term storage of carbon makes the protection and restoration of BCE an important natural or nature-based solution to reduce greenhouse gas emissions, as part of a package of measures to mitigate the effects of climate change (Kelleway et al. 2016, Arias-Ortiz et al. 2018, Ewers Lewis et al. 2018, Alongi 2020, Bulmer et al. 2020). These effects include marine heatwaves, increased frequency of severe weather events, ocean acidification, and sea-level rise, all of which can impact coastal communities, coastal and estuarine ecosystems, and the important functions undertaken by ecological communities within them. In addition to carbon sequestration, coastal wetland ecosystems provide a myriad of other important ecosystem services such as coastal protection, provision of resources, water quality regulation, and biodiversity enhancement (Barbier et al. 2011, Horstman et al. 2018, Basher et al. 2019b, Macreadie et al. 2021). Despite their value, threats such as land conversion, development, and pollution have caused huge losses in BCE extent and degradation of many remaining BCE areas. Saltmarsh ecosystems have lost between 25 per cent and 50 per cent of their historical coverage worldwide (Duarte et al. 2009, Crooks et al. 2011). In Aotearoa New Zealand, Ausseil et al. (2011) estimate that only 18.4 per cent of saline wetlands remain compared to historic pre-human extents. These threats will only be exacerbated by worsening climate change, with sea level rise predicted to lead to migration of coastal ecosystems inland and loss of shallow coastal habitats when migration is not possible (Rullens et al. 2022a).

Loss and degradation of BCE reduces the capacity of these habitats to sequester carbon as well as limiting the provision of other ecosystem services (Lovelock et al. 2017). Conversely, the enhancement or restoration of BCE has the potential to reduce emissions from degraded areas (e.g. degraded low lying grasslands) and increase sequestration (Suyadi et al. 2020, Macreadie et al. 2021, Lovelock et al. 2022). In recognition of this value provided by BCE, in Australia landowners can gain carbon credit units (ACCU) through coastal restoration projects (Lovelock et al. 2022). In New Zealand, while carbon credits (referred to as emission units – NZU) can be obtained for land-based projects (e.g., native and pine plantations), a blue carbon market and the associated carbon credits is not yet established (Stewart-Sinclair et al. 2024). Nevertheless, a key step for improving the management of BCE and enhancing carbon sequestration potential is to quantify their distribution and associated carbon sequestration and emission rates (Bulmer et al. 2024b); this quantification of current BCE will highlight their role in sequestering carbon as well as the potential carbon that could be emitted if these habitats become degraded or lost (Lovelock et al. 2017). This knowledge will also provide insights into the additional carbon that can be sequestered through habitat recovery and restoration of new BCE. Such added carbon sequestration potential could contribute to meeting domestic and international goals for reducing carbon emissions. In the future, this may include contributing to the Climate Change Response Act 2002 and the Zero Carbon Amendment Act 2019 that were developed to help New Zealand meet greenhouse gas emission reduction targets of the International Paris Agreement.

Te-Tāruke-ā-Tāwhiri Auckland's Climate Plan has two clear goals 1) to reduce regional greenhouse gas emissions by 50 per cent by 2030 and achieve net zero emissions by 2050, and 2) to adapt to the impacts of climate change. Identifying and valuing BCEs can play an important role in both reducing greenhouse gas emissions and in adaptation and resilience planning by supporting implementation of nature-based solutions. One action within Te Tāruke-ā-Tāwhiri is to maximise the potential of terrestrial and marine ecosystems to capture carbon. Estimations of BCE extents and their associated carbon sequestration rates in this report strengthens evidence for the importance of BCEs in mitigation and adaptation, and supports coastal management decisions around the use, protection and potential restoration of these ecosystems.

2.2 This report

This report uses a spatial analysis and literature review of blue carbon ecosystems (BCE) within the Auckland region to produce a regional assessment of current blue carbon sequestration rates.

This project expands on the previous report by EnviroStrat (2022) which used Auckland Council's existing coastal vegetated BCE (seagrass, mangroves, saltmarsh) extent maps and carbon sequestration rates sourced from international literature to estimate carbon sequestration rates for the Auckland region. Additionally, this project refines previous research conducted by Tidal Research, NIWA and the University of Auckland, which identified the current extent of BCE and restoration opportunity at a national/coarse scale and carbon sequestration rates and potential (based on carbon sequestration rates measured in Australasia) within Aotearoa New Zealand (Bulmer et al. 2024a, Bulmer et al. 2024b, Stewart-Sinclair et al. 2024). Specifically, this project improves the regional spatial habitat maps for the Auckland region (using a refined mapping approach detailed below), summarises knowledge of carbon sequestration from blue carbon ecosystems with a focus on Auckland specific datasets (as well as reviews of the sequestration potential for kelp and phytoplankton), and calculates a revised regional blue carbon sequestration rate estimate.

3 Methods

3.1 Carbon sequestration and emission factors

Three sources of data were collated to provide estimates of carbon sequestration, stocks, and greenhouse gas emissions (as described in Bulmer et al. (2024b)). Details of the variability observed with all compiled measurements are provided, so that variability can be accounted for in future carbon abatement calculations. In addition, data from the Auckland region was isolated from the wider dataset to inform Auckland specific sequestration values (and data gaps). The first data source was collated as part of a New Zealand national science project (Bulmer et al. 2023); Ministry of Business, Innovation and Employment Smart Idea (C01X2109)). Data relevant to blue carbon accounting is presented and the methods used to collect and analyse sediment cores are consistent with best practice methodology (Howard et al. 2014). The second data source is a review paper of carbon stocks and sequestration across saltmarsh, mangrove and seagrass habitats throughout Aotearoa New Zealand (Ross et al. 2024). The final data source is the data on carbon sequestration and greenhouse gas emissions used to populate Australia's BlueCAM model. As the methodology has been used within the Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022 of the Emissions Reduction Fund (ERF) (which is Australia's voluntary carbon market scheme), the data and approach has been reviewed and assessed as suitable to inform restoration action (Lovelock et al. 2021b, Hagger et al. 2022, Lovelock et al. 2023).

Australia has many similarities in species composition and climate (within the temperate regions) to Aotearoa New Zealand, so provides a good surrogate where data are missing or uncertain, or to support emerging data that may not yet be published. For example, while significant efforts are underway to collect measurements of CH_4 and N_2O from blue carbon ecosystems (BCE) in Aotearoa New Zealand, no measurements are currently available to inform carbon abatement estimates. Southern Australian BCE (e.g., such as those in Tasmania and Victoria) are at a similar climate to northern New Zealand, and contain many of the same species of saltmarsh, mangroves and seagrass, thus carbon sequestration potential is likely similar. All three data sources above are broadly comparable in measurement rates and variability, providing additional confidence in the underpinning data and transferability of the Australian values. Additional information, including baseline soil carbon stocks and greenhouse gas emissions from other land types can be found within Lovelock et al. (2021b).

The three datasets were used as input parameters to inform blue carbon abatement calculations using the Australian BlueCAM methodology (Lovelock et al. 2021b, Hagger et al. 2022, Lovelock et al. 2023). More details on the specific data used to inform the regional scale calculations are described in the results section below. The BlueCAM approach is the basis for the national Australian carbon credit system for coastal wetland restoration and is used to calculate carbon abatement due to restoration of BCE (including carbon stored within living vegetation and soil, i.e. carbon stocks) as well as carbon sequestration by existing blue carbon habitats.

To estimate carbon sequestration rates in existing BCE (saltmarsh, mangrove, seagrass, unvegetated) the following assumptions were applied. The majority of below ground biomass in BCE was assumed to be accounted for in Sediment Carbon Accumulation Rates (SCAR) (methods used in the field and laboratory to quantify soil carbon stocks typically integrate fine roots into the soil organic carbon stocks). Greenhouse gas emissions (CH_4, N_2O, CO_2) were assumed to be negligible, as they represented <0.02 tC ha^{-1} yr^{-1} when converted to carbon (Table 3), and CO_2 emissions were assumed to be balanced by primary productivity (as per Lovelock et al. (2022)). Above ground biomass (including mangrove pneumatophores) is not included in carbon sequestration rates for existing mature habitats, as the biomass has already reached maturity, and therefore the net change in carbon within the biomass through time is considered zero and therefore carbon accumulation rates are based entirely on SCAR (Lovelock et al. 2022). However, it is also worth noting that the carbon in above ground biomass is immediately lost if the habitat is lost, whereas the carbon in the sediment may remain locked up in that location despite habitat loss (e.g. if mangroves invade saltmarsh habitat) and therefore is likely to be less transient. SCAR represents long term sequestration of carbon (in anoxic sediment environments) and is calculated by measuring organic carbon and ^{210}Pb with depth to calculate carbon accumulation through time (Sanchez-Cabeza et al. 1998). Estimates of habitat carbon sequestration rates for unvegetated habitat was based purely on SCAR measurements.

3.2 Targeted literature review (kelp and phytoplankton)

A brief literature review was undertaken to help assess the carbon sequestration capacity of kelp forests and phytoplankton. Our review focused on New Zealand literature (as well as global reviews for kelp carbon sequestration) and where possible we included studies undertaken in the Auckland coastal regions. This review included four studies on kelp carbon dynamics (including quantifications of net primary production, standing stocks and overall carbon production) and six studies on phytoplankton carbon dynamics (depth-integrated net primary production).

3.3 Blue carbon spatial extent

To assess the BCE spatial extent in the Auckland region, we applied supervised classification with random forest on the Sentinel-2 derived reflectance in the visible and near infrared bands (Band blue, green, red and near infrared) (Shao et al. 2024), improving on the coarser method applied nationally by Bulmer et al. 2024b. The Sentinel-2 imagery was derived at the low tides from European Space Agency (ESA, https://dataspace.copernicus.eu/explore-data/data-collections/sentinel-data/sentinel-2; extracted from 12 June 2023 to 11 January 2024). A total of 1,380,425 samples were derived from over 100 training/validation polygons throughout the east and west coast of the Auckland region for each habitat type, including mangroves (117,955 samples), seagrass (942,570 samples), saltmarsh (35,225 samples) and unvegetated flats (284,675 samples). These samples were randomly split into training/validation (80 per cent) and testing (20 per cent). Training and validation data was identified based on expert knowledge of existing habitat by the project team, with expert review by Auckland Council team, providing a high level of confidence in the mapping outputs. The training and validation data has been provided as a datafile which can also be used in future mapping efforts. Five-fold cross-validation was applied to the training and validation dataset to determine the optimal hyperparameters for the random forest model. The selected values for hyper-parameters including the number of trees, minimum sample split, minimum sample leaf and maximum tree depth were 260, 4, 4 and 9, respectively.

In order to constrain the model extent (i.e. reduce false positive classification within terrestrial areas), the estuarine extent within the Auckland region was clipped in QGIS 3.18 using the New Zealand coastal and island boundary vector layer (available on LINZ). After classification, the results were converted from raster layers to vector layers in QGIS 3.18 for data visualization. An additional distribution map of mangroves and saltmarsh was incorporated in the post analysis of the results to match with classification (see Table 1 for details). We also included rocky reef habitats obtained from existing layers provided by Auckland Council (see Table 1 for details). The addition of the rocky reef layers significantly reduced false positive seagrass detection in the mapping outputs, given rocky reef habitats were otherwise incorrectly identified as seagrass, further improving the seagrass mapping compared to previous efforts (e.g. the national mapping by Bulmer et al. 2024b). BCE spatial extent (area ha) was calculated using a geometry calculation analysis for each of the BCE habitats based on the combined habitat classification (i.e. habitats from supervised classification and rocky reef).

Table 1: Summary information and sources of the spatial layers used for performing the Blue Carbon (BC) habitats classification in the Auckland region.

Id	Layer	Source	Original layer name	Specifications
1	BC habitat classification in the East Coast of Auckland Region	This project	NA	Habitat derived from supervised classification
2	BC habitat classification in the West Coast of Auckland Region	This project	NA	Habitat derived from supervised classification
3	Mangroves and Saltmarsh habitats in the East coast of Auckland Region	Auckland Council	Ecosystem Current Extent*	Original layer was reclassified and clipped to match with ML classification and extent.
4	Mangroves and Saltmarsh habitats in the West coast of Auckland Region	Auckland Council	Ecosystem Current Extent*	Original layer was reclassified and clipped to match with ML classification and extent.
5	Rocky reef extent	Auckland Council	East_Rockyreef_Auckland_2021	Original layer was dissolved and clipped to match with ML extent
6	Rocky reef extent	Auckland Council	West_Rockyreef_Auckland_2021	Original layer was dissolved and clipped to match with ML extent
7	Final BC habitat classification for the East coast of the Auckland Region	This project	NA	BC habitat classification combining layers 1,3,5 for the east coast of the Auckland Region
8	Final BC habitat classification for the West coast of the Auckland Region	This project	NA	BC habitat classification combining layers 2,4,6 for the West coast of the Auckland Region

* For more information on this classification see Singers, N.; Osborne, B.; Lovegrove, T.; Jamieson, A.; Boow, J.; Sawyer, J.; Hill, K.; Andrews, J.; Hill, S.; Webb, C. 2016. *Indigenous terrestrial and wetland ecosystems of Auckland. Auckland Council.*

3.4 Blue carbon sequestration rates for the Auckland region

We estimated current BCE (saltmarsh, mangrove, seagrass, unvegetated) sequestration rates for the Auckland region using a combination of the collated carbon sequestration/emission factors and the spatial analysis. In addition, we identified gaps where further research is needed to improve our understanding of blue carbon potential in the Auckland region. While unvegetated habitats were not specifically mapped in this study, we estimated unvegetated habitat extent by assuming that all habitats within the Auckland Region Coastal Marine Area (to the 12 nautical-mile limit) that were not saltmarsh, mangrove, seagrass or rocky reef were unvegetated (which included any intertidal flats plus any water habitat extent (i.e. subtidal), which was also assumed to be unvegetated unless it was rocky reef). Unvegetated carbon sequestration rates were then adjusted by estimated unvegetated habitat extent.

We also provide an estimate of the carbon sequestration provided by kelp for the Auckland region. We note that as kelp grows on rocky reefs rather than sediment, the carbon which is produced by kelp is either retained in standing biomass or cycled throughout the system. Measurements of the amount of carbon sequestered in adjacent soft sediment habitats that is derived from kelp biomass were not able to be sourced. However, in a global study of carbon sequestration by macroalgae, Krause-Jensen and Duarte (2016) estimate that approximately 11.37 per cent of net primary production by macroalgae ends up being sequestered in marine sediments. Hence, we estimated carbon sequestration by kelp by taking 11.37 per cent of reported estimates of net primary production by kelp in the Hauraki Gulf, noting that these estimates are not as reliable as sediment carbon sequestration/SCAR measurements based on sediment cores for saltmarsh, mangrove, seagrass and unvegetated habitats. As the extent of kelp was not mapped in this study, to estimate the potential carbon sequestration and stocks of kelp in the Hauraki Gulf, and explore how this may change with varying kelp extents, kelp extent was assumed to cover 10 per cent and 50 per cent of all rocky reef habitats in the region (noting that we do not expect kelp to occupy all rocky reefs in the region due to factors such as tidal inundation (many rocky reefs are intertidal), predation by kina, and sedimentation). Measurements of carbon stocks within mature above ground biomass should not be confused with an annual rate of sediment carbon sequestration, as carbon is not accumulating and being locked away through time. Carbon in above ground biomass could therefore be lost if the habitat is lost in the future (e.g. through kina barren predation on kelp forests, or removal of mangroves).

Phytoplankton carbon sequestration rates were not estimated, as no reliable data was sourced to inform carbon sequestration rates, however rates of primary production were summarised to give an indication of carbon cycling processes.

4 Results

4.1 Carbon stock and sequestration

Mangroves sequestered an estimated 0.9 tC ha^{-1} yr^{-1} (3 sites) and unvegetated habitats 0.26 tC ha^{-1} yr^{-1} (15 sites) based on data collected throughout the Auckland region (Table 2). Values from the Auckland region were closely aligned with national values (Table 2 and Table 3), however, no data was available from the Auckland region to estimate saltmarsh or seagrass carbon sequestration rates (Table 2). Therefore, to provide carbon sequestration values for the saltmarsh and seagrass habitats, and to increase the total number of sites informing estimates, data from outside of Auckland was used to provide habitat specific carbon sequestration rates (Table 3). As discussed in Bulmer et al. 2024b, the seagrass sites in Aotearoa where carbon sequestration measurements were available were derived from two relatively sandy seagrass locations in the Whangarei Harbour, which contained very low carbon stocks and sequestration rates (0.04 (SCAR) tC ha^{-1} yr^{-1}). Given the low sample size and low sequestration rates, comparable data from temperate Australian seagrass habitat (with the same species – *Zostera muelleri*) was instead used to inform seagrass carbon sequestration estimates (Table 3). Based on this wider dataset, the following carbon sequestration values for existing blue carbon ecosystems (see Methods for calculations) were used to calculate carbon sequestration throughout the Auckland region:

- Saltmarsh = 0.89 (SCAR) tC ha^{-1} yr^{-1} (based on 2 sites throughout Northland)
- Mangrove = 0.64 (SCAR) tC ha^{-1} yr^{-1} (based on 7 sites throughout Auckland and Northland)
- Seagrass = 0.32 (SCAR) tC ha^{-1} yr^{-1} (based on 43 sites throughout temperate Australia)
- Unvegetated = 0.26 (SCAR) tC ha^{-1} yr^{-1} (based on 17 sites throughout Auckland and Northland)

Table 2: Estimates of sediment organic carbon accumulation rate (sequestration) and stocks in blue carbon ecosystems from sites in the Auckland region.

	Habitat type	Mean	SE	Min	Max	Number of sites	Source	Source notes
Sediment Carbon Accumulation Rate (tC ha^{-1} yr^{-1})	Saltmarsh							No data
	Mangrove	0.90	0.61	0.22	2.12	3	Bulmer et al. (2024b)	Collected from 3 locations throughout the Auckland Region
	Seagrass							No data
	Unvegetated	0.26	0.04	0.11	0.64	15	Bulmer et al. (2024b)	Collected from 15 locations throughout the Auckland Region
Sediment Carbon Stock (tC ha^{-1} to 100 cm depth)	Saltmarsh							No data
	Mangrove	67.6	9.2	34.3	114	10	Bulmer et al. (2024b)	Collected from 10 locations throughout the Auckland Region
	Seagrass							No data
	Unvegetated	38.7	4.0	18.1	69.6	15	Bulmer et al. (2024b)	Collected from 15 locations throughout the Auckland Region
Above Ground Biomass (tC ha^{-1})	Saltmarsh							No data
	Mangrove	22.0	5.4	3.8	58.3	10	Bulmer et al. (2024b)	Collected from 10 locations throughout the Auckland Region
	Seagrass							No data
Habitat Carbon Stock (Above Ground Biomass + Sediment (tC ha^{-1} to 100 cm depth)	Saltmarsh							No data
	Mangrove	89.7	8.6	50.1	131.1	10	Bulmer et al. (2024b)	Collected from 10 locations throughout the Auckland Region
	Seagrass							No data
	Unvegetated	38.7	4.0	18.1	69.6	15	Bulmer et al. (2024b)	Collected from 15 locations throughout the Auckland Region

Table 3: Estimates of sediment organic carbon accumulation rate (sequestration), stocks and greenhouse gas emissions in blue carbon ecosystems at sites across Aotearoa and Australia.

	Habitat type	Mean	SE	Min	Max	Number of sites	Source	Source notes
Sediment Carbon Accumulation Rate (tC ha^{-1} yr^{-1})	Saltmarsh	0.89	0.15	0.74	1.05	2	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour
	Mangrove	0.64	0.25	0.22	2.12	7	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour and 5 locations throughout the Auckland Region
	Seagrass	0.04	0.01	0.02	0.05	2	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour
	Unvegetated	0.26	0.04	0.02	0.64	18	Bulmer et al. (2024b)	Collected from three locations within Whangārei harbour and 15 locations throughout the Auckland Region
Sediment Carbon Stock (tC ha^{-1} to 100 cm depth)	Saltmarsh	92.50	12.42	68.62	131.97	5	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour and data compiled from Bulmer et al. (2020)
	Mangrove	57.44	6.29	30.00	113.97	17	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour and data compiled from Bulmer et al. (2020) and Bulmer et al. (2016)
	Seagrass	17.22	6.12	7.53	33.09	4	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour and data compiled from Bulmer et al. (2020)
	Unvegetated	33.60	3.32	7.56	69.61	22	Bulmer et al. (2024b)	Collected from three locations within Whangārei harbour, 15 locations throughout the Auckland Region, and data compiled from Bulmer et al. (2020)
Above Ground Biomass (tC ha^{-1})	Saltmarsh	4.51	1.39	1.58	8.78	5	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour and data compiled from Bulmer et al. (2020)
	Mangrove	22.36	5.43	2.51	84.88	17	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour and data compiled from Bulmer et al. (2020), Bulmer et al. (2018)
	Seagrass	0.11	0.04	0.03	0.23	4	Bulmer et al. (2024b)	Collected from two locations within Whangārei harbour and data compiled from Bulmer et al. (2020)
Habitat Carbon Stock (Above Ground Biomass + Sediment (tC ha^{-1} to 100 cm depth)	Saltmarsh	97.01	13.81	70.2	140.75	5	Bulmer et al. (2024b)	Combination of the above
	Mangrove	79.8	11.72	32.51	198.85	17	Bulmer et al. (2024b)	Combination of the above
	Seagrass	17.33	6.16	7.56	33.32	4	Bulmer et al. (2024b)	Combination of the above
	Unvegetated	33.60	3.32	7.56	69.61	22	Bulmer et al. (2024b)	Combination of the above
Sediment Carbon Accumulation Rate (tC ha^{-1} yr^{-1})	Saltmarsh	0.46	0.16				Ross et al. (2023)	Albot et al. (unpublished data) and Berthelsen et al. (2023).

	Habitat type	Mean	SE	Min	Max	Number of sites	Source	Source notes
Sediment Carbon Stock (tC ha^{-1} to 100 cm depth)	Saltmarsh			38.00	57.00		Ross et al. (2023)	Albot et al. (unpublished data) and Berthelsen et al. (2023).
	Seagrass			14.00	27.00		Ross et al. (2023)	The range between Bulmer et al. (unpublished data) and Berthelsen et al. (unpublished data)
	Habitat type	**Mean**	**SE**	**95% lower CI**	**95% upper CI**	**Number of sites**	**Source**	**Source notes**
Sediment Carbon Accumulation Rate (tC ha^{-1} yr^{-1})	Saltmarsh	0.77	0.22	0.32	1.21	28	Lovelock et al. (2022)	Collected from Australian estuaries
	Mangrove	1.4	0.16	0.95	1.73	48	Lovelock et al. (2022)	Collected from Australian estuaries
	Seagrass	0.32	0.05	0.23	0.42	43	Lovelock et al. (2022)	Collected from Australian estuaries
Emissions CH_4 (kg ha^{-1} yr^{-1})	Saltmarsh	0.11		-0.21	0.44	2	Lovelock et al. (2022)	Collected from temperate Australian estuaries
	Mangrove	2.19		0.91	3.31	3	Lovelock et al. (2022)	Collected from temperate Australian estuaries
	Seagrass	0				1	Lovelock et al. (2022)	Collected from temperate Australian estuaries
Emissions N_2O (kg ha^{-1} yr^{-1})	Saltmarsh	0.13		0.02	0.23	2	Lovelock et al. (2022)	Collected from temperate Australian estuaries
	Mangrove	0.24		0.17	2.75	2	Lovelock et al. (2022)	Collected from temperate Australian estuaries
	Seagrass	0				1	Lovelock et al. (2022)	Collected from temperate Australian estuaries
Above Ground Biomass (tC ha^{-1})	Saltmarsh	7.89	6.1			49	Lovelock et al. (2022)	Collected from temperate Australian estuaries
	Mangrove	70.4	41			9	Lovelock et al. (2022)	Collected from temperate Australian estuaries
	Seagrass	0.57	0.66			74	Lovelock et al. (2022)	Collected from temperate Australian estuaries

4.2 Kelp and phytoplankton

In the Hauraki Gulf, annual carbon standing stocks have been reported to range from 0.37 to 4.17 tC ha^{-1} (Blain et al. 2021, Qu et al. 2023) with overall carbon production (net primary production and mortality/biomass production) of up to ~15 tC ha^{-1} yr^{-1} in *Ecklonia* kelp forests (Blain et al. 2021). Also, within the Hauraki Gulf, Rodgers and Shears (2016) reported average net primary production rates by *Ecklonia* kelp forests ranging from 3.74 to 6.15 tC ha^{-1} yr^{-1}. While measurements of kelp sediment carbon sequestration were not available, carbon sequestration by kelp was estimated by adjusting estimates of net primary production by kelp in the Hauraki Gulf (mid-point of range presented above – 4.95 tC ha^{-1} yr^{-1}) by published estimates of carbon sequestration by macroalgae (11.37 per cent of net primary production) (Krause-Jensen and Duarte 2016).

- Kelp = 0.56 (SCAR) tC ha^{-1} yr^{-1} (estimated based on global studies rather than measured)

This value is within the range of globally reported net primary production rates for *Ecklonia* sp. assuming a range of 1 and 20 per cent of production is sequestered (0.07 to 1.5 tC ha^{-1} yr^{-1}) (Eger et al. 2024).

Similarly, measurements of sediment carbon sequestration by phytoplankton were not obtained. However, reported rates of water-column phytoplankton net primary production (depth-integrated) in New Zealand range from approximately 0.4 to 17.8 tC ha^{-1} yr^{-1} (daily rates scaled up to yearly) (Vincent et al. 1989, Gall and Zeldis 2011, Bury et al. 2012, Gall et al. 2024). Within the Hauraki Gulf, reported rates of water-column phytoplankton net primary production (depth-integrated) range from ~1.2 to 5.1 tC ha^{-1} yr^{-1} (daily rates scaled up to yearly) (Vincent et al. 1989, Gall and Zeldis 2011, Bury et al. 2012, Gall et al. 2024).

4.3 Blue carbon spatial extent

Saltmarsh, mangroves, and seagrass habitats across the Auckland region covered a total of 22,763 ha (Table 4; Figure 1 & 2). The highest coverage of all habitats was observed on the west coast, with 2820 ha of saltmarsh, 5318 ha of mangrove and 8042 ha of seagrass (Table 4, Figure 1, Figure 2). Rocky reef (as derived from Auckland Council maps – Table 1) covered 2415 ha on the west coast and 425 ha on the east coast, for a total extent of 2840 ha (Table 4).

The Kappa value for the accuracy assessment of the habitat maps was 0.96. The greatest mapping accuracy was observed for mangroves and water (≥0.97), which was higher than unvegetated (0.93). The lowest accuracy was observed for seagrass (0.79) and saltmarsh (0.80).

Table 4: Spatial extent of Blue Carbon (and rocky reef) habitats in the Auckland region (split by east and west coast).

Habitat classification	East coast area (ha)	West coast area (ha)	Auckland region (ha)
Saltmarsh	767	2820	3587
Mangroves	2862	5318	8181
Seagrass	2953	8042	10,995
Total (saltmarsh, mangrove, seagrass)	6582	16,180	22,763
Rocky reef habitat	425	2415	2840
Unvegetated habitat (within EEZ)	755,975	237,831	993,806

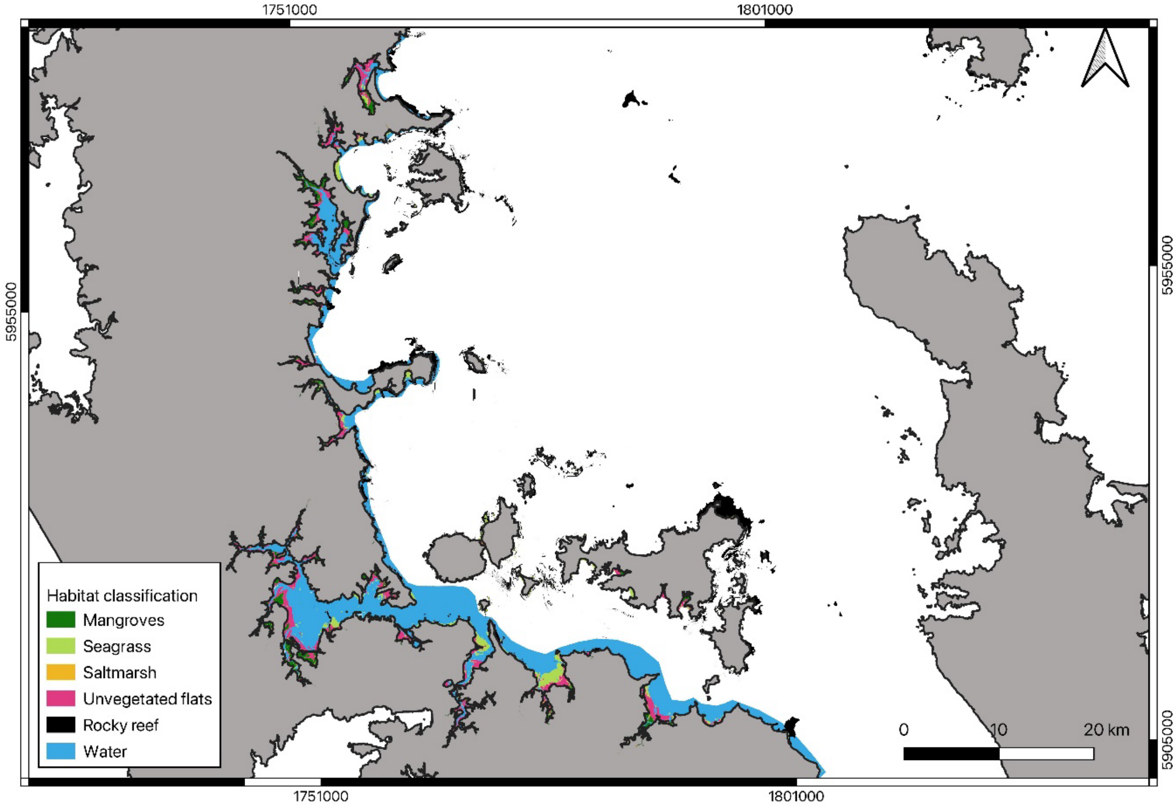

Figure 1: Map of the east coast of the Auckland region showing the extent of blue carbon ecosystems.

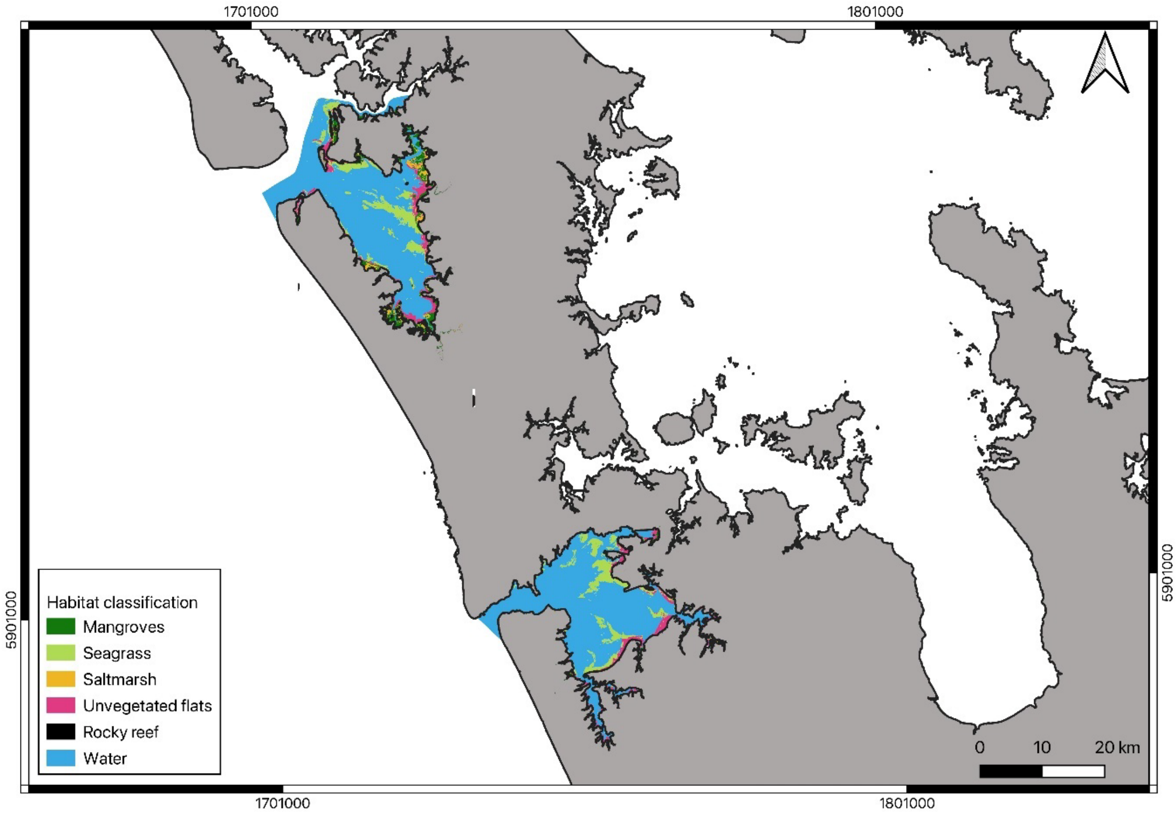

Figure 2: Map of the west coast of the Auckland region showing extent of blue carbon ecosystems.

4.4 Blue carbon sequestration rates for the Auckland region

Here we summarise the area adjusted carbon sequestration rates for saltmarsh, mangrove, seagrass as well as unvegetated habitat for the Auckland region. As sediment carbon sequestration rates were not available for kelp, we provide an estimate of kelp carbon sequestration using global estimates of sequestration by macroalgae. To demonstrate the scale of potential carbon sequestration and stocks by kelp ecosystems within Auckland, we calculated regional scale carbon sequestration and carbon stocks based on two hypothetical scenarios where kelp covered 10 per cent and 50 per cent of all reefs in Auckland. Estimates of phytoplankton carbon sequestration were not available and therefore regional scale sequestration estimates were not possible.

Adjusted for their habitat extents, saltmarsh sequestered 3192 tC yr^{-1}, mangroves 5236 tC yr^{-1} and seagrass 3518 tC yr^{-1} throughout the Auckland region with a combined carbon sequestration of 11,946 tC yr^{-1} (Table 5). Carbon sequestration by kelp was estimated at 160 and 798 tC yr^{-1}, based on kelp occupying 10 per cent and 50 per cent of all rocky reef habitats throughout the Auckland region, respectively. Despite having lower per unit area carbon sequestration rates than all other habitats, unvegetated habitat within the Auckland Region Coastal Marine Area occupied 993,806 ha (Table 4), with an associated carbon sequestration rate of 258,389 tC yr^{-1} (Table 5).

Carbon standing stocks from above ground biomass (i.e., carbon stored in living biomass) of saltmarsh was estimated at 16,177 tC, mangroves 182,923 tC and seagrass 1209 tC (Table 5). Additionally, carbon standing stock was 645 tC or 3223 tC for kelp based on 10 per cent or 50 per cent kelp coverage of all rocky reef within the region, respectively.

Table 5: Spatial extent of Blue Carbon (and rocky reef) habitats and associated carbon sequestration and carbon standing stock estimates in the Auckland region.

	Spatial extent (ha)	Carbon sequestration (tC yr^{-1})	Carbon standing stock (tC within above ground biomass)
Saltmarsh	3587	3192	16,177^
Mangroves	8181	5236	182,923^
Seagrass	10,995	3518	1209^
Total (saltmarsh, mangrove, seagrass)	**22,763**	**11,946**	**200,309**
Unvegetated habitat	993,806	258,389	
Rocky reef habitat	2840		
Kelp occupy 10% of Rocky reef habitat	284	160#	645*
Kelp occupy 50% of Rocky reef habitat	1420	798#	3223*

^ Above ground biomass values from Table 2 (Aotearoa values)
** Above ground biomass based on midpoint of 37-417 g C m^{-2} (Blain et al. 2021; Qu et al. 2023) = 227 g C m^{-2} or 2.27 tC ha^{-1}*
 # Estimated based on 11.37% of net primary production (NPP) for macroalgae sequestered in sediment (Krause-Jensen and Duarte 2016), using NPP estimates for kelp in Hauraki Gulf (4.95 tC ha^{-1} yr^{-1}) = 0.56 tC ha^{-1} yr^{-1}

5 Discussion

This study quantifies the extent of blue carbon ecosystems (BCE; saltmarsh, mangrove and seagrass) in the Auckland region and the associated carbon sequestration rates. The extent and carbon sequestration by unvegetated habitats was also estimated and the hypothetic extent of kelp habitat and associated carbon sequestration rate was quantified based on two scenarios (kelp cover occupying 10 per cent and 50 per cent of rocky reefs). To fill gaps in the empirical dataset, a short review was also conducted to summarise the carbon stocks and primary production of kelp and phytoplankton to better understand their potential contribution to carbon sequestration within the Auckland region. This report builds on previous reports of carbon sequestration developed for the Auckland region (EnviroStrat 2022) and nationally for Aotearoa New Zealand (Bulmer et al. 2024b) by incorporating coastal habitats other than coastal wetlands (seagrass, mangroves and saltmarsh) and using refined spatial mapping techniques to create an improved regional layer of BCE habitat extent.

Saltmarsh occupied 3587 ha, mangroves 8181 ha, and seagrass 10,995 ha, with the west coast of Auckland containing over twice the extent of these habitats than the east coast (16,180 ha vs 6582 ha). Carbon sequestration was estimated at 3192 tC yr^{-1} for saltmarsh, 5236 tC yr^{-1} for mangrove, and 3518 tC yr^{-1} for seagrass, with a total regional carbon sequestration rate of 11,946 tC yr^{-1}. In a recent national scale analysis (and using a coarser habitat mapping approach than applied in the present study) approximately 20,932 ha of saltmarsh, 30,533 ha of mangrove and 61,340 ha of seagrass habitat was identified throughout Aotearoa New Zealand (Bulmer et al. 2024b). Based on national habitat extents, carbon sequestration from saltmarsh, mangrove and seagrass at a national scale was estimated at 57,800 tC yr-^{1}. When compared to the coarser national scale habitat mapping analysis by Bulmer et al. 2024b, the revised mapping conducted in this study noticeably improved the mapping outputs, particularly for seagrass habitat, with much lower false positive seagrass detected in locations such as subtidal channels and on rocky reef habitats throughout the region (noting that the rocky reef overlay was not used on the national extent mapping; 10,995 ha seagrass revised mapping vs. 20,631 ha national scale mapping). This is despite comparable accuracy assessment results (0.78 for seagrass in the national analysis vs. 0.79 for the revised regional analysis) highlighting that accuracy assessment results alone are unlikely to reflect how well habitat maps quantify habitat extent. In contrast, the revised mapping technique and the national scale technique produced similar extents for the saltmarsh (3587 ha vs 3121 ha) and mangrove habitats (8181 ha vs. 9237 ha). Based on the national scale mapping undertaken by Bulmer et al. 2024b, the Auckland region contributes approximately 29 per cent of the total national saltmarsh, mangrove and seagrass extent and carbon sequestration capacity (Bulmer et al. 2024b). National scale habitat mapping also revealed that the Auckland and Northland regions contributed the greatest extent of BCE in Aotearoa New Zealand. The large estuarine area throughout the Auckland region and the suitable environmental conditions for mangroves to thrive (in New Zealand, mangroves are restricted to north of 38°S) are key contributing factors for the large BCE extent (Bulmer et al. 2024b).

Despite a lack of core data to inform estimates of sediment carbon sequestration from exported detritus, kelp are highly productive (Blain et al. 2021, Qu et al. 2023). Kelp sequestration rates were estimated at 160 and 798 tC yr^{-1}, based on 10 per cent and 50 per cent coverage of kelp across rocky reef habitats throughout Auckland (and assuming 11.37 per cent of kelp primary production is sequestered in sediment systems). Other habitats/species such as saltmarsh, mangrove and seagrass (as well as phytoplankton) also produce organic matter which is exported and stored in other sediment habitats. For example, significant proportions of carbon within unvegetated sediment habitats in Tairua Estuary were estimated to be derived from saltmarsh (14 per cent), mangrove (15 per cent), seagrass (11 per cent), microphytobenthos (13 per cent) or phytoplankton (46 per cent) (Bulmer et al. 2020). However, carbon export and sequestration outside of the habitat footprint, or within unvegetated sediments, is not typically accounted for in blue carbon abatement calculations (Lovelock et al. 2021a, Lovelock et al. 2022) presumably due to difficulties in reliably measuring and attributing the sources of organic matter; therefore, estimates of kelp carbon sequestration should be treated with caution.

While unvegetated habitats sequester relatively low quantities of carbon per unit area, when adjusted for their potential distribution throughout Auckland, carbon sequestration by unvegetated habitat was estimated to be 258,389 tC yr^{-1}, approximately 21-fold the combined rate of sequestration by other vegetated BCEs throughout the region. Thus, despite unvegetated habitats not usually being considered in carbon abatement calculations (Lovelock et al. 2022), when adjusted for their extent, they can store large amounts of carbon. This number should be treated with caution given that the unvegetated cores used to estimate carbon sequestration were collected from estuaries, with typically muddier and more organically enriched sediment than sandier coastal sediments which may be more frequently disturbed and resuspended, and therefore may overestimate carbon sequestration potential. Regardless, the extent adjusted values may be useful for providing a first pass valuation of marine carbon sequestration occurring within the entire Coastal Marine Area for the Auckland region. These regional scale estimates illustrate that protection and enhancement of BCE and other coastal habitats is an important consideration due to their contribution in sequestering large amounts of carbon.

Providing a financial valuation of the services provided by ecosystems is complex and unlikely to adequately reflect the full value of these ecosystems. However, finance is a key driver of ecological degradation and recovery, and therefore providing financial valuations of ecosystem services can help to enhance restorative actions (Ferretti et al. 2023, Bulmer et al. 2024a). Carbon abatement is one of the services which can be relatively easily quantified in economic terms. While a carbon market is currently not set up in New Zealand to recognise blue carbon, markets such as these have been established in other countries, including Australia (Lovelock et al. 2021a, Lovelock et al. 2022). Using emission unit prices (ETS NZU; ~NZD$50 price per metric tonne of carbon (carbon dioxide equivalent)) to value the carbon sequestration services of BCE in the Auckland region, this service equates to $2,192,000 per annum (based on a sequestration of 11,946 tC yr^{-1} for saltmarsh, mangrove and seagrass, or 43,841 tCO_2 yr^{-1}).

There are many other ecosystem services, functions, and values provided by blue carbon habitats outside of carbon abatement. For example, wetlands are estimated to reduce sediment surface erosion by 60 to 80 per cent (Basher et al. 2019a), contribute to nutrient and sediment filtration and trapping, mitigate against flooding and storm impacts (Horstman et al. 2014), as well as provide a myriad of other ecosystem services and benefits that have cascading impacts including improving the health of marine ecosystems (Macreadie et al. 2021). By quantifying the additional ecosystem services and benefits blue carbon habitats provide, it is possible to differentiate them from other carbon abatement actions (e.g., pine plantations), even if the carbon abatement value was comparable. Better quantification of ecosystem services provided by coastal habitats will also enable their ecological benefits (and costs of their loss) to be better weighed up against social, cultural and economic considerations and values (Bulmer et al. 2024a, Douglas and Lohrer 2024). Applying an economic value to ecosystem services other than carbon abatement is complex, however, other more holistic valuation approaches provide an example of how ecosystem services could be better included in valuation metrics and management decision making. In Queensland, the Land Restoration Fund is a co-benefits scheme that deliver additional environmental (e.g., biodiversity), socio-economic (e.g., generation of economic benefits) and First Nations co-benefits to carbon projects. The incorporation of co-benefits by the Land Restoration Fund resulted in an increase of ~120 to 410 per cent in the contracted price compared to the unit price for carbon alone (based on median land restoration fund contracted price per unit of carbon and the ACCU carbon spot price for the year in which the land restoration fund rounds closed). Recent monetary estimates of ecosystem services in the Hauraki Gulf (Clough et al. 2023) have also indicated that the value gained from carbon sequestration makes up ~1.3 per cent of the total value of regulating and support services in the harbour (NZ$188.3 million per year), meaning that the consideration of additional regulatory services (water quality and biodiversity health) could lead to a 75 times higher credit unit price. Further, additional benefits from provisioning services (e.g. commercial fishing, cruise tourism) and cultural services (e.g. recreation) would only add to the potential monetary value of these habitats.

A similar approach to that applied by the Land Restoration Fund could be implemented in Aotearoa New Zealand, which would enable the wider range of ecosystem services and values of blue carbon ecosystems to be included in valuation metrics, without requiring specific valuations on each individual service. For example, the implementation of a biodiversity credit scheme is currently being explored in New Zealand (Waterford et al. 2022) and could prove to be a promising avenue for promoting the protection and restoration of coastal wetlands. Biodiversity credits could be packaged with carbon credits to ensure blue carbon restoration actions also enhance biodiversity, rather than potentially result in adverse ecological outcomes or occur in areas that may not have the same level of co-benefits.

Recommendations for next steps to progress towards Auckland Council's aim of maximising the potential of marine ecosystems to capture carbon include:

- *Improved region specific carbon sequestration data*. No sediment carbon sequestration data was available from saltmarsh or seagrass habitats in Auckland, and very little for seagrass habitats exist nationally. Collection of additional carbon sequestration data from the Auckland region would strengthen regionally specific blue carbon sequestration estimates and abatement calculations. Collection of samples under a range of environmental conditions could also improve the rates used to estimate carbon sequestration (e.g. many of the current samples are from muddy intertidal locations rather than sandier subtidal areas). Further understanding of the drivers of BCE carbon sequestration could also allow more accurate estimates to be gained (e.g. if carbon sequestration and mud content are correlated for the region, mud may be used as a predictor for carbon sequestration).

- *Supporting the development of habitat mapping approaches which enable Auckland Council to map change in habitat distributions through time.* Using the best analysis methods and imagery available with consistent training/validation data and mapping approaches, and undertaking additional expert review of mapping outputs, is critical for assessing and maximising the quality of the mapping moving forward (and its use as a tool for tracking change through time). The accuracy of future habitat mapping can be significantly enhanced with the inclusion of high-resolution (<10 m) satellite imagery (e.g., Worldview, RapidEye, and aerial photos) and additional relative variables such as DEM/LiDAR, which are useful to distinguish saltmarsh and mangroves. While previous research indicated that water depth does not significantly impact detection accuracy (Shao et al. 2024), seagrass coverage in subtidal regions might be distorted due to water column effects on reflectance. To mitigate this, employing the bottom reflectance index derived from visible bands (Sagawa et al. 2010), which creates distinct indexes for various seabed types (Ha et al. 2024), is expected to improve the machine learning model's performance. Additionally, conducting a detailed spectral signature analysis of different landcovers in coastal regions is recommended, particularly for patchy and sparse habitats and to improve capacity to measure successional stage (maturity) and change in density. Different seagrass density may exhibit very different spectral signatures; for instance, the signature of sparse seagrass tends to be similar to that of unvegetated flats, which potentially introduces classification errors. Mapping the presence/absence of seagrass rather than the density also means that seagrass is typically overestimated. Artificial neuro-network modelling approaches have shown promise in their capacity to predict the percentage cover of vegetation based on visible bands and near infrared band (Shao et al. 2024).
- *Recognition of other ecosystem services.* There are likely to be regionally specific ecosystem services or values that are key considerations in management decision making. Various tools have now been developed to help obtain this type of information (https://www.sustainableseaschallenge.co.nz/tools-and-resources/roadmaps-to-ebm/). For example, Bayesian Network models can use both empirical datasets as well as expert opinion and local values to inform management actions of interest and could be applied to inform estuarine and coastal management strategies with wider consideration than solely carbon (Bulmer et al. 2022). Spatially mapping other ecosystem services (in addition to blue carbon) provides an opportunity to identify areas where multiple ecosystem benefits could be maximised in management decisions (e.g., Rullens et al. (2022b)), and could inform ecosystem credits bundling.
- *Restoration opportunity and the implications of sea level rise.* The present study did not investigate the potential for restoration throughout the Auckland region. Spatially mapping areas of low lying land which are currently below the high tide level (yet prevented from being inundated by seawalls or pumps) allows areas of land adjacent to estuaries and coasts

to be identified for potential blue carbon restoration projects (Bulmer et al. 2024b). As sea-level rises, current intertidal areas will migrate landwards and areas of low lying land that have potential for BCE restoration are likely to increase. However, if physical structures (e.g. seawalls, drainage systems) impede the ability of BCE to develop in these low-lying areas then BCE may be lost as they become submerged (Rullens et al. 2022a). Considering restoration opportunity, and how this varies with sea level rise, will support future planning and efforts to maintain biodiversity values, ecosystem resilience and preserve the many benefits derived from intact coastal ecosystems such as carbon sequestration and flood/storm mitigation.

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