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RESEARCH ARTICLE

Blue carbon habitats in Aotearoa New Zealand—opportunities for conservation, restoration, and carbon sequestration

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Coastal marine habitats (i.e. mangroves, saltmarshes, and seagrasses) have a high capacity for carbon sequestration (termed "blue carbon") and the potential to reduce the effects of greenhouse gas emissions. However, blue carbon habitats have historically decreased as a consequence of land conversion, coastal development, and pollution and are under threat in many locations. Restoration of these habitats can reverse historic losses and generate carbon credits through increased carbon sequestration. With a long coastline, we hypothesized that there would be significant opportunities for coastal blue carbon in Aotearoa New Zealand. Results revealed Aotearoa estuaries and coastal areas contain approximately 20,932 ha of saltmarsh, 30,533 ha of mangrove, and 61,340 ha of seagrass, estimated to sequester a total of approximately 57,800 tC/year. A further 87,861 ha of land was estimated to be potentially suitable for blue carbon projects via tidal restoration, of which 56,482 ha was suitable for saltmarsh restoration (equivalent to 60,435 tC yr if restored), 17,291 ha was suitable for mangroves (26,455 tC/year), and 14,087 ha was suitable for seagrass (4790 tC/year). Both existing extent and restoration opportunity varied throughout the country, with greater opportunity in some regions than others. Nationwide, the total sequestration potential for blue carbon restoration was estimated at 91,680 tC yr^{-1} if all potential areas were restored. Carbon credits generated by blue carbon projects could be traded on a carbon market in Aotearoa, generate revenue for landowners, provide an additional pathway to meet domestic and international climate change targets, and result in a diversity of other ecological, social, and cultural co-benefits from coastal restoration.

Key words: blue carbon, carbon abatement, ecosystem services, mangrove, saltmarsh, seagrass

Implications for Practice

- This first national assessment of blue carbon habitats and opportunities for Aotearoa New Zealand can inform priorities for coastal restoration.
- Determining the carbon abatement of a blue carbon restoration project can offset the costs of restoration and empower restorative actions.
- Quantifying the magnitude and spatial variability of national blue carbon extent and restoration opportunity can inform where restorative management actions may be targeted for greatest restorative success.

Introduction

Background

Blue carbon habitats such as mangroves, saltmarshes, and seagrasses have a high capacity for carbon sequestration and, in many areas, can exceed the capacity of terrestrial habitats on a per unit area basis (Arias-Ortiz et al. 2018; Bulmer et al. 2020). This high carbon storage is mainly due to carbon accumulated belowground (in low-oxygen environments), which can stay captured in the sediment for long time periods, resulting in large carbon stores. The carbon sequestration/storage potential differs by habitat type and condition (Ewers Lewis et al. 2018; Alongi 2020), and as a result, even small shifts in the proportions of different habitat types within an ecosystem can lead to large shifts in overall carbon storage and sequestration and an associated reduction in atmospheric greenhouse gas (GHG) concentrations through sequestration in coastal wetland habitats (Doughty et al. 2015; Kelleway et al. 2016; Bulmer et al. 2020). This dynamic enhances the potential for management interventions that restore blue carbon habitats to alter net GHG emissions from an ecosystem, relative to

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many other ecosystem types. Appropriate and timely management interventions could, therefore, contribute to a regional reduction in GHG emissions.

Restoration of blue carbon habitats is an important nature-based solution to reducing GHG emissions. In addition to carbon sequestration, blue carbon habitats also provide other important ecosystem services (i.e. co-benefits), including cultural and recreational benefits, coastal protection, water filtration, and an important habitat for fish and birds, which enhances biodiversity (Barbier et al. 2011; Horstman et al. 2018). However, blue carbon habitats have undergone huge losses of extent and many of the remaining areas are under threat from land conversion, coastal development, and pollution. Saltmarsh ecosystems have lost between 25 and 50% of their historical coverage worldwide (Duarte et al. 2009; Crooks et al. 2011), and only 18.4% of saline wetlands remain when compared to historic pre-human extents throughout Aotearoa New Zealand (hereafter Aotearoa) (Ausseill et al. 2011). These threats will only be exacerbated by worsening climate change, with sea level rise predicted to lead to the migration of blue carbon habitats inland and loss when migration is not possible (Rullens et al. 2022).

Loss and degradation of blue carbon habitats reduces the capacity of these ecosystems to sequester carbon and limits the provision of other ecosystem services. Often, habitat loss or degradation of coastal wetlands results in an increase in carbon emissions through increased fluxes of CO_2 and other GHG's from sediments to the atmosphere (Lovelock et al. 2011; Bulmer et al. 2015; Lovelock et al. 2017). Conversely, restoration of coastal wetland ecosystems for blue carbon has the potential to reduce emissions from degraded areas and increase sequestration if phased appropriately in space and time (Macreadie et al. 2021; Lovelock et al. 2023). The net capture of carbon through coastal restoration generates carbon credits that can be traded on a carbon market in Aotearoa. The current price of carbon credits on the voluntary market varies widely but could offset restoration costs and, in some cases, produce a net financial benefit. Carbon units in the New Zealand Emissions Trading Scheme (NZ ETS) are called New Zealand units (NZUs), which represent 1 metric ton of carbon dioxide, or the equivalent of any other GHG, from industries covered by the NZ ETS. NZU prices vary with the market, and are sold both through national government auctions as well as through secondary markets; the NZU value as per the latest government auction in March 2024 was $64 New Zealand Dollar (NZD). Coastal wetland restoration for blue carbon is still in its infancy within Aotearoa, yet further development overseas (e.g. temperate regions of Australia) can be leveraged to inform blue carbon restoration in Aotearoa (Lovelock et al. 2023; Stewart-Sinclair et al. 2024). The appropriate restoration methodology will depend on the study site and can range from reinstating tidal flows to actively replanting organisms. Elsewhere, restoration methods have been demonstrated to be affordable on a per hectare basis and can achieve rapid results (e.g. Australian saltmarsh; Rankin et al. 2023).

Aotearoa has a long coastline with significant opportunities for coastal blue carbon, and potential for a blue carbon market within the NZ ETS is being explored, though a blue carbon market and associated carbon price are not yet in place (Stewart-Sinclair et al. 2024). For landowners, blue carbon projects could generate revenue on marginal coastal land via tidal restoration on land that is currently drained or on land that is predicted to be tidally influenced under sea level rise. For the government, blue carbon projects could contribute to meeting domestic and international climate change targets, such as the target set to reach net-zero emissions by 2050 under the Climate Change Response Act 2002 (Stewart-Sinclair et al. 2024).

However, information on the spatial distribution of blue carbon habitats, both historical and present extents, is limited, and varies between both habitats and regions of Aotearoa. A national dataset of land cover includes some coastal vegetation (saltmarsh and mangrove) (Table 1); however, extents are coarsely mapped, particularly with respect to saline coastal wetlands. Unitary authorities often have detailed mapping of blue carbon habitats, many of which have been updated for regional coastal planning activities in the last decade; for example, Tai Timu Tai Pari, the Hauraki Gulf Marine Spatial Plan, which included high resolution spatial distributions of mangrove and seagrass habitats based on available vegetation surveys in the prior decade. Similarly, Northland Regional Council commissioned vegetation surveys to support their regional coastal plan (Macdonald et al. 2020). The Department of Conservation has compiled an estuarine vegetation database with a mix of point and polygon records of varying dates and resolutions. Further, many of these habitats have shown recent increasing trends, for example, mangroves (Suyadi et al. 2019) and seagrass meadows (Lundquist et al. 2018). Thus, an accurate, current record of the spatial distribution of blue carbon habitats in Aotearoa is not available and is a requirement for understanding the current and potential distribution of blue carbon habitats.

Here we summarized the current distribution and extent of blue carbon habitats in Aotearoa at a national scale using validated satellite imagery. We further assessed the current opportunity for blue carbon projects via tidal restoration, that is, in drained coastal areas at elevations suitable for tidal restoration. Based on this analysis, we quantify the current abatement potential for blue carbon in Aotearoa through conservation of current blue carbon habitats and restoration of potential blue carbon areas. This investigation aims to fill key knowledge gaps on the scale and distribution of blue carbon opportunity in Aotearoa in order to prioritize next steps and future directions for Aotearoa's blue economy.

Methods

The current distribution and potential areas for blue carbon projects were assessed at a regional level in Aotearoa. Regional areas corresponding to regional or territorial authorities were chosen as the unit of scale as it is likely that legislation pertaining to blue carbon projects will operate at a regional or national level (Fig. 1).

Blue Carbon Habitat Classification and Mapping

Aotearoa coastal and estuarine ecosystems contain a diversity of blue carbon habitats, including saltmarsh (e.g. *Juncus* spp. and Oioi/*Apodasmia similis*), mangrove forests (single species—*Avicennia marina* subsp. *australasica*), seagrass meadows (single species—*Zostera muelleri* subsp. *novozelandica*), and unvegetated

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Table 1. Summary information and sources for the data input used in the spatial analyses.

Data description	*Data name*	*Data source*
Tidal information	Tide predictions for 2022	https://www.linz.govt.nz/products-services/tides-and-tidal-streams/tide-predictions
Datum conversion	Local Mean Sea Level Datums	https://www.linz.govt.nz/guidance/geodetic-system/coordinate-systems-used-new-zealand/vertical-datums/local-mean-sea-level-datums
Digital elevation models	Coastal LiDAR DEM 1 minute	https://data.linz.govt.nz/
Regional Council/ Unitary Authority delineation	Regional Council 2022 (generalized)	https://datafinder.stats.govt.nz/layer/106666-regional-council-2022-generalised/
Land use information	LUCAS NZ Land Use Map	https://data.mfe.govt.nz/layer/52375-lucas-nz-land-use-map-1990-2008-2012-2016-v008/
Crown land information	Central Record of State Land	https://www.linz.govt.nz/products-services/data/types-linz-data/crown-land-data/central-record-state-land
Land/vegetation cover information	Land Cover Database LCDB v5.0	https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/

intertidal and subtidal sand and mud flats (occupied by microphytobenthic algal and other macrofaunal communities).

Sentinel-2 satellite imagery was used to distinguish between the blue carbon habitats. Sentinel-2 imagery is multispectral (13 bands), has a resolution of 10 m with a 5-day revisit time, and has been providing images since 2015. Imagery was extracted using the "rgee" package (Aybar et al. 2020) in R software (R version 4.3.0) to obtain low-tide and cloud-free images along the coastline of Aotearoa. Imagery was collected between June 2021 and April 2023, with a preference toward summer images where available. Variation in the geographic distribution of coastal vegetation (e.g. mangroves only occurring in the upper North Island and the dominant presence of macroalgae in the South Island) resulted in the coastline being divided into four analysis areas: upper North Island, lower North Island, upper South Island, and lower South Island. Satellite imagery was merged into one raster per section before being clipped to include only estuarine and coastal areas. Estuarine extents were based on an existing national dataset that uses mean high water springs (MHWS) to define the boundary between land and sea (LINZ); see also Gerbeaux and Hume (2022) for recent clarifications on estuary landward and seaward boundaries. However, we note that these boundaries are based on historical tidal measurements; the landward boundary based on MHWSs will move shoreward with sea level rise.

Estuarine blue carbon habitat maps for the areas of interest were generated using routine machine learning approaches (Howard et al. 2014; Tait et al. 2021; Shanahan et al. 2023) (Supplement S1).

The accuracy of the classifications was assessed by an equalized stratified random sampling procedure using 600 validation points (100 per class for mangrove, saltmarsh, seagrass, unvegetated, macroalgae, and water). Others have noted challenges in using remote sensing images to delineate intertidal and shallow subtidal habitats, for example, due to issues of reflectance during tidal submergence and water clarity (Suyadi et al. 2018; Ha et al. 2021; Li et al. 2023). The combined agreement between the classified dataset and the validation samples was computed into an error matrix using Cohen's κ. To incorporate blue carbon habitat located above mean high water within our regional-scale analysis, the habitat classification was then merged with the Land Cover Database LCDB v5.0 extents for saltmarsh/saline vegetation and mangrove habitats (using methods described below "Restoration opportunity analysis") to create the final blue carbon habitat map.

Restoration Opportunity Analysis

In addition to mapping existing blue carbon habitats within each Regional Council area, the total area of blue carbon opportunity (i.e. drained land within the area of tidal influence) and intertidal zones within these areas were identified. The current land uses and the land tenure (Crown/public or privately owned) within potential blue carbon areas were also identified (Table 1). To identify land tenure, the assumption was made that land was privately owned if it was not Crown land (Table 1).

Tidal restoration here is defined as the complete removal of a tidal barrier, such as a sea wall or a tidal gate, allowing tidal flows to be reinstated.

Tidal Area. To identify the intertidal zone, the tidal range of each region was classified using tidal predictions (Table 1), where the height of mean spring and neap tides, relative to mean sea level (MSL), is given for standard and secondary ports around Aotearoa New Zealand (ANZ). Each Regional Council area was assigned a standard and secondary port, and tidal heights from each port were averaged to generate a tidal range for the region for MHWS tides, mean high water neap (MHWN tides), MSL, mean low water neap (MLWN tides), and mean low water spring (MLWS tides). For all tidal height data, local vertical datums were converted to the New Zealand vertical datum (NZVD), since tidal data use the local datum for MSL while the digital elevation models (DEMs) are projected in a different vertical datum,

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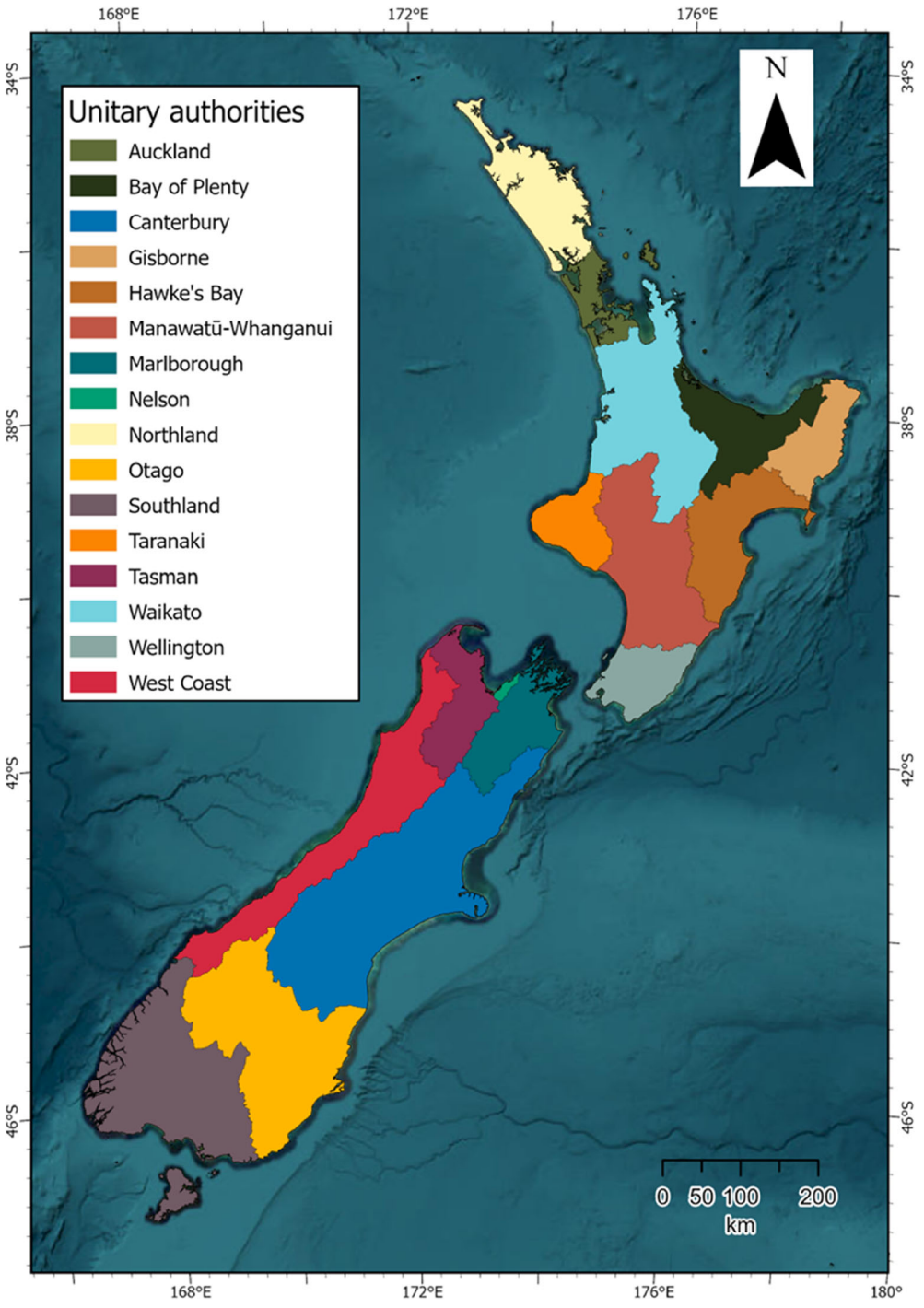


Figure 1. Regions of Aotearoa where the current distribution of blue carbon habitats and potential for blue carbon projects were mapped.

New Zealand Vertical Datum 2016 (NZVD2016) (Table 1). Correction values were applied based on the datum relationship for each region, as in Table S1.

Digital Elevation Models. Regional 1 m resolution Light Detection and Ranging (LiDAR) DEM data were used to identify coastal areas that were currently, or could potentially be, tidally influenced (Table 1). These datasets are available as part of the New Zealand National Elevation Programme, and are based on 1 m gridded bare Earth DEM and digital surface model elevation models (in New Zealand Transverse Mercator 2000 [NZTM2000] projection and NZVD2016). Minimum accuracy for inclusion in the national dataset is a vertical

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accuracy of 95% (≤20 cm), horizontal accuracy of 95% (≤100 cm), and pulse density ≥4 pls/m^2 (Toitū Te Whenua Land Information New Zealand 2022). The year that DEM data were collected varied, and there were some significant gaps in data availability, which limited the analysis to areas with data available. These data gaps have the greatest impact on spatial coverage for the West Coast Regional Council.

Tidal zone is important as it determines the type of habitat suitable for restoration at each site, which will also affect the carbon sequestration potential and co-benefits. In Aotearoa, saltmarsh generally occupies the upper intertidal zone. For each region, areas within the tidal zone were extracted from the DEM and classified into tidal zones as follows: (1) low intertidal (MLWS to MLWN); (2) low-mid intertidal (MLWN to MSL); (3) mid-upper intertidal (MSL to MHWN); and (4) upper intertidal (MHWN to MHWS) (Table S1).

Mangroves occupy the area above MSL at latitudes north of 38°, though they are more typically found in sheltered areas in the mid-upper and upper intertidal zones (McBride et al. 2016). Seagrass can grow sub-tidally through the mid-upper intertidal zone (McBride et al. 2016). Prior to European arrival in Aotearoa, subtidal seagrass was extensive; however, the majority of extant seagrass is intertidal (Inglis 2003; Schwarz et al. 2006). Mixed vegetation communities are common, for example, with seagrass or saltmarsh found within mangrove forests (e.g. Graeme 2013); however, satellite images only detect the dominant vegetation (mangroves). It is worth noting that restoration of low-lying land may not be suitable for some habitat types regardless of tidal elevation if other environmental conditions are unsuitable, e.g. seagrass has limited tolerance to mud and is not typically found in areas where mud exceeds 35% (Crawshaw 2020). Further, seagrass research in Aotearoa suggests a diversity of factors other than tidal height influence restoration success (e.g. water clarity, tidal flow, and sediment characteristics; Matheson and Schwarz 2007; Matheson et al. 2017; Lundquist et al. 2018; Zabarte-Maeztu et al. 2021). Many prior restoration projects have been unsuccessful in habitats that were perceived as suitable for seagrass; thus, it is likely that our methods over-estimate possible seagrass restoration areas.

Drained Land. To identify areas of currently drained land that are at an elevation that would allow for tidal restoration, tidal zone data were overlaid with land use data from the Ministry for the Environment's land use map (Table 1). All land uses that were categorized as wetland (open water and vegetated non-forest) were removed since these areas are either not drained land or may currently be coastal wetland and therefore not suitable for blue carbon projects. The remaining potential blue carbon areas are currently drained land at an elevation that would be subject to tidal influence if there were no tidal barriers.

Blue Carbon Sequestration, Stocks, and Greenhouse Gas Emissions

Three sources of data contributed to estimates of carbon sequestration, stocks, and GHG emissions. Details of the variability observed with all compiled measurements are provided, so that variability can be accounted for in future carbon abatement calculations. These datasets were used as input parameters to inform blue carbon abatement calculations using the Australian BLUECAM methodology, and average carbon metrics are provided in Table 2 (Lovelock et al. 2021, 2023; Hagger et al. 2022). The BLUECAM approach is the basis for the national Australian carbon credit system for coastal wetland restoration and is used to calculate carbon abatement accounts for the potential change in carbon sequestration due to restoration of blue carbon habitat (including carbon stored within living vegetation and soil). It also accounts for the change (generally reduction) in GHG emissions (CH_4 and N_2O) due to increased salinity levels in both soil and water (Supplement S1).

To estimate carbon sequestration rates in blue carbon ecosystems (saltmarsh, mangrove, and seagrass), the following assumptions were applied. For restored blue carbon ecosystems, mature aboveground biomass was assumed to occur after approximately 25 years (Lovelock et al. 2021). The majority of belowground biomass was assumed to be accounted for in Sediment Carbon Accumulation Rates (SCAR) (given that methods used in the field and laboratory to quantify soil carbon stocks typically integrate fine roots into the soil organic carbon stocks). GHG emissions (CH_4, N_2O, and CO_2) were assumed to be negligible, as they represented less than 0.02 tC ha^{-1} yr^{-1} when converted to C (Table 2), and CO_2 emissions were assumed to be balanced by primary productivity (as per Lovelock et al. 2021). For existing blue carbon ecosystems, aboveground biomass was not included in carbon sequestration rates as it was assumed that existing habitats had already reached maturity, and therefore carbon accumulation rates are based entirely on SCAR.

Using the above approach, the following habitat carbon sequestration rates based on mean values from this study (for saltmarsh and mangrove) and Lovelock et al. (2021, 2023) (for seagrass) were calculated.

Restored blue carbon ecosystems:

- Saltmarsh = 4.51 (aboveground biomass)/25 years = 0.18 (aboveground biomass) tC ha^{-1} yr^{-1} + 0.89 (SCAR) tC ha^{-1} yr^{-1} = *1.07 tC ha^{-1} yr^{-1}*
- Mangrove = 22.36 (aboveground biomass)/25 years = 0.89 (aboveground biomass) tC ha^{-1} yr^{-1} + 0.64 (SCAR) tC ha^{-1} yr^{-1} = *1.53 tC ha^{-1} yr^{-1}*
- Seagrass = 0.57 (aboveground biomass)/25 years = 0.02 (aboveground biomass) tC ha^{-1} yr^{-1} + 0.32 (SCAR) tC ha^{-1} yr^{-1} = *0.34 tC ha^{-1} yr^{-1}*

Existing blue carbon ecosystems:

- Saltmarsh = *0.89 (SCAR) tC ha^{-1} yr^{-1}*
- Mangrove = *0.64 (SCAR) tC ha^{-1} yr^{-1}*
- Seagrass = *0.32 (SCAR) tC ha^{-1} yr^{-1}*

Results

Blue Carbon Habitat Extent

National. The κ value for the accuracy assessment of the merged national estuarine classification was 0.86, which was based on a stratified random sampling procedure (Table S2). The greatest

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Table 2. Estimates of sediment organic carbon accumulation rate (sequestration), stocks, and greenhouse gas emissions 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	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data)
	Mangrove	0.64	0.25	0.22	2.12	7	This study	Collected from two locations within Whangārei harbor and five locations throughout the Auckland Region (Bulmer et al., unpublished data)
	Seagrass	0.04	0.01	0.02	0.05	2	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data)
	Unvegetated	0.26	0.04	0.02	0.64	18	This study	Collected from three locations within Whangārei harbor (Bulmer et al., unpublished data) and 15 locations throughout the Auckland Region
Sediment carbon stock (tC/ha to 100 cm depth)	Saltmarsh	92.50	12.42	68.62	131.97	5	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data) and data compiled from Bulmer et al. (2020)
	Mangrove	57.44	6.29	30.00	113.97	17	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data) and data compiled from Bulmer et al. (2020)
	Seagrass	17.22	6.12	7.53	33.09	4	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data) and data compiled from Bulmer et al. (2020)
	Unvegetated	33.60	3.32	7.56	69.61	22	This study	Collected from three locations within Whangārei harbor, 15 locations throughout the Auckland Region (Bulmer et al., unpublished data), and data compiled from Bulmer et al. (2020)
Aboveground biomass (tC/ha)	Saltmarsh	4.51	1.39	1.58	8.78	5	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data) and data compiled from Bulmer et al. (2020)
	Mangrove	22.36	5.43	2.51	84.88	17	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data) and data compiled from Bulmer et al. (2018, 2020)
	Seagrass	0.11	0.04	0.03	0.23	4	This study	Collected from two locations within Whangārei harbor (Bulmer et al., unpublished data) and data compiled from Bulmer et al. (2020)
Habitat carbon stock (aboveground biomass + sediment [tC/ha to 100 cm depth])	Saltmarsh	97.01	13.81	70.2	140.75	5	This study	Combination of the above
	Mangrove	79.8	11.72	32.51	198.85	17	This study	Combination of the above
	Seagrass	17.33	6.16	7.56	33.32	4	This study	Combination of the above
	Unvegetated	33.60	3.32	7.56	69.61	22	This study	Combination of the above

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Table 2. Continued

	Habitat type	Mean	SE	Min	Max	Number of sites	Source	Source notes
Sediment carbon accumulation rate (tC ha^{-1} yr^{-1})	Saltmarsh	0.46	0.16				Ross et al. (2024)	Albot et al. (unpublished data) and Ross et al. (2024).
	Mangrove	0.90		0.21	2.12		Ross et al. (2024)	Bulmer et al. (unpublished data)
Sediment carbon stock (tC/ha to 100 cm depth)	Saltmarsh			38.00	57.00		Ross et al. (2024)	Albot et al. (unpublished data) and Berthelsen et al. (2023).
	Mangrove	61.60	6.90				Ross et al. (2024)	Bulmer et al. (unpublished data)
	Seagrass			14.00	27.00		Ross et al. (2024)	The range between Bulmer et al. (unpublished data) and Berthelsen et al. (2023)

	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. (2023)	Collected from Australian estuaries
	Mangrove	1.4	0.16	0.95	1.73	48	Lovelock et al. (2023)	Collected from Australian estuaries
	Seagrass	0.32	0.05	0.23	0.42	43	Lovelock et al. (2023)	Collected from Australian estuaries
Emissions CH_4 (kg ha^{-1} yr^{-1})	Saltmarsh	0.11		−0.21	0.44	2	Lovelock et al. (2023)	Collected from temperate Australian estuaries
	Mangrove	2.19		0.91	3.31	3	Lovelock et al. (2023)	Collected from temperate Australian estuaries
	Seagrass	0				1	Lovelock et al. (2023)	Collected from temperate Australian estuaries
Emissions N_2O (kg ha^{-1} yr^{-1})	Saltmarsh	0.13		0.02	0.23	2	Lovelock et al. (2023)	Collected from temperate Australian estuaries
	Mangrove	0.24		0.17	2.75	2	Lovelock et al. (2023)	Collected from temperate Australian estuaries
	Seagrass	0				1	Lovelock et al. (2023)	Collected from temperate Australian estuaries

	Habitat type	Mean	SD	Number of sites	Source	Source notes
Aboveground biomass (tC/ha)	Saltmarsh	7.89	6.1	49	Lovelock et al. (2023)	Collected from temperate Australian estuaries
	Mangrove	70.4	41	9	Lovelock et al. (2023)	Collected from temperate Australian estuaries
	Seagrass	0.57	0.66	74	Lovelock et al. (2023)	Collected from temperate Australian estuaries

mapping accuracy was observed for macroalgae, mangrove, and saltmarsh areas (>0.9), which was higher than unvegetated (0.85), and the lowest was observed for seagrass (0.79).

Saltmarsh and seagrass are observed throughout the country, whereas mangroves are latitudinally constrained to the northern half of the North Island, north of latitudes of approximately 38°N. Within estuaries in Aotearoa, a total of 20,932 ha of saltmarsh, 30,533 ha of mangrove, and 61,340 ha of seagrass were estimated based on satellite remote sensing. Geospatial blue carbon habitat layers are available at https://niwa.co.nz/coasts/te-ukaipo-o-hinemoana-cumulative-effects. Adjusted by habitat-specific carbon sequestration rates, saltmarsh sequestered an

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Table 3. Spatial extent (ha) of blue carbon habitats in estuaries for Regional Council areas in Aotearoa New Zealand.

Region	*Mangroves*	*Saltmarsh*	*Seagrass*	*Total (ha)*
Northland	16,073	4020	11,020	31,113
Auckland	9237	3123	20,631	32,990
Waikato	3466	1095	3221	7781
Bay of Plenty	1758	624	4405	6788
Gisborne		78	44	122
Taranaki		10	231	241
Manawatū-Whanganui		322	920	1242
Hawke's Bay		1228	337	1564
Wellington		63	914	977
Tasman		2086	9458	11,544
Nelson		133	499	633
Marlborough		1494	2216	3710
West Coast		1624	140	1764
Canterbury		1694	661	2355
Otago		909	2665	3573
Southland		2428	3979	6407
Total (ha)	30,533	20,932	61,340	112,806

estimated 18,630 tC/year, mangrove 19,541 tC/year and seagrass 19,629 tC/year (Tables 2 & 3).

Regional Analysis. At a regional scale, Northland and Auckland had the largest amount of blue carbon habitat (with 31,113 and 32,990 ha of total blue carbon habitat, respectively). In Northland, there were 4020 ha of saltmarsh, 16,073 ha of mangrove, and 11,020 ha of seagrass. Using habitat-specific sequestration rates (see Section 2.3), this is equivalent to carbon sequestration of 3578 tC/year in saltmarsh, 10,287 tC/year in mangrove, and 3526 tC/year in seagrass, with a total sequestration of 17,391 tC/year. In Auckland, there were 3123 ha of saltmarsh, 9237 ha of mangrove, and 20,631 ha of seagrass, which is equivalent to carbon sequestration of 2780 tC/year in saltmarsh, 5912 tC/year in mangrove, and 6602 tC/year in seagrass, with a total sequestration of 15,294 tC/year.

Blue Carbon Opportunity

National. At a national scale, there were 87,861 ha of blue carbon opportunity, which is defined here as drained land within the tidal zone. Of this, 3361 ha were in the low intertidal (MLWS to MLWN), 10,726 ha were in the low-mid intertidal (MLWN to MSL), 29,625 ha were in the mid-upper intertidal (MSL to MHWN), and 44,149 ha were in the upper intertidal (MHWN to MHWS) zone.

Assuming that the area of blue carbon opportunity in the high intertidal (44,149 ha) would be appropriate for saltmarsh restoration, this would be equivalent to 47,239 tC/year. South of the range for mangroves, the mid-upper tidal zone (12,333 ha) could be occupied by saltmarsh and would have a sequestration potential of 13,196 tC/year. This gives a nationwide potential of 56,482 ha for saltmarsh restoration, with a total 60,435 tC/year carbon equivalent.

Table 4. Land uses of total area of drained land available for blue carbon restoration in Aotearoa. Other: any other remaining land that does not fall into any of the other land use categories.

Land use (2016)	*Area (ha)*
Grassland—high producing	62,186
Grassland—low producing	9580
Natural forest	4621
Cropland—Annual	2795
Other	2725
Settlements or built-up area	1895
Grassland—with woody biomass	1861
Cropland—orchards and vineyards (perennial)	1316
Planted forest—pre-1990	776
Post-1989 forest	106

Mangroves have a restricted distribution in the north half of the North Island; thus, estimates were performed conservatively for their potential in tidal zone 3 (MSL to MHWN) for Northland, Auckland, Waikato, and Bay of Plenty Region (17,291 ha), which would have a total sequestration potential of 26,455 tC/year. Seagrass restoration would be suitable in areas below mean tide (14,087 ha total), which would have a total sequestration potential of 4790 tC/year. Nationwide, we estimate a total sequestration potential for blue carbon restoration of 91,680 tC/year if all potential areas were restored.

Within the area of blue carbon restoration opportunity, approximately 84% of the land is classified as grassland (73,627 ha), with a further approximately 5% (4111 ha) as cropland. Both land uses could reasonably be converted into blue carbon habitats via tidal restoration. Conversely, settlements and other built-up areas are unlikely to be suitable areas for blue carbon restoration; however, these only contribute approximately 2% (1895 ha) to the total area of opportunity (Table 4).

The land tenure within blue carbon areas of opportunity was mostly privately owned, with only 17% of the total area owned by the government (15,021 ha). Of the government owned land, most was central government land (11,253 ha), with the remaining 3768 ha owned by the local government.

Regional. At a regional level, Waikato had the highest amount of area available for blue carbon projects, followed by Northland, Otago, and the Bay of Plenty (Table 5). Detailed regional calculations are provided for Northland (Tables S3 & S4); Auckland (Tables S5 & S6); Waikato (Tables S7 & S8); Bay of Plenty (Tables S9 & S10); Gisborne (Tables S11 & S12); Taranaki (Tables S13 & S14); Manawatu-Wanganui (Tables S15 & S16); Hawke's Bay (Tables S17 & S18); Wellington (Tables S19 & S20); Tasman (Tables S21 & S22); Nelson (Tables S23 & S24); Marlborough (Tables S25 & S26); West Coast (Tables S27 & S28); Canterbury (Tables S29 & S30); Otago (Tables S31 & S32); and Southland (Tables S33 & S34). Regions with the highest blue carbon potential are those with more estuarine areas (see Fig. 2 for estuarine examples), whereas regions with more rocky-coast habitat (e.g. Taranaki) have less opportunity for blue carbon projects.

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Table 5. Spatial extent of blue carbon opportunity for Regional Council areas in Aotearoa in (1) low intertidal (MLWS to MLWN), (2) low-mid intertidal (MLWN to MSL), (3) mid-upper intertidal (MSL to MHWN), and (4) upper intertidal (MHWN to MHWS) zones.

	Tidal zone				
Region	*1*	*2*	*3*	*4*	*Total (ha)*
Northland	150	586	3454	8765	12,954
Auckland	115	581	1887	2422	5004
Waikato	289	966	7298	13,320	21873
Bay of Plenty	545	1688	4652	2996	9881
Gisborne	95	137	747	289	1267
Taranaki	55	164	218	177	615
Manawatū-Whanganui	139	532	1154	1970	3795
Hawke's Bay	292	683	794	496	2265
Wellington	279	199	283	827	1588
Tasman	55	92	228	544	920
Nelson	25	22	66	236	348
Marlborough	233	465	1592	2476	4766
West Coast	251	796	859	1074	2980
Canterbury	121	226	972	3237	4556
Otago	540	2954	4275	3154	10,923
Southland	178	635	1145	2168	4126
Total (ha)	3361	10,726	29,625	44,149	87,861

Most regional areas follow national trends where the majority of the blue carbon opportunity area was above mid tide (tidal zones 3 and 4) and classified as grassland or cropland (with the exception of the West Coast, which had 37% natural forest) (Fig. 3). These areas are also mostly privately owned land, and any that are government owned are majority central government land (except for Manawatu-Wanganui and the West Coast, which had 52 and 57% of blue carbon potential area government owned). More details on regional variability in blue carbon restoration opportunities are given in Table S3.

Discussion

Restoration of blue carbon habitats has great potential to provide a range of benefits to Aotearoa. Our results show that the current distribution of blue carbon habitats and associated restoration potential varies considerably between regions, with the largest extents in areas with extensive estuarine area, e.g. Northland and Auckland. For some regions, there are relatively large opportunities for blue carbon restoration (such as Waikato, Northland, Otago, and the Bay of Plenty), while those with less extensive estuaries generally have fewer opportunities for blue carbon projects. This variability in restoration opportunity is consistent with other countries, where the scale and type of restoration opportunity vary considerably across regions (Hagger et al. 2022). The choice of restoration action will depend on a range of factors other than purely carbon abatement and spatial extent, however, our analysis provides the first national-scale mapping of coastal wetland blue carbon habitats, as well as a regional-scale assessment of existing habitat extents and restoration opportunities to help guide these decisions.

Blue Carbon Extent

At a national scale, Aotearoa has an estimated 20,932 ha of saltmarsh, 30,533 ha of mangrove, and 61,340 ha of seagrass, estimated to sequester a total of approximately 57,800 tC/year. While minimal change in saltmarsh/saline wetlands has been observed in the past 20 years (based on the analysis of the national Land Use Cover Database from 1996 to 2018), significant reductions have been recorded historically. Ausseill et al. (2011) estimate that only 18.4% of saline wetlands remain when compared to historic pre-human extents throughout Aotearoa New Zealand. In contrast, mangroves have been increasing in extent in many locations over the past 50–100 years due to impacts such as sedimentation/intertidal infilling and a changing climate (such as mangrove expansion), with potential ecological and carbon storage implications (Swales et al. 2015; Suyadi et al. 2019). Similarly, seagrass has naturally recolonized a number of locations in the last 20 years (Lundquist et al. 2018).

In addition to carbon sequestered by coastal vegetation, unvegetated habitats (dominated by shellfish/macrofauna and microphytobenthic communities) are known to store considerable amounts of carbon (Bulmer et al. 2020). Estuaries in Aotearoa cover an estimated 703,780 ha of area (Hume et al. 2016). If we constrain our coastal vegetation habitat mapping to estuaries, the net area of saltmarsh, mangrove, and seagrass within estuaries is 71,148 ha. Assuming that the remaining 632,630 ha is primarily unvegetated habitat (noting that a small proportion of this will be made up of other habitats, such as rocky reef/kelp-dominated habitats or macroalgae), we estimate that unvegetated habitats sequester a further 164,483 tC/year (0.26 tC ha^{-1} yr^{-1}), with significantly greater sequestration rates if coastal extents were also included. Similar observations have been made by Bulmer et al. (2020), where unvegetated habitats in an Aotearoa estuary were found to contain most estuarine carbon stocks when adjusted for their large extent. Our results demonstrate that unvegetated habitats, when adjusted for their extent, are likely to be a primary contributor to marine carbon sequestration.

Restoration Opportunity

Analysis of blue carbon restoration opportunity indicates that there is potential for restoring 87,861 ha of land that is currently below MHWS tide. While it is unlikely that all areas of land below MHWS would be suitable for blue carbon restoration (for instance, if occupied by key infrastructure or other high-value land/ecosystem type), nationwide we estimate a total sequestration potential for blue carbon restoration of 91,680 tC/year if all potential areas were restored. Of this total area, 56,482 ha would be suitable for saltmarsh restoration (equivalent to 60,435 tC/year if restored), 17,291 ha are within the tidal elevation and distribution suitable for mangroves (26,455 tC/year), and 14,087 ha are within the tidal elevation suitable for seagrass habitats (4790 tC/year).

Across all regions, most of the area of blue carbon opportunity (i.e. drained areas) was above the mean tide level. This was expected as these areas are at a higher elevation, therefore more easily drained and kept dry. The current land use of blue carbon opportunity was most commonly grassland and cropland and

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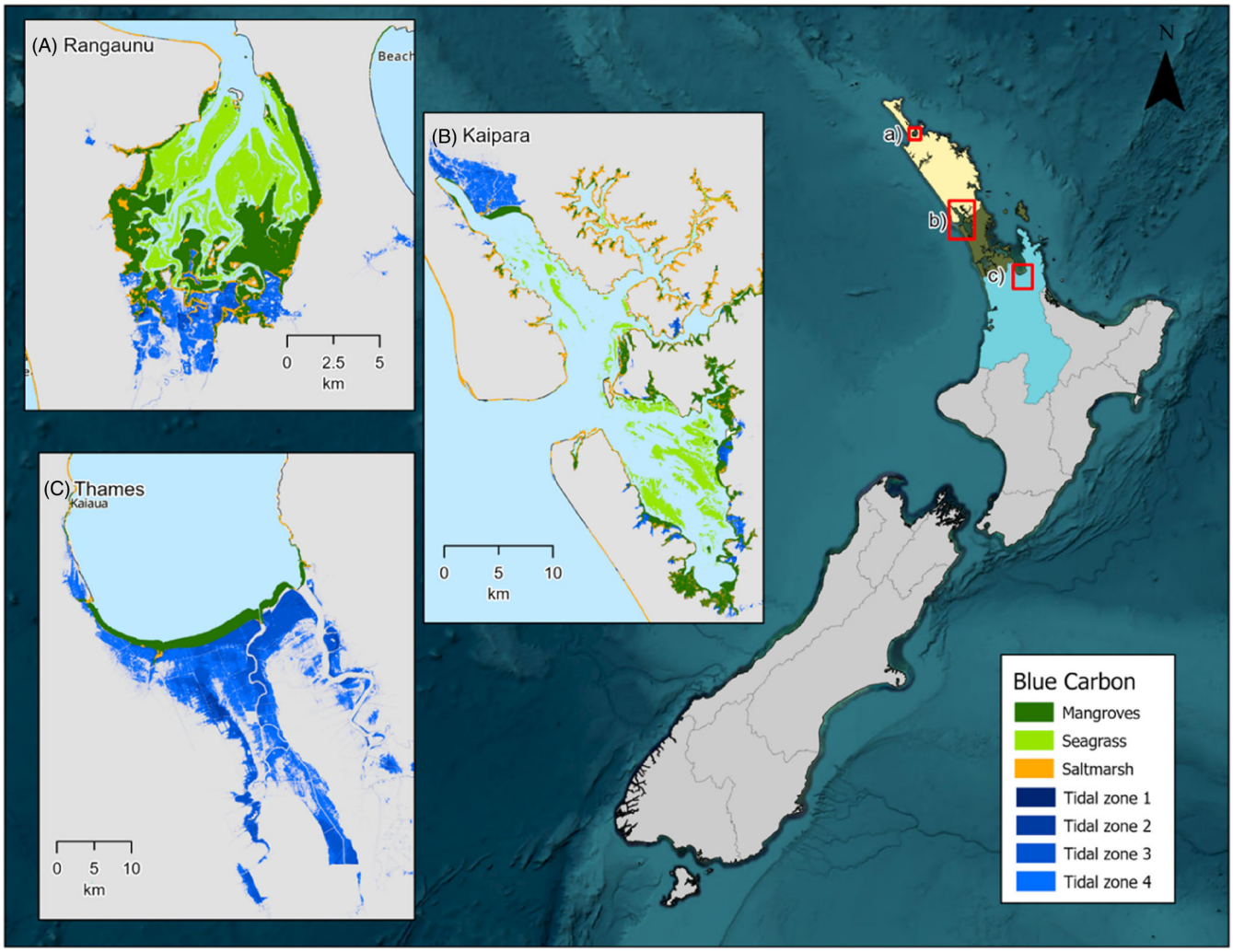


Figure 2. Map of Aotearoa with examples of the distribution of blue carbon (mangrove, saltmarsh, and seagrass) and blue carbon restoration opportunity by tidal zone.

privately held, which was expected as this was the primary purpose for reclamation/draining of the land in the first place. Tidal restoration of these areas under a blue carbon scheme could follow guidelines set out by the BlueCAM approach to estimate carbon abatement in Australia (Lovelock et al. 2021, 2023; Hagger et al. 2022). To maximize uptake of blue carbon projects, it would make sense to prioritize a methodology whereby privately owned grassland or cropland at a suitable elevation for saltmarsh or mangrove is converted to tidal habitats through tidal restoration (Stewart-Sinclair et al. 2024). Areas that require elevation modification (e.g. to move from an elevation suitable for seagrass to an elevation suitable for saltmarsh/mangrove) are likely to incur considerably greater costs than areas with an elevation already suitable for saltmarsh/mangrove. In the lower elevation areas, it may be possible to restore seagrass over marginal farmlands; however, the sediment characteristics and water clarity requirements of seagrass may limit restoration success (e.g. seagrass in Tauranga Harbor, Aotearoa has been observed to be constrained to a surface mud content of less than 35%; Crawshaw 2020).

While the majority of the opportunity areas identified for blue carbon projects here were grassland (71% of all blue carbon opportunity), the opportunity cost of restoration (i.e. lost revenue) will depend upon the type of grassland (e.g. high vs. low producing) and the sub-categories within these (e.g. sheep, beef, or dairy farming). The average annual profit for all grazing land uses in Aotearoa in 2020–2021 was $165.4/ha ($115,422 per farm with an average farm size of 698 ha; Beef and Lamb New Zealand 2022). These different land use types will also have different net carbon sequestration estimates, with high producing farmlands also likely to have higher enteric emissions from stock. Other land uses such as cropping, or plantation forestry will have different baseline emissions as well as ecological and economic factors to consider. These opportunity costs would have to be considered in a cost–benefit analysis alongside upfront restoration costs (including permitting) and maintenance. It is possible that current carbon prices would not offset these costs. However, current costs and benefits may change in the future as climate change impacts begin to impact coastal marginal land and carbon prices may increase.

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Figure 3. Land uses extent across Regional Councils in Aotearoa New Zealand.

While saltmarsh restoration is underway at many sites around Aotearoa, most restoration sites are pilot projects, and as a result costs are likely to be higher than if restoration actions were more routinely undertaken. The Bay of Plenty Regional Council has been trialing saltmarsh restoration projects at five sites ranging in size from 20 to 30 ha throughout the region. Costs range from an average of $30,000/ha, with the highest around $190,000/ha and the lowest around $20,000/ha. Costs ranged primarily based on the amount of consulting required (engineering fees etc.), and if the restoration is a "rewet, plant and walk away" type of approach or requiring additional interventions such as modifying depth and tidal influence. These costs did not include the cost of the land (Crawshaw, 2023, Bay of Plenty Regional Council personal communication). Internationally, Bayraktarov et al. (2016) estimated the average restoration costs of mangrove and saltmarsh were $52,000 and $151,000 USD/ha, respectively, which is considerably higher than costs emerging from trials in the Bay of Plenty. However, their review highlights orders of magnitude differences in costs across projects, suggesting that much can be learned from low cost projects that have had successful restoration outcomes (Bayraktarov et al. 2016).

While the scale of blue carbon opportunity within each Regional Council area is small compared to terrestrial carbon sequestration types (e.g. pine plantations), there are many other ecosystem services, functions, and values provided by blue carbon habitats outside of carbon abatement. For example, in Aotearoa, increased sedimentation is a primary driver of the loss of estuarine and coastal biodiversity (Thrush et al. 2004).

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Wetlands are estimated to reduce sediment surface erosion by 60–80% (Basher et al. 2019), 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). Aotearoa is currently exploring the creation of biodiversity credits (Waterford et al. 2022), which could be packaged with carbon credits to enhance blue carbon restoration value over other forms of carbon abatement that may not have the same level of co-benefits (e.g. plantation pine forestry).

While not modeled in this study, sea level rise will also create additional areas for blue carbon restoration. For example, under RCP 8.52081-2100, sea levels are predicted to increase by 0.71 m (Hagger et al. 2022; Lovelock et al. 2023). While the impact of sea level rise on restoration opportunity was not quantified within this analysis, in comparable studies from Australia, the area of potential restoration opportunity increased by approximately twofold based on a 1 m sea level rise (Hagger et al. 2022). In addition to increasing the potential area for restoration, sea level rise is likely to reduce the value of land that becomes tidally inundated, particularly in areas where the costs of preventing inundation are prohibitive (e.g. for areas of marginal farmland). In addition to sea level rise, climate change is changing the frequency and intensity of extreme weather events throughout Aotearoa (Bell et al. 2017).

Other Considerations

Carbon Sequestration Estimates. Relatively high variability in blue carbon sequestration rates between and across habitat types was observed in the data compilation, implying that site specific factors are an important factor influencing carbon sequestration rates within Aotearoa New Zealand. To enable the impact of this variability to be better accounted for in carbon abatement calculations, the range of carbon sequestration rates observed across the sampling sites that were collated was provided. Site specific sampling would provide greater certainty in regard to carbon abatement valuations.

Data Layers. Data layers used and created within this analysis are considered reliable and robust resource if viewed at appropriate scales. They are not intended to be used to show land/habitat cover at an individual property scale, but instead provide larger scale insights into land cover and change through time. The national data layers represent the best available data and have been used to inform many land use management decisions throughout Aotearoa. For example, the Land Use and Carbon Accounting System (LUCAS) dataset was developed to enable Aotearoa to meet its reporting and accounting obligations to the United Nations Framework on Climate Change, and under Article 3.3 of the Kyoto Protocol (the first commitment period [CP-1], 2008–2012).

Coastal/Estuarine Boundaries and Areas of Blue Carbon Restoration Opportunity. This study followed a similar approach to identify blue carbon restoration opportunity as applied in Australia's BLUECAM methodology (Lovelock et al. 2021, 2023; Hagger et al. 2022). This methodology analyzes DEMs and uses local tide data (where available) to identify areas below the mean high spring tide. Many regions or estuaries have limited tidal gage data available. Because tidal ranges change within regions and within estuaries, adjustments based on the limited available tidal gages are a simplification of the tidal ranges observed and will have some associated error, particularly as distance from tidal gages increase. To account for potential error in tidal adjustments, a mean spring high tide adjustment was applied (rather than the highest astronomical tide) within the restoration opportunity analysis. However, this means that the estimates of estuarine extent and restoration opportunity are likely to be conservative and underestimate the potential area of tidal influence. We chose this adjustment as mean spring high tide is the most commonly used measure of high tide in Aotearoa, and to ensure that areas that are identified as potential blue carbon restoration locations are unlikely to be erroneously above the area of potential tidal inundation. Improved mapping of the area of tidal inundation would improve accuracy in determining suitable areas for restoration. For example, although hydrodynamic modeling is unlikely to be practical at large spatial scales, hydrodynamic modeling at select locations could provide greater accuracy if required.

Digital Elevation Models. Coastal LiDAR 1 m DEM data were used to determine what areas of the coast could be influenced by tides. The resolution of these data is good where available; however, there are significant data gaps. The largest gap is on the west coast of the South Island, where there is no coastal DEM data available. This means the West Coast Regional Council area was excluded from the calculation of blue carbon opportunity (i.e. potential restoration sites).

Underpinning Imagery and Blue Carbon Classification. Sentinel-2 satellite imagery at 10 m resolution was extracted for the estuarine blue carbon habitat classification/mapping. Imagery was extracted at low tide, during cloud-free periods, with a preference toward summer images where available. While 10 m or greater resolution is commonly used in habitat mapping efforts, obtaining finer resolution imagery at a restoration site scale would likely lower classification error (Howard et al. 2014; Tait et al. 2021; Ha et al. 2023; Shanahan et al. 2023). In addition, while the overall estuarine blue carbon habitat mapping classification had good accuracy (κ value of 0.86), greater error was observed in seagrass habitat than mangrove or saltmarsh. This is likely to be in part due to surface water altering spectral signatures and therefore confounding machine learning classification, with overlapping spectral signatures between water, unvegetated habitat, and seagrass habitats (Suyadi et al. 2018). Further, our habitat mapping training points were located based on expert knowledge of the species present based on previous field visits to primarily estuaries throughout the country, with dominant species clearly discernible in satellite imagery. Unlike saltmarsh and mangroves, which were mostly observed in estuaries (or captured in national land use cover datasets), approximately 40% of seagrass was observed coastally within the habitat maps, increasing the likelihood that error in the classification would occur for coastal

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seagrass due to a lack of training data within these locations. However, seagrass appears to have the lowest carbon sequestration potential when compared to saltmarsh or mangrove, and therefore the net impact of higher potential variability in seagrass extent on carbon abatement calculations is reduced. In addition, the mapping in this study was not able to derive metrics of habitat condition, which would provide additional opportunity for habitat restoration to enhance condition.

The purpose of the habitat mapping elements of this study was to provide the first national and regional scale maps of blue carbon habitats to inform management decisions. While the mapping classification accuracy was adequate for a national scale map, the mapping analysis had greater error than if conducted on a smaller spatial scale (e.g. due to including a large amount of stitched imagery collected from 2020 to 2022, including multiple estuaries with different sediment characteristics and spectral signatures, and incorporating existing land use cover maps for saltmarsh and mangrove outside of estuaries). The habitat classification is also limited to one class per pixel, resulting in pixels with multiple vegetation classes being classified as the dominant vegetation class (e.g. areas where saltmarsh and mangroves are both present; patchy seagrass within unvegetated areas). Running finer-scale habitat mapping analysis (e.g. at individual estuaries) would reduce mapping error and should be considered when making management decisions that may be sensitive to finer-scale error, for example, to map change in blue carbon habitat distributions through time within an estuary of interest.

Land Tenure. The land tenure and carbon rights of any potential restoration projects will be important, and the results of this study showed that the current areas of restoration opportunity are mostly privately owned in all Regional Council areas. At present, land tenure under the high tide mark is heavily contested in Aotearoa (see Marine and Coastal Area [Takutai Moana] Act 2011) and it is not clear what the implications of land tenure would be under a tidal restoration scenario. Under the Marine and Coastal Area (Takutai Moana) (MACA) Act (2011), ownership of the foreshore is not possible (Stewart-Sinclair et al. 2024).

This paper summarizes the extent of blue carbon habitats in Aotearoa and estimates the total carbon storage these represent at a regional scale. Areas of restoration opportunity for blue carbon projects were identified, and the associated carbon sequestration potential of these areas was estimated. The scale of blue carbon abatement and opportunity for a blue carbon restoration in Aotearoa was quantified in order to inform strategic decision-making that incorporates spatially explicit considerations regarding both the location of the restoration opportunity as well as the current land use type to maximize the likelihood of restoration success.

Logical next steps to further progress this research include the following: (1) Sea Level Rise (SLR) and climate change are going to drive significant changes to blue carbon habitats, including changing the area suitable for restoration (and the value of alternative land uses within the coastal zone). Quantifying the impact of SLR on blue carbon restoration actions will empower management decisions which account for its potential impacts; (2) carbon sequestration is one important ecosystem service provided by coastal habitats but there are other ecosystem services, functions, and values (co-benefits) associated with restoration projects which if identified and appropriately quantified will improve the value of blue carbon projects; and (3) Future research will help to improve our understanding of how carbon sequestration varies between and within blue carbon habitats (including within unvegetated habitats), which can be used to create a standardized methodology for estimating the net abatement of a blue carbon project in Aotearoa.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Further details on methodology.
Table S1. Tidal ranges based on average 2022 tides for each region in NZ and conversion to NZVD 2016 from local vertical datums.
Table S2. Estuarine habitat classification accuracy assessment scores.
Table S3. Land uses and spatial extent of blue carbon opportunity in Northland.
Table S4. Area and land tenure of blue carbon opportunity for Northland.
Table S5. Land uses and spatial extent of blue carbon opportunity in Auckland.
Table S6. Area and land tenure of blue carbon opportunity for Auckland.
Table S7. Land uses and spatial extent of blue carbon opportunity in Waikato.
Table S8. Area and land tenure of blue carbon opportunity for Waikato.
Table S9. Land uses and spatial extent of blue carbon opportunity in the Bay of Plenty.
Table S10. Area and land tenure of blue carbon opportunity for Bay of Plenty.
Table S11. Land uses and spatial extent of blue carbon opportunity in Gisborne.
Table S12. Area and land tenure of blue carbon opportunity for Gisborne.
Table S13. Land uses and spatial extent of blue carbon opportunity in Taranaki.
Table S14. Area and land tenure of blue carbon opportunity for Taranaki.
Table S15. Land uses and spatial extent of blue carbon opportunity in Manawatū-Whanganui.
Table S16. Area and land tenure of blue carbon opportunity for Manawatū-Whanganui.
Table S17. Land uses and spatial extent of blue carbon opportunity in Hawke's Bay.
Table S18. Area and land tenure of blue carbon opportunity for Hawke's Bay.
Table S19. Land uses and spatial extent of blue carbon opportunity in Wellington.
Table S20. Area and land tenure of blue carbon opportunity for Wellington.
Table S21. Land uses and spatial extent of blue carbon opportunity in Tasman.
Table S22. Area and land tenure of blue carbon opportunity for Tasman.
Table S23. Land uses and spatial extent of blue carbon opportunity in Nelso.
Table S24. Area and land tenure of blue carbon opportunity for Nelson.
Table S25. Land uses and spatial extent of blue carbon opportunity in Marlborough.
Table S26. Area and land tenure of blue carbon opportunity for Marlborough.
Table S27. Land uses and spatial extent of blue carbon opportunity in West Coast.
Table S28. Area and land tenure of blue carbon opportunity for West Coast.
Table S29. Land uses and spatial extent of blue carbon opportunity in Canterbury.
Table S30. Area and land tenure of blue carbon opportunity for Canterbury.
Table S31. Land uses and spatial extent of blue carbon opportunity in Otago.
Table S32. Area and land tenure of blue carbon opportunity for Otago.
Table S33. Land uses and spatial extent of blue carbon opportunity in Southland.
Table S34. Area and land tenure of blue carbon opportunity for Southland.

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