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BLUE CARBON HABITATS IN THE OTAGO REGION

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Prepared for Otago Regional Council

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EXECUTIVE SUMMARY

Marine and coastal ecosystems contain a myriad of important habitats, many of which can sequester and store carbon in their sediments and biomass, and assist in mitigating global climate change. The capacity of these marine and coastal habitats to capture and store carbon is termed blue carbon. Blue carbon habitats include coastal wetlands (salt marshes, seagrass meadows and mangrove forests) and unvegetated soft sediments. Many of these habitats provide a critical role in protecting coastlines from storm damage, providing nursery grounds, improving water quality and supporting rich biodiversity. They are naturally occurring coastal marine systems, and with increased efforts towards climate change mitigation, blue carbon ecosystems have become a hotspot for nature-based solutions.

The Otago Region has 22 hydrosystems / estuaries, many of which contain blue carbon habitats. Otago Regional Council (ORC) has commissioned Cawthron Institute (Cawthron) to identify and summarise the extent of blue carbon habitats across the Otago Region. In addition, ORC requested that Cawthron investigate historical data to determine loss of blue carbon habitats, and to estimate current blue carbon stock (current area of blue carbon habitat encompassing both above- and below-ground carbon pools) and sequestration rates.

This report reviewed 16 estuaries for which blue carbon habitat information was available: Catlins Estuary, Blueskin Bay Estuary, Papanui Inlet / Makahoe Estuary, Pleasant River Estuary, Waikouaiti River Estuary, Pūrākaunui Inlet Estuary, Tautuku Estuary, Tokomairiro River Estuary, Akatore Inlet Estuary, Shag Estuary, Kaikorai Estuary, Tahakopa River Estuary, Hoopers Inlet Estuary, Waipati Estuary, Kakanui Estuary and Otago Harbour. There are a further six coastal hydrosystems where blue carbon data are currently unavailable.

The current study found that unvegetated intertidal sediments and saltmarsh habitats were present in all 16 estuaries, covering a total area of 524 ha[1] and 2,182 ha,[2] respectively. Seagrass was present in seven estuaries, covering a total area of 197 ha.[1] Catlins Estuary contained the greatest extent of blue carbon habitats (653 ha), which was dominated by unvegetated intertidal soft sediments. Kakanui Estuary had the smallest extent of blue carbon habitats (1.1 ha), with very little unvegetated intertidal soft sediments or salt marsh, and no presence of seagrass. Overall, there has been a 61% loss of salt marsh in the Otago Region. Currently, there is no information available to quantify the extent of the region's seagrass loss. It is possible that seagrass has been lost from some estuaries, whereas for others it may have never been present.

Blue carbon stocks and sequestration rates were estimated for all 16 estuaries and were calculated based on previously estimated values from within Aotearoa New Zealand. Overall, estuaries within the Otago Region store an estimated 96,414 tonnes of carbon (tC), with the highest proportion stored within unvegetated intertidal soft sediments (56,725 tC), followed

[1] Saltmarsh and seagrass data are incomplete for Otago Harbour.
[2] Unvegetated intertidal soft sediment data are incomplete for Otago Harbour and absent for Hoopers Inlet.

by salt marsh (34,134 tC) and seagrass (5,556 tC). Catlins Estuary had the highest carbon stock estimates, which ranged from 16,752 tC to 17,376 tC. For sequestration rates, the lower and upper estimate within salt marshes was 659 tCO_2/ha/yr and 1,366 tCO_2/ha/yr, respectively, while sequestration rates were unavailable for seagrass and unvegetated soft sediments.

All 16 estuaries in the Otago Region contained blue carbon habitats, but losses of salt marsh (and possibly seagrass) have occurred, reducing their ability to sequester and store carbon. As such, protection and restoration of these important habitats is critical. We provide a high-level summary of approaches for protection and restoration of these habitats. We recommend conducting broadscale surveys for the estuaries in the Otago Region that have incomplete blue carbon habitat extent information (six unmapped coastal hydrosystems / estuaries, plus Otago Harbour and Hoopers Inlet). We also recommend collecting blue carbon sediment data from the Otago Region to provide more accurate blue carbon stock and sequestration rates values. Protection for the existing habitats and regular monitoring to identify any threats or losses to these habitats will be critical. Furthermore, we suggest that sea-level rise assessments are undertaken for individual estuaries to ensure restoration plans are viable long term. Decision-making frameworks and ongoing monitoring will be critical to help guide decisions for protection and / or restoration of these important habitats.

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1. INTRODUCTION

1.1. Overview and scope

The Otago Region has 22 coastal hydrosystems / estuaries, including beach streams, tidal river mouths, tidal lagoons and deep drowned valleys (Hume et al. 2016). Many of these estuaries contain 'blue carbon' habitats, which are naturally occurring coastal marine systems that can store carbon in their sediments and biomass (Lovelock and Reef 2020). Blue carbon habitats include salt marshes, seagrass meadows, mangrove forests and unvegetated soft sediments (Hamilton et al. 2020; Macreadie et al. 2021). Information on the extent of these blue carbon habitats is available for 16 estuaries in the Otago Region. Otago Regional Council (ORC) has requested that Cawthron Institute (Cawthron) review the existing available information to:

- identify and summarise the extent of blue carbon habitats across the Otago Region
- identify any historical data to summarise the habitat area loss of the identified blue carbon habitats
- estimate current blue carbon stocks (stored carbon pools above- and below-ground) and carbon sequestration rates.

This report also provides background information on the benefits and vulnerability of blue carbon habitats and recommendations for protecting and restoring these habitats within the Otago Region. We believe this information will serve as a valuable resource to inform management decisions associated with blue carbon habitats.

1.2. Significance of blue carbon habitats

Chronic and increasing anthropogenic greenhouse gas emissions (GHG) emissions contribute significantly to global change (Pendleton et al. 2012). Worldwide, ecosystems and people are negatively impacted by this global climate change, with coastal and marine ecosystems and communities particularly vulnerable to these effects (Doney et al. 2012; Gattuso et al. 2015). To limit future climate change impacts, it is critical that there is a focus on reducing anthropogenic CO_2 emissions. However, there is also emerging interest in identifying and understanding the potential of naturally occurring ecosystems, such as blue carbon habitats, to mitigate climate change through sequestration.

Coastal wetlands (mangroves, salt marsh and seagrass) are ecologically important ecosystems that play a critical role in mitigating global climate change (Howard et al. 2014; Cooley et al. 2022). These blue carbon habitats are known for their carbon sequestration capabilities (Otero 2021), making them a hotspot for nature-based solutions.[3] Salt marsh (Figure 1A) is vegetation found in the upper intertidal reaches of coastal areas. Seagrass (Figure 1B) is a marine flowering plant found growing on tidal flats and deeper parts of coastal systems. Mangroves (Figure 1C) are trees or shrubs that grow primarily in coastal water that is saline or brackish. These habitats sequester a large proportion of their carbon in the sediments of the ground (or sea floor) beneath them, rather than in above-ground biomass such as their leaves (McLeod et al. 2011). Carbon is also stored in unvegetated soft sediment habitats (e.g. mudflats / sandflats; Figure 1D). Although they often have lower carbon stocks per area compared to coastal wetlands, unvegetated soft sediments can cover a large area and thus play an important role in carbon storage overall (Bulmer et al. 2020; Hamilton et al. 2020).

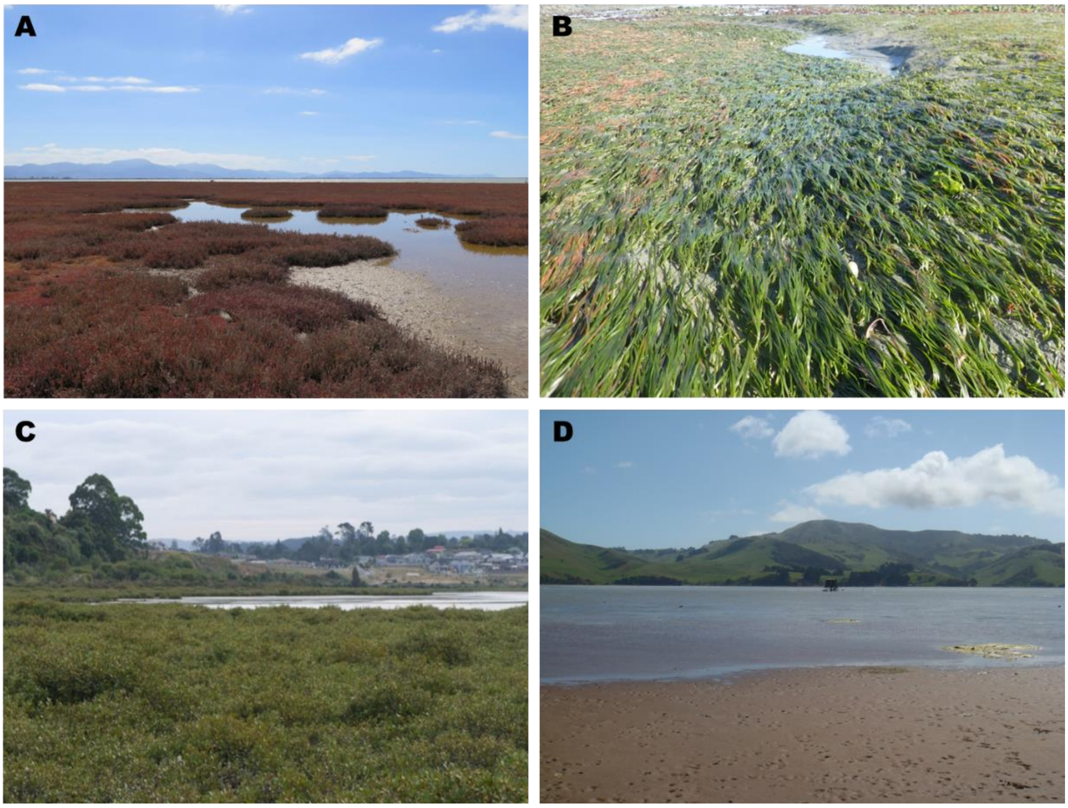

Figure 1. Photographs of the various blue carbon habitats in Aotearoa New Zealand. A) saltmarsh habitat in Wairau Lagoon, Marlborough (Photo: Anna Berthelsen, Cawthron), B) seagrass meadow from the Nelson Region (Photo: Cawthron), C) mangroves in Tauranga Harbour (Photo: Noel Peterson), D) a mudflat on Otago Peninsula (Photo: Dana Clark, Cawthron).

In addition to sequestering carbon, coastal wetlands provide several other co-benefits for people and the environment. Biodiversity is enhanced by providing a place for animals, such as invertebrates, birds and fish, to live, shelter and / or forage for food

3 Nature-based solutions address socio-environmental challenges through sustainable management and use of natural features and processes.

(Howard et al. 2014; Turner and Schwarz 2006). Coastal wetlands improve water quality by trapping sediments and nutrients and stabilising the seabed (Turner and Schwarz 2006; Thomsen et al. 2009), and they can protect land and people that are vulnerable to risk of coastal flooding (Van Coppenolle and Temmerman 2020). Moreover, many of these habitats are culturally significant to Māori (Crawshaw and Fox 2022). Although unvegetated soft sediments do not provide the same full suite of co-benefits as coastal wetlands, they are important for biodiversity, coastal productivity and processing contaminants from the land (Thrush et al. 2013). Collectively, blue carbon habitats provide a natural climate solution with a range of co-benefits, leading to recent efforts for better recognition, protection and restoration.

In Aotearoa New Zealand, many coastal wetland habitats have been degraded and / or lost altogether (Turner and Schwarz 2006; Denyer and Peters 2020). This change reduces their ability to sequester and store carbon and can lead to an increase in the release of previously stored carbon back into the atmosphere through GHG emissions (Macreadie et al. 2013; Kroeger et al. 2017). Therefore, the conservation and restoration of these habitats is critical to maintain and increase carbon sequestration and other co-benefits for marine ecosystems and people.

2. BLUE CARBON EXTENT AND LOSS

2.1. Blue carbon habitats in the Otago Region

The Otago Region contains numerous estuaries with various blue carbon habitats. Below we briefly describe existing blue carbon habitats based on information from broadscale habitat mapping reports. These reports quantify the extent of key habitats using aerial imagery combined with ground-truthing. Our focus is on three blue carbon habitats: 1) seagrass[4] (*Zostera muelleri*) meadows, 2) salt marsh (relating to a number of different plant habitat types characterised by certain species including key types: herbfield, rushland, estuarine shrub, sedgeland, tussockland and grassland), and 3) unvegetated intertidal soft sediments. For unvegetated soft sediments, all mud and / or sand substrate categories (e.g. sandy mud, soft mud) recorded for an estuary were summed together. Although our focus was on intertidal areas, subtidal habitats, including soft sediments and seagrass meadows, also store carbon. However, quantifying subtidal carbon storage for the Otago Region was beyond the scope of this report. Mangroves were not included in our summary, as they are not present in the Otago Region. Recorded historical losses of salt marsh and seagrass meadows were also summarised, along with the general state of health of each estuary.

Information on blue carbon habitats was available for the following 16 estuaries (Figure 2): Catlins Estuary, Blueskin Bay Estuary, Papanui Inlet / Makahoe Estuary, Pleasant River Estuary, Waikouaiti River Estuary, Pūrākaunui Inlet Estuary, Tautuku Estuary, Tokomairiro River Estuary, Akatore Inlet Estuary, Shag Estuary, Kaikorai Estuary, Tahakopa River Estuary, Hoopers Inlet Estuary, Waipati Estuary, Kakanui Estuary and Otago Harbour. There are a further six coastal hydrosystems where blue carbon data are currently unavailable: Orore Creek, Stony Creek, Waikouaiti Lagoon, Tomahawk Lagoon, Taieri River, Clutha River.

[4] In Aotearoa New Zealand, this species was previously named *Zostera capricorni* or *Z. novaezelandiae*; it is commonly referred to as eelgrass, karepō, nana, rehia and rimurehia.

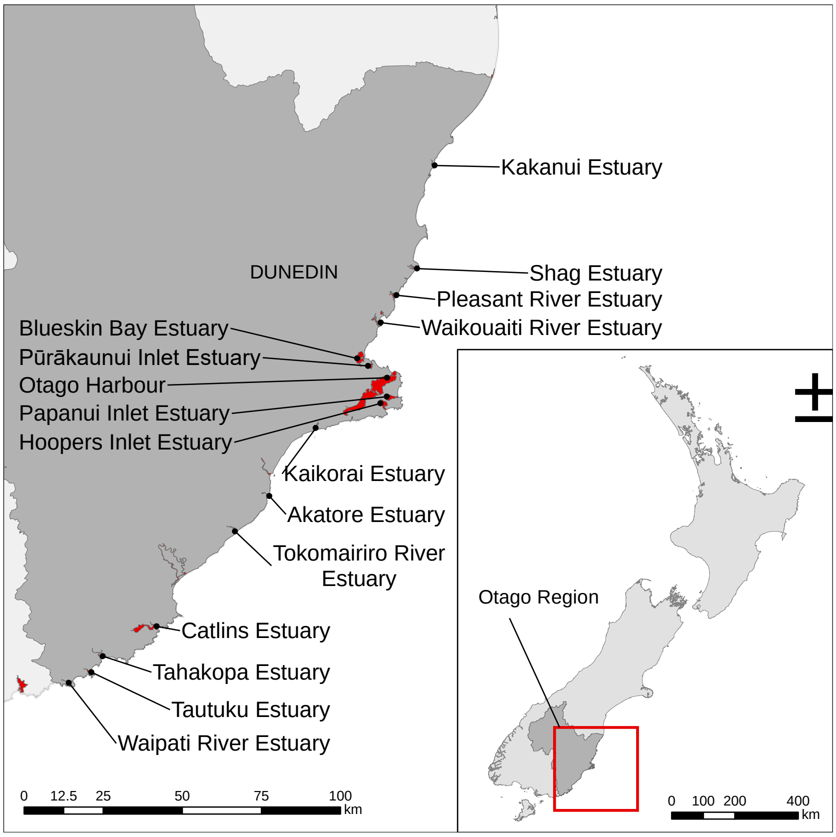

Figure 2. Location of the 16 estuaries in the Otago Region reviewed in this report.

2.1.1. Catlins Estuary

Catlins Estuary was last mapped in 2016 (Stevens and Robertson 2017a), with 12.1 ha of the 830 ha estuary comprising salt marsh (1.5% of the estuary), 610.3 ha comprising unvegetated intertidal soft sediments (73.5% of the estuary) and 30.3 ha comprising seagrass (3.7% of the estuary). Seagrass may have been more extensive historically, but no estimate of the historical extent is available. Stevens and Robertson (2017a) estimated that there has been more than 300 ha (approximately 96%) of salt marsh loss since 1850. Overall, the estuary was rated as being in a moderate state in the broadscale report, and excessive sedimentation and eutrophication were highlighted as the main concerns regarding ecosystem health.

2.1.2. Blueskin Bay Estuary

Blueskin Bay Estuary was last mapped in 2021 by Roberts et al. (2021a), with 35.4 ha of the 690 ha estuary comprising salt marsh (5.2% of the estuary), 536.8 ha comprising unvegetated intertidal soft sediments (77.8% of the estuary) and 33.5 ha comprising seagrass (3.8% of the estuary). Although the historical extent of salt marsh and seagrass has not been formally mapped, historical imagery from 1956 shows seagrass beds in relatively the same area as current maps. Aside from one patch that has reduced in size, it is estimated that 50% of the historical saltmarsh extent remains (a loss of approximately 35 ha). Overall, Blueskin Bay Estuary was rated as being in good health (Roberts et al. 2021a).

2.1.3. Papanui Inlet / Makahoe Estuary

Papanui Inlet Estuary was last mapped in 2021 (Roberts et al. 2022a), with 12.9 ha of the 378 ha estuary comprising salt marsh (3.4% of the estuary) and 248.5 ha comprising unvegetated intertidal soft sediments (75.3% of the estuary). There were also extensive seagrass beds, which covered 111.1 ha (29.4% of the estuary). It is estimated that seagrass extent increased between 1958 and 1985, when it covered 60–70 ha[5] of the estuary; however, the seagrass meadows may have declined slightly from their peak cover of 135 ha[3] in 2000, as well as shifted over time (Roberts et al. 2022a). Salt marsh had a historical loss of 6 ha (30%), although the time frame for this loss was not reported. Overall, Roberts et al. (2022a) rated the estuary as being in very good condition; however, the authors noted that the seagrass beds were vulnerable to waterfowl grazing and vehicle damage, and the salt marsh is susceptible to localised erosion of herbfields.

2.1.4. Pleasant River Estuary

Pleasant River Estuary was last mapped in 2021 (Roberts et al. 2022b), with 80.4 ha of the 216 ha estuary comprising salt marsh (37.2% of the estuary) and 184.5 ha comprising unvegetated intertidal soft sediments (85.4% of the estuary). There was no seagrass recorded in the broadscale survey, and it is unknown if seagrass has grown in the estuary historically. However, a small patch (less than 0.5 ha) of seagrass was observed in the lower estuary during a fine-scale survey (pers. comm. Keryn Roberts, Salt Ecology), suggesting seagrass may have been more abundant in the past. Historically, saltmarsh cover was about 128 ha, indicating that only 63% of the natural extent remains (a loss of approximately 48 ha). Overall, Pleasant River Estuary was determined to be in poor condition (Roberts et al. 2022b). Due to the high mud content, many of the sediments are poorly oxygenated, which makes this estuary vulnerable to excess sedimentation, eutrophication and the proliferation of opportunistic macroalgae.

2.1.5. Waikouaiti River Estuary

Waikouaiti River Estuary was last mapped in 2017 (Stevens and Robertson 2017b), with 80.3 ha of the 229 ha estuary comprising salt marsh (35.1% of the estuary), 92.8 ha comprising unvegetated intertidal soft sediments (40.5% of the estuary) and 1.7 ha comprising seagrass (0.7% of the estuary). Previous reporting estimated that the area of salt marsh was 111 ha in 2006, indicating about 31 ha of area has been lost in the past 10 years (Stewart 2007). Historically, there has been about 150 ha (approximately 65%) of overall salt marsh loss (Stevens and Robertson 2017b), and

[5] Includes subtidal seagrass meadows and only seagrass >50% cover.

the historical extent of seagrass is unknown (historical images have not been reviewed). Overall, Stevens and Robertson (2017b) rated the estuary as being in moderate condition and noted that it is vulnerable to excessive sedimentation and eutrophication.

2.1.6. Pūrākaunui Inlet Estuary

Pūrākaunui Inlet Estuary was last mapped in 2022 (Stevens et al. 2023), with 23.6 ha of the 103 ha estuary comprising salt marsh (22.9% of the estuary) and 118 ha comprising unvegetated intertidal soft sediments (90.8% of the estuary). There was no seagrass present in 2022, and images from 1956 suggest seagrass likely was not present in Pūrākaunui Inlet Estuary in the past. Historical records indicate a decline of 24% in saltmarsh extent since 1956 (a loss of approximately 7 ha). Overall, the estuary was rated to be in good to very good condition but may be vulnerable to catchment-derived sediment inputs and saltmarsh losses (Stevens et al. 2023).

2.1.7. Tautuku Estuary

Tautuku Estuary was last mapped in 2021 (Roberts et al. 2022c), with 34.4 ha of the 94 ha estuary comprising salt marsh (36.5% of the estuary) and 79.6 ha comprising unvegetated intertidal soft sediments (84.7% of the estuary). There was no seagrass present in the 2021 survey. Seagrass is unlikely to have been present in the past, as the freshwater inputs to this estuary are very tannin-rich (low salinity and light could inhibit growth), and there are limited suitable intertidal flats on which it could grow (i.e. highly mobile mid to lower estuary; Roberts et al. 2022c). Salt marsh had a historical loss of 2 ha (5%); however, the time frame for this loss was not reported. Overall, the estuary was rated to be in very good condition (Roberts et al. 2022c).

2.1.8. Tokomairiro River Estuary

Tokomairiro River Estuary was last mapped in 2018 (Stevens 2018a), with 57 ha of the 150 ha estuary comprising salt marsh (37.9% of the estuary), 39.4 ha comprising unvegetated intertidal soft sediments (26.3% of the estuary), and very little seagrass recorded (20 m^2; 0.002 ha). The historical cover of seagrass within the estuary is unknown because historical images that potentially document changes in seagrass cover have not been reviewed. It is estimated that there has been a historical loss of about 95 ha (63%) of salt marsh due to reclamation and drainage. Overall, the condition of Tokomairiro Estuary was rated to be moderate, with susceptibility to excess sedimentation and eutrophication noted (Stevens 2018b).

2.1.9. Akatore Estuary

Akatore Estuary was last mapped in 2021 (Roberts et al. 2022d), with 26.9 ha of the 69 ha estuary comprising salt marsh (39% of the estuary), 58 ha comprising unvegetated intertidal soft sediments (84.1% of the estuary). Seagrass was not present in 2001 or in historical imagery, and it is unknown if seagrass has ever grown in Akatore Estuary. However, the estuary was significantly modified in the earliest available imagery (Roberts et al. 2022d), thus historical loss may have already occurred. It is estimated that 70% of the historical saltmarsh extent remains (a loss of approximately 12 ha) and overall, Akatore Estuary was rated as being in good to very good health (Roberts et al. 2022d).

2.1.10. Shag Estuary

Shag Estuary was last mapped in 2016 (Stevens and Robertson 2017c), with 46.3 ha of the 120 ha estuary comprising salt marsh (38.5% of the estuary area) and 37.6 ha comprising unvegetated intertidal soft sediments (31.3% of the estuary). Seagrass was not present in 2016, and it is unknown if seagrass has grown in the estuary historically. A reported 60 ha (56%) of salt marsh has been lost, with 33 ha of this loss occurring since 2006. Overall, the estuary was rated as being in a moderate state and was considered to be vulnerable to eutrophication and excessive sedimentation (Stevens and Robertson 2017c). It is also likely that historical habitat modification has affected habitat health.

2.1.11. Kaikorai Estuary

Kaikorai Estuary was last mapped in 2018 (Stevens 2018b), with 33.8 ha of the 94 ha comprising salt marsh (35.9% of the estuary) and 46.6 ha comprising unvegetated intertidal soft sediments (49.6% of the estuary). Seagrass was not present in the habitat mapping undertaken in 2018 or 2000 (Robertson et al. 2002). It is unknown whether seagrass has grown in this estuary historically. However, conditions are not favourable for seagrass growth because the entrance to the estuary is restricted or closes for extended periods of time (pers. comm. Keryn Roberts, Salt Ecology). It was reported that about 100 ha (approximately 75%) of salt marsh has been lost, but the time frame for this loss was not provided. Overall, the estuary was rated as being in moderate condition in 2018 and was vulnerable to excessive muddiness, eutrophication and poor sediment oxygenation (Stevens 2018b).

2.1.12. Tahakopa / Papatowai Estuary

Tahakopa / Papatowai Estuary was last mapped in 2022, and the report is still in preparation (Roberts et al. 2023 [forthcoming]). Preliminary estimates indicate that 17.7 ha of the 120 ha estuary comprise salt marsh (14.8% of the estuary) and 42.9 ha comprise unvegetated intertidal soft sediments (35.8% of the estuary). There is no previous record of seagrass, including in 2022, and it is unlikely seagrass ever grew in this estuary due to the tannin-rich freshwater inputs (low salinity and light could inhibit growth) and the limited suitable intertidal flats on which it could grow (i.e. highly mobile mid to lower estuary). It is estimated that more than 80% of the historical saltmarsh extent remains, with only a relatively small decline (approximately 9%) in saltmarsh cover since 1948 (a loss of approximately 2 ha; Roberts et al. 2023 [forthcoming]). Overall, the estuary was rated to be in a healthy state but was vulnerable to ongoing catchment-derived inputs and nutrients (Roberts et al. 2023 [forthcoming]).

2.1.13. Hoopers Inlet Estuary

Hoopers Inlet Estuary was last mapped in 2022, and the report is still in preparation (Roberts 2023 [forthcoming]). Preliminary estimates of the current saltmarsh extent are 58.8 ha (13.5%) of the 437 ha estuary, with 85% of the historical salt marsh remaining (a loss of approximately 10 ha). The extent of seagrass and unvegetated intertidal soft sediments were not quantified because the tidal flats did not completely drain due to the restricted entrance of this estuary. Although seagrass extent was not mapped, seagrass was observed in 2022 (estimated > 20 ha) and has been present (estimated to be between 10 ha and 40 ha) since at least 1942 (pers. comm., Keryn Roberts, Salt Ecology). The salt marsh was rated in good to very good condition but was vulnerable to stock, vehicles and reclamation (Roberts 2023 [forthcoming]).

2.1.14. Waipati River Estuary

Waipati River Estuary was last mapped in 2022 (Forrest et al. 2023), with 5 ha of the 68 ha estuary comprising salt marsh (7.4% of the estuary) and 49.7 ha comprising unvegetated intertidal soft sediments (73.1% of the estuary). There was no seagrass present in 2022, and it is unlikely that seagrass ever grew in the estuary due to the tannin-rich freshwater inputs (low salinity and light could inhibit growth). The earliest historical imagery showed about 6.5 ha of salt marsh in 1948, equating to a decline of approximately 25% over the last 75 years (a loss of approximately 1.5 ha). Overall, the estuary was considered to be in a healthy state but was vulnerable to catchment-derived muddy sediment inputs (Forrest et al. 2023).

2.1.15. Kakanui Estuary

Kakanui Estuary was last mapped in 2021 (Roberts et al. 2021b), with 0.4 ha of the 25 ha estuary comprising salt marsh (0.16% of the estuary) and 1.03 ha comprising unvegetated intertidal soft sediments (0.04% of the estuary). There was no seagrass present in 2021, and it is unknown if seagrass ever grew within this estuary. A 2009 survey indicated an apparent loss of salt marsh (Stewart and Bywater 2009); however, given the sparse patches of salt marsh present, this loss was considered negligible. There is no available record of the historical extent of salt marsh in Kakanui Estuary. Overall, the estuary was considered to be in good health; however, studies in 2013 and 2015 highlighted concerns regarding the proliferation of *Ulva* spp. and the deterioration in estuary health (Roberts et al. 2021b). Along with algal proliferation, the estuary is also vulnerable to eutrophication, particularly when there is a reduction in flushing time.

2.1.16. Otago Harbour

There is limited information on the extent of blue carbon habitats in Otago Harbour, although salt marsh, seagrass and unvegetated intertidal soft sediments are known to be present in this area (e.g. e3Scientific 2022). There are some estimates of seagrass cover within this region that are based on a survey of Te Rauone Beach. This survey reports approximately 9.1 ha of seagrass cover in 2018 (Tait et al. 2020), but the cover of seagrass for the whole harbour has not been reported. ORC has documented the size of the Aramoana salt marsh (74.5 ha; ORC 2020); however, this estimate includes flax-dominated swamp areas, which likely contribute to an overestimate of the blue carbon habitat in this particular location. Historical images show evidence of salt marshes in 1956, but their total area was not quantified (King 2022).

2.2. Summary of current extent and loss of blue carbon habitats

Figure 3 illustrates the current extent (hectare; ha) of blue carbon habitats (unvegetated intertidal soft sediments, seagrass and salt marsh) in each estuary based on the most recent mapping. Otago Harbour is not included in Figure 3 because these values were incomplete, and Hoopers Inlet did not have any area value for unvegetated sediments. Salt marsh was present in all estuaries, with the greatest extent in Waikouaiti and Pleasant River. Seagrass was only found in seven of the 16 estuaries (refer to Table 1 for values), with the most extensive seagrass cover in Papanui Inlet (111.1 ha) and smallest extent in Tokomariro Estuary (0.002 ha). Catlins Estuary contained the greatest extent of blue carbon habitats, which were dominated by unvegetated intertidal soft sediments. Kakanui Estuary had the smallest extent of blue carbon habitats, with very little unvegetated intertidal soft sediments or salt marsh and no seagrass present.

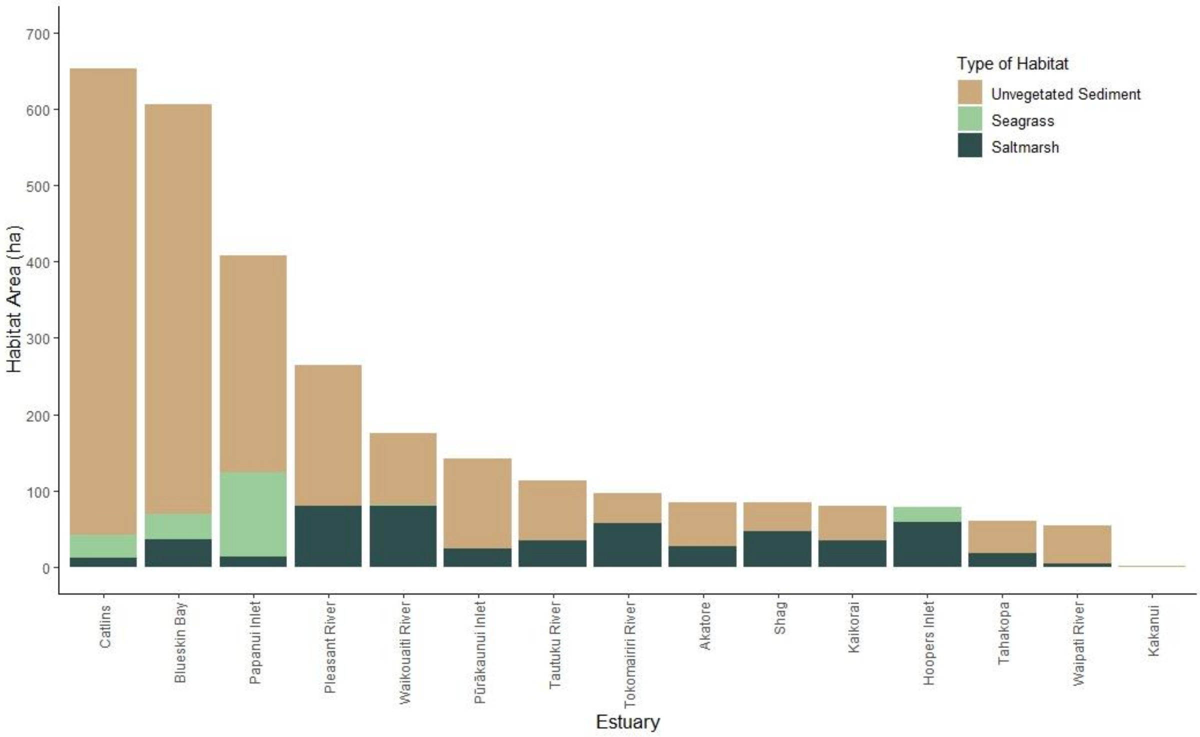

Figure 3. Total area of intertidal blue carbon habitats for 15 estuaries from the Otago Region. Extent is based on the most recent values from broadscale habitat mapping. The habitats are salt marsh (dark slate grey), seagrass (light green) and unvegetated intertidal soft sediments (light brown) plotted within each estuary. Seagrass value for Hoopers Inlet is a preliminary estimate and no area value was available for unvegetated sediments. Values for Otago Harbour were incomplete and are not shown. Seagrass extent was often only provided for seagrass above a certain percentage cover, e.g. 20% or 50% – refer to broadscale monitoring reports for further details.

Table 1 summarises the current extent of salt marsh, seagrass and unvegetated intertidal soft sediments in each estuary. It also includes the most up-to-date estimated area of loss for saltmarsh cover, given as a percentage value. Estimated loss of salt marsh (%) was calculated by dividing the area of lost salt marsh (ha) by the historical saltmarsh extent (ha) and multiplying by 100. Overall, 61% of salt marsh has been lost in the region, and this is mainly attributed to reclamation, drainage and habitat modification. There is little information on historical seagrass extent and no information to quantify historical loss. Seagrass was possibly more extensive historically in the Catlins Estuary and the Waikouaiti River Estuary, but no historical images have been reviewed to describe these changes. There is evidence of a small amount of change in seagrass cover in Blueskin Bay, and Papanui Inlet has always had extensive seagrass meadows (refer to 2.1.3). It is likely some estuaries (Tautuku, Kaikorai, Tahakopa, Waipati, Kakanui) have never had seagrass cover.

Table 1. Summary of the most recent reported areas of salt marsh, seagrass and unvegetated intertidal soft sediments for 16 estuaries in the Otago Region. Values are provided as hectares (ha) for all three habitats. The estimated loss of saltmarsh areas (%) are in brackets and the symbols indicate the method used to determine estimate loss; † indicates estimates from expert opinions provided in reports and Δ indicates estimates from LiDAR / aerial imagery. The limited historical information for seagrass is included in the brackets.

Estuary	**Existing saltmarsh area (ha); [% of estimated loss]**	**Existing seagrass area (ha)*; [any historical information]**	**Existing unvegetated intertidal soft sediments area (ha)**
Catlins	12.1 [96% loss†]	30.3 [historical extent unknown]	610.3
Blueskin Bay	35.4 [50% loss†]	33.5 [little historical change since 1956]	536.8
Papanui Inlet	12.9 [32 loss Δ]	111.1 [extent increased since 1958]	284.5
Pleasant River	80.4 [37% loss Δ]	0 [unknown if present historically]	184.5
Waikouaiti River	80.3 [65% loss†]	1.7 [historical extent unknown]	92.8
Pūrākaunui Inlet	23.6 [24% loss Δ]	0 [unknown if present historically]	118
Tautuku River	34.3 [5% loss†]	0 [unlikely to have been present historically]	79.6
Tokomairiri River	56.8 [63% loss†]	0.002 * [historical extent unknown]	39.4
Akatore	26.9 [31% loss †]	0 [unknown if present historically]	58
Shag	46.3 [56% loss†]	0 [unknown if present historically]	37.6
Kaikorai	33.8 [75% loss†]	0 [unlikely to have been present historically]	46.6
Tahakopa River	17.7 [10% loss Δ]	0 [unlikely to have been present historically]	42.9
Hoopers Inlet	58.8 [15% loss Δ]	20 [present since at least 1942]	no data

Estuary	**Existing saltmarsh area (ha); [% of estimated loss]**	**Existing seagrass area (ha)*; [any historical information]**	**Existing unvegetated intertidal soft sediments area (ha)**
Waipati River	5 [23% loss Δ]	0 [unlikely to have been present historically]	49.7
Kakanui	0.04 [unknown]	0 [unlikely to have been present historically]	1.03
Otago Harbour	74.5** [unknown]	9.2*** [historical extent unknown]	no data
Total	**524.3 ha [~61% loss]**	**196.6 ha**	**2,181.7 ha**

* For some estuaries, the seagrass area only includes seagrass cover that is 20% or 50% (or more) of the substrate – see associated monitoring reports for more detail. The overall area of seagrass may therefore be higher than reported.
** Estimated area is for one location (i.e. Aramoana) and does not cover all the saltmarsh sites in the harbour. The estimated area also includes flax-dominated swamp and therefore may be an overestimate of blue carbon associated with this particular wetland (ORC 2020).
*** Estimated area likely does not cover all the seagrass in the harbour.

3. BLUE CARBON STOCKS AND SEQUESTRATION RATE

3.1. Estimating carbon stocks and sequestration rate

We estimated blue carbon stocks and sequestration rates for 16 Otago estuaries based on the most recent recorded extent values for existing habitats (i.e. salt marsh, seagrass and unvegetated intertidal soft sediments). Blue carbon stocks encompass both above- and below-ground carbon pools. Above-ground pools relate to live biomass or vegetation found above the ground, e.g. plant leaves and stems. Below-ground carbon pools consist of live biomass found below the ground, e.g. roots, soil and litter / deadwood. Blue carbon habitats primarily sequester carbon in below-ground carbon pools (McLeod et al. 2011; Bulmer et al. 2020), which can represent more stable (i.e. longer term) sequestration compared to above-ground pools. As such, below-ground carbon is the primary focus for our carbon stock and sequestration rate estimates. It was outside our scope to estimate greenhouse gas (GHG) emissions, which can occur for all three blue carbon habitats in our study, especially if they are degraded (Hamilton et al. 2020; Kroeger et al. 2017).

To our knowledge, carbon stock and sequestration rate data are currently unavailable for blue carbon habitats for the Otago Region. Therefore, to estimate the region's blue carbon stocks and sequestration rates, we used previously estimated data from other regions around Aotearoa New Zealand as a proxy where available (derived from the literature). The proxy blue carbon values used were:

- Salt marsh: the lower and upper values were 38–57 tC/ha, respectively, for below-ground biomass. These values represent the range between means used by Ross et al. (2023) for a preliminary estimate of blue carbon stocks for Aotearoa New Zealand. The values are based on a study by Albot et al. (2023 [in prep.]) across three North Island sites at varying sediment depths and a study by Berthelsen et al. (2023) at Waimea Inlet (Tasman Region) to a 40 cm sediment depth.
- Seagrass: the lower and upper values were 14–27 tC/ha, respectively, for below- and above-ground[6] carbon pools. These values represent the range between means used by Ross et al. (2023 [forthcoming]) to estimate blue carbon stocks for Aotearoa New Zealand. The values are based on studies in Tairua Estuary (Coromandel) by Bulmer et al. (2020) and Farewell Spit / Onetahua (Tasman Region) by Berthelsen et al. (2023).
- Unvegetated intertidal soft sediments: this report used a value of 26 tC/ha, based on an average value from the Tairua Estuary study (Bulmer et al. 2020).

[6] In some cases, it was not possible to separate out the above-ground carbon from the below-ground for seagrass habitat. Above-ground carbon is expected to be only a small proportion of the carbon pool (Bulmer et al. 2020).

For the proxy carbon sequestration rate in salt marsh, we used a value of 1.69 ± 0.59 tCO_2/ha/yr[7,8] (as per Ross et al. 2023 [forthcoming]) to calculate lower and upper sequestration rate estimates. The proxy value is preliminary from Albot et al. (2023 [in prep.]) and is based on data collected from Pāuatahanui salt marsh (Wellington Region). The sequestration rate was calculated using historical data (i.e. 1855 formation of Pāuatahanui salt marsh after a magnitude 8.2 earthquake). Carbon sequestration rates are currently unavailable for seagrass habitats and unvegetated intertidal soft sediments in Aotearoa New Zealand. Overseas sequestration rate data for these two habitat types are available, but we used only the NZ-derived proxy values for our study.

To estimate blue carbon stocks and sequestration rates for a given habitat, we multiplied the area of habitat or substrate for each Otago estuary by the proxy carbon stock or sequestration rate value. We also summed carbon stock and sequestration rate estimates overall per estuary and per habitat type (across estuaries).

3.2. Carbon stock and sequestration rate results and discussion

Blue carbon habitats are present in all 16 estuaries in our study (Table 1; Figure 3). There are a further six coastal hydrosystems where blue carbon data are currently unavailable. Overall, we estimated that Otago estuaries (intertidal zone only) store 96,414 tC, with the highest proportion stored by unvegetated intertidal soft sediments (considering caveats around proxy values below), followed by salt marsh and seagrass, respectively. The overall lower and upper estimates for the carbon sequestration rate by salt marsh for all estuaries combined are 659 tCO_2/ha/yr and 1,366 tCO_2/ha/yr, respectively. Carbon stocks can be highly variable within blue carbon habitats (Bulmer et al. 2020) and we assume this is also the case for sequestration. Our calculations provide a general estimate only; they do not consider within-habitat variability or GHG emissions. In addition, the calculations are based on proxy data from other regions in Aotearoa New Zealand (i.e. not from Otago) and are only from certain soil depths. In particular, the unvegetated intertidal soft sediment carbon stock and salt marsh sequestration rate estimates should be used with caution, as they are based on proxy data from only one estuary each (in the North Island). More detailed results are summarised below.

Estuaries with the largest total area of blue carbon habitat within the Otago Region are Catlins Estuary, Blueskin Bay and Papanui Inlet. These three estuaries also had the highest carbon stock estimates, ranging from 16,752 tC to 17,376 tC for Catlins Estuary, 15,771 tC to 16,879 tC for Blueskin Bay and 9,442 tC to 11,132 tC for Papanui Inlet. Notably, these estuaries have the largest areas of soft sediments,

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[7] Carbon was converted to CO_2 by a factor of 3.67.

[8] Based on this, we used a proxy value of 1.1 tCO_2/ha/yr for the lower likely value and 2.28 tCO_2/ha/yr for the upper likely value to account for variation based on standard error.

demonstrating the important role that unvegetated intertidal soft sediments play in storing carbon. Although these unvegetated sediments store less carbon per hectare, they are often larger in total area compared to other blue carbon habitats and, therefore, can store large amounts of carbon overall (Bulmer et al. 2020). It is also important to note that unvegetated intertidal soft substrates, in particular, may rely on subsidies from other blue carbon or terrestrial habitats (Bulmer et al. 2020; Zaiko and Pearman 2022).

If we consider only salt marshes and seagrass (i.e. exclude unvegetated soft sediments), the three estuaries with highest estimated carbon stocks are Waikouaiti River (3,075 tC and 4,623 tC – lower and upper estimate, respectively), Pleasant River (3,055 tC and 4,583 tC) and Hoopers Inlet (2,514 tC and 3,892 tC). Compared to all other estuaries, Waikouaiti and Pleasant River contain the largest area of saltmarsh habitat, followed by Hoopers Inlet. Otago Harbour has the third largest overall area of salt marsh, but this included flax-dominated swamp and is likely to be an overestimate of blue carbon–associated wetland. In terms of seagrass habitat, Waikouaiti River has only a very small area, Pleasant River has none and, based on a preliminary estimate, Hoopers Inlet has 20 ha. Estuaries with the next highest estimated carbon stock are Tokomairiro River (with a relatively large area of salt marsh) and Papanui Inlet (with the largest area of seagrass and moderate salt marsh).

Although not reflected in our estimates, blue carbon stocks can be highly variable within habitats (Bulmer et al. 2020). For example, preliminary results for salt marshes at various North Island sites found that geomorphic setting appeared to strongly influence organic carbon stocks (from Albot et al. 2023 [in prep.]), with fluvially influenced areas of the marshes having higher stocks than areas only subject to marine influence. However, Albot et al. (2023 [in prep.]) found that site differences in saltmarsh soil organic carbon stocks appeared to be independent of the dominant vegetation type. Furthermore, seagrass patches can be dynamic and vary seasonally and between years (Turner and Schwarz 2006); therefore, the ‘existing’ area on which our calculations are based may not necessarily reflect the coverage over long time periods. Knowledge of the ecological history of blue carbon habitats in the Otago estuaries could aid with interpretation of the drivers of soil carbon stocks. Traditional and local knowledge is particularly valuable for understanding longer landscape processes. As mentioned above, carbon in blue carbon habitats often originates from surrounding habitats (Bulmer et al. 2020; Zaiko and Pearman 2022), and thus it is important to consider the wider system, including the mosaic of habitats present.

Historical and more recent losses of salt marsh habitat have been recorded for many Otago estuaries (see Section 2), and seagrass loss also may have occurred at some sites. A likely consequence of these losses is a reduction in carbon sequestration and storage capacity, which could be significant for estuaries with particularly large losses. Carbon stock reduction in degraded (including lost) saltmarsh habitats can occur by release of below-ground carbon through increased GHG emissions (Macreadie et al. 2013; Kroeger et al. 2017). However, we cannot accurately quantify this loss because the fate of the carbon stored in these degraded or lost habitats is unknown (i.e. some carbon stocks may still remain).

Table 2. Estimated carbon stocks and carbon sequestration rates of blue carbon habitats for 16 estuaries in the Otago Region based on the most recent estimates of blue carbon habitat extent. The habitats are salt marsh, seagrass and unvegetated intertidal soft sediments. Refer to report methods for estimate calculations and origin of the carbon stock and sequestration proxy values used. 'No data' indicates no data are available.

	Salt marsh			**Seagrass**		**Unvegetated intertidal soft sediments**	**Total**		
Estuary	Carbon stock – *lower* range (tC/ha)	Carbon stock – *upper* range (tC/ha)	CO_2 rate (i.e. sequestration) (tCO_2/ha/yr). Lower and upper likely values, respectively	Carbon stock – *lower* range (tC/ha)	Carbon stock – *upper* range (tC/ha)	Carbon stock (tC/ha)	Total area of blue carbon habitats (ha)	Carbon stock – lower range (tC/ha)	Carbon stock – upper range (tC/ha)
Catlins	459.8	689.7	13.3 to 27.6	424.2	818.1	15,867.8	652.7	16,751.8	17,375.6
Blueskin Bay	1,345.2	20,17.8	38.9 to 80.7	469	904.5	13,956.8	605.7	15,771.0	16,879.1
Papanui Inlet	490.2	735.3	14.2 to 29.4	1,555.4	2,999.7	7,396.5	408.5	9,442.1	11,131.5
Pleasant River	3,055.2	4582.8	88.4 to 183.3	0	0	4,797.0	264.9	7,852.2	9,379.8
Waikouaiti River	3,051.4	4,577.1	88.3 to 183.1	23.8	45.9	2,412.8	174.8	5,488.0	7,035.8
Pūrākaunui Inlet	896.8	1,345.2	26.0 to 53.8	0	0	3,068.0	141.6	3,964.8	4,413.2
Tautuku River	1,303.4	1,955.1	37.7 to 78.2	0	0	2,069.6	113.9	3,373.0	4,024.7
Tokomairiri River	2,158.4	3,237.6	62.5 to 129.5	0**	0	1,024.4	96.2	3,182.8	4,262.0
Akatore	1,022.2	1,533.3	29.6 to 61.3	0	0	1,508.0	84.9	2,530.2	3,041.3
Shag	1,759.4	2,639.1	50.9 to 105.6	0	0	977.6	83.9	2,737.0	3,616.7
Kaikorai	1,284.4	1,926.6	37.2 to 77.1	0	0	1,211.6	80.4	2,496.0	3,138.2
Tahakopa River	672.6	1,008.9	19.5 to 40.4	0	0	1,115.4	60.6	1,788.0	2,124.3
Hoopers Inlet	2,234.4	3,351.6	64.7 to 134.1	280.0***	540.0***	No data	78.8	2,514.4	3,891.6
Waipati River	190.0	285.0	5.5 to 11.4	0	0	1,292.2	54.7	1,482.2	1,577.2

	Salt marsh			Seagrass		Unvegetated intertidal soft sediments	Total		
Kakanui	1.5	2.3	0.04 to 0.09	0	0	26.8	1.1	28.3	29.1
Otago Harbour*	2,831.0	4,246.5	82.0 to 169.9	128.5	247.8	No data	83.7	2,959.5	4,494.3
Total	**22,755.9**	**34,133.9**	**658.7 to 1,365.4**	**2,880.9**	**5,556.0**	**56,724.5**	**2,986.2**	**8,2361.3**	**96,414.3**

* Values for salt marsh were calculated using an estimated area for one location within the harbour (refer to Table 1); therefore, our carbon stock and sequestration estimates are also only for the estimated area.

** There is a very small area of seagrass recorded for Tokomairiri River, but the value was too small to include in our carbon stock estimates.

*** The area of seagrass for Hoopers Inlet used for our carbon stock calculation is based on a preliminary estimate only.

4. PROTECTING AND RESTORING BLUE CARBON HABITATS

Blue carbon habitats are present in the Otago Region but are threatened by a range of anthropogenic stressors (refer to Section 2). While sea-level rise (SLR) poses a future threat to saltmarsh habitats (Lovelock 2020; Rullens et al. 2022), it is also an opportunity for restoration, as new areas become suitable for colonisation (Costa et al. 2022). Protecting and restoring blue carbon habitats is therefore critical to ensure they provide climate mitigation and adaptation, as well as many other, benefits. There are various approaches for protection and restoration, with some restoration already underway for several Otago estuaries. Below, we provide a high-level summary of approaches and recommendations for protecting and restoring blue carbon habitats in the Otago Region. Additional information on restoration approaches for blue carbon (and other) habitats can be found in reviews for other regions in Aotearoa New Zealand, e.g. Handley (2022) for Te Tauihu (top of the south), Morrison (2021) for the Hauraki Gulf and Zeldis et al. (2019) for Southland.

4.1. Saltmarsh habitats

4.1.1. Summary of approaches

Protecting existing salt marsh from current and future anthropogenic threats is the most effective way to maintain the ecological benefits of this habitat. However, restoration will be required to bring back or compensate for saltmarsh loss or degradation that has already occurred. The legislative framework for protecting and restoring salt marsh in Aotearoa New Zealand has been summarised by Crawshaw and Fox (2022). Following on from this, restoration and protection approaches require a combination of ecological knowledge, careful planning and use of specific techniques. Common approaches and example reference/s are as follows:

- Limiting or reversing land reclamation (Zeldis et al. 2019).
- Weeding and pest control to reduce the impacts of non-indigenous plants and animals (Weaver et al. 2022).
- Restoring tidal flow through re-wetting (Rogers et al. 2022). For example, reversing conversion of tidal wetlands to pasture by draining and installing barriers such as bunds.
- Re-planting saltmarsh plant species. Many key species are available in commercial nurseries or can be grown from seed (Zeldis et al. 2019). This can be facilitated by actions such as placing chenier ridges offshore and / or using biodegradable structures, particularly in higher wave-energy environments (Stevens and Southwick 2019; Handley 2022).
- Removing existing, and ceasing to build more, human-built barriers to inland saltmarsh migration in response to future sea-level rise (Rullens et al. 2022).

Barriers include hard structures such as sea walls. Instead, the focus is on facilitating 'living' shorelines (Handley 2022).

- Managing sediment. Sediment control can be beneficial in some contexts but detrimental in others. A key benefit of controlling sediment is reducing smothering of sensitive blue carbon habitats, such as seagrass (Turner and Schwarz 2006). Conversely, lower sedimentation rates limit the ability of salt marsh to accrete vertically, which reduces carbon sequestration and resilience against SLR (Liu et al. 2021). It is therefore important to consider the wider perspective, which will be site specific when considering sediment management.

Specific restoration and protection technical approaches will vary depending on the characteristics of each saltmarsh site and its associated threats; tailored approaches will therefore be required. Sea-level rise poses a significant threat (and potential opportunity) to existing and restored saltmarsh habitats, making SLR assessment tools a critical component of future restoration projects; example case studies can be found in Crawford and Fox (2022). Frameworks can be used to guide decision-making processes for restoration. For example, a preliminary scoring framework was developed and used by Stevens and Southwick (2021) to assess saltmarsh rehabilitation options for Waimea Inlet (Nelson and Tasman Regions / Te Tauihu). Another example is the restoration assessment for Avon Ōtākaro Red Zone using a local knowledge approach (Orchard et al. 2017). Furthermore, regular monitoring of protected and restored salt marsh allows evaluation of the effectiveness of an approach and can inform any required modifications to a management strategy.

4.1.2. Recommendations for Otago

First and foremost, we recommend that existing blue carbon habitats are protected from further degradation. Mapping needs to be undertaken for the six coastal hydrosystems for which broadscale monitoring has not yet occurred (Orore Creek, Stony Creek, Waikouaiti Lagoon, Tomahawk Lagoon, Taieri River, Clutha River), and also for Otago Harbour, to obtain a more complete understanding of overall blue carbon habitat extent. A key action to protect existing salt marsh is to reduce impacts of anthropogenic threats to these habitats. This requires a tailored approach for each estuary and should align with other environmental protection initiatives (e.g. National Policy Statement for Freshwater Management 2020). To progress restoration and protection, we recommend that options for individual sites are further investigated based on detailed site assessments and future SLR predictions. Consultation with local communities (including mana whenua) will also provide important insights for restoration projects. Potential funding or support mechanisms for restoration could focus on government, philanthropic avenues (including volunteer support) and offsetting (Weaver et al. 2022).

Estuaries previously identified as having potential for saltmarsh restoration include Pleasant River (Roberts et al. 2022b), Blueskin Bay (Roberts et al. 2021a) and

Akatore Estuary (Roberts et al. 2022d); these reports can be referred to for further restoration recommendations. Saltmarsh restoration is already underway at some sites in Pleasant River and Pūrākaunui Inlet.

4.2. Seagrass

4.2.1. Summary of approaches

As for salt marsh, protecting existing seagrass meadows is critical to maintain the benefits they provide to an ecosystem. We currently have no information to quantify the extent of seagrass loss in the Otago Region. It is possible that seagrass has been lost from some estuaries (e.g. Catlins Estuary and Waikouaiti River Estuary), whereas for others it may have never been present (e.g. Tautuku Estuary, Kaikorai Estuary, Tahakopa Estuary, Waipati River Estuary, Kakanui Estuary). If seagrass loss or degradation has occurred, or does occur in the future, then restoration may need to be undertaken. Removing anthropogenic pressures (e.g. sediment and nutrient reductions) may enable seagrass to recover naturally over time (e.g. Leschen et al. 2010; Gibson and Marsden 2016; Riemann et al. 2016). Seagrass may have some resilience to SLR, given *Z. muelleri* as a species can live in subtidal environments (Rullens et al. 2022). However, sediment inputs need to be controlled because seagrass require a certain light level to photosynthesise underwater. A more intensive (i.e. 'active') restoration approach may be required in some cases, for example, when seagrass is reintroduced in areas where there are no existing plants or propagule supply. Traditional seagrass restoration methods include transplanting plugs from donor meadows (e.g. Matheson et al. 2017). Seed-based restoration techniques for Aotearoa New Zealand are currently being developed to enable larger scale restoration with lower impact on existing donor meadows (Hindmarsh and Hooks 2022; Fearn et al. 2023 [forthcoming]). A variety of seagrass restoration frameworks are available to guide decision-making for seagrass restoration (see summary by Clark and Berthelsen 2021).

4.2.2. Recommendations for Otago

Seven estuaries in our study contained seagrass meadows, with the most extensive meadows recorded from Papanui Inlet, followed by Blueskin Bay and Catlins Estuary. These meadows need to be protected, with regular monitoring required to enable early identification of any anthropogenic threats and seagrass loss or degradation. Seagrass habitat mapping is needed for Hoopers Inlet Estuary in particular, given we understand this has not been carried out previously. Mapping is also needed for any other currently unmapped estuaries that contain seagrass, as well as for Otago Harbour, to obtain a more complete understanding of overall seagrass extent. It would be useful to quantify historical loss of seagrass where possible. If future seagrass loss does occur in any of the estuaries, then restoration techniques could be considered.

4.3. Unvegetated intertidal soft sediments

4.3.1. Summary of approaches

Human stressors that influence the amount of carbon stored and sequestered in unvegetated intertidal soft sediments include sediment and nutrient inputs (Hamilton et al. 2020). In some cases, these stressors have the potential to increase the amount of carbon stored in unvegetated soft sediments; however, this is unlikely to have undesirable outcomes for overall ecological health. For example, fine sediments can have adverse effects on estuarine communities by directly smothering organisms (Norkko et al. 2002), altering food quality (Cummings et al. 2003), clogging filter-feeding structures (Ellis et al. 2002), affecting larval settlement (Rhoads and Young 1970), reducing benthic primary production (Pratt et al. 2014), and ultimately resulting in a loss of biodiversity and a reduction in functioning (Thrush et al. 2003). Similarly, if nutrient concentrations surpass the assimilation capacity of the estuary, serious adverse effects can result via eutrophication. Eutrophication occurs when excess nutrients promote the growth of phytoplankton and opportunistic algae (e.g. sea lettuce), increasing organic inputs to the seabed. Decomposition of this additional organic material consumes oxygen, resulting in oxygen depletion in benthic habitats and the overlying water column. This process can cause declines in water quality, shifts in species diversity and functioning, loss of submerged aquatic vegetation, occurrences of harmful algal blooms, and mass mortalities of fish and benthic organisms (Smith 2003; Bricker et al. 2014). Therefore, it is important to consider the broader picture when managing unvegetated intertidal soft sediments for carbon sequestration.

Protecting and restoring surrounding blue carbon habitats and terrestrial indigenous vegetation will likely facilitate transport of blue carbon material from these habitats to unvegetated intertidal soft sediments where they may then be sequestered. This process occurs because these habitats have been found to subsidise blue carbon in unvegetated intertidal sediments (Bulmer et al. 2020; Zaiko and Pearman 2022).

4.3.2. Recommendations for Otago

When considering the wider picture of ecological condition, it is important that estuarine sediments in Otago estuaries are managed for good health, rather than simply carbon sequestration value.

4.4. Social considerations and benefits of restoration

Public participation in environmental management is increasingly recognised as crucial for the success of management practices (e.g. the study for Blueskin Bay by Finlayson and Neilson 2021). Partnerships can encourage collaboration between stakeholders to help ensure a holistic and culturally sensitive approach to restoration.

This can also lead to more effective decision-making, resource sharing and a broader range of expertise.

Furthermore, restoration projects can have additional benefits beyond their intended environmental outcomes. An example of a blue carbon-related project for which social outcomes were evaluated is Core and Restore in the Te Tauihu / Top of the South region. Indicators that were scored highly for this project were ‘knowledge integration’, ‘empowerment and equity’, ‘new partnerships’, ‘social networks’ and ‘innovations’. See Berthelsen et al. (2023) for assessment methods and more detailed results.

5. NEXT STEPS

5.1. Quantifying blue carbon

Habitat mapping data are currently unavailable for six coastal hydrosystems / estuaries in the Otago Region, as well as for seagrass meadows and unvegetated intertidal soft sediments in Hoopers Inlet. Mapping of blue carbon habitats is also incomplete for Otago Harbour. We recommend that broadscale surveys of these estuaries is carried out to create a more complete assessment of blue carbon habitats in the region.

Ideally, blue carbon sediment data would be collected from the Otago Region to increase accuracy of blue carbon stock and sequestration estimates. However, estimates could also be refined by using more representative proxy data from other regions. For example, burial rates and variability in carbon accumulation for unvegetated intertidal soft sediments are currently being investigated for North Island estuaries (research by Jack Hamilton and Richard Bulmer), and tools to estimate blue carbon stocks are being developed for Aotearoa New Zealand. Factoring in GHG emissions, such as those from degraded wetlands, would also increase knowledge of restoration benefits, particularly once local or national data become available.

5.2. Protecting and restoring blue carbon habitats

We recommend that existing blue carbon habitats are protected from degradation in all Otago estuaries. A key action is therefore to reduce impacts of anthropogenic threats to these habitats using a tailored approach for each estuary. It is worth noting that climate change presents a threat to blue carbon habitats – for example, via SLR, marine heatwaves, increased sediment delivery to coastal areas, and disturbance from storms (e.g. Smale et al. 2019; Aoki et al. 2021; Lovelock 2020). Although these threats are not all manageable on a local scale, reducing other stressors can increase the resilience of these habitats to climate change (Brown et al. 2013; Gurney et al. 2013).

Regular monitoring (both at broad- and fine-scales) of blue carbon habitats is recommended to allow early identification of any threats to, or losses of, these habitats. This will provide critical information for informing management actions and priorities.

We also recommend that individual estuaries or sites previously identified for their restoration potential are further investigated, and that SLR assessments for these estuaries are carried out to ensure restoration plans are viable in the long term. Sea-level rise assessments for other estuaries may also identify additional sites that have potential for future restoration. Frameworks can be used to guide decision-making around restoration, and community engagement and support will be important for restoration success.

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