Mapping the benefits and costs of management actions for coastal wetlands in Victoria

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VICTORIA State Government
Environment, Land, Water and Planning

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Photo: Noyan Yilmaz

Acknowledgement of Country

The Blue Carbon Lab proudly acknowledges Victoria's Aboriginal community and their rich culture. we also acknowledge and pay our respects to the traditional owners and elders past, present and emerging throughout Australia and recognise their continuing connection to land, waters and culture. They hold the memories, traditions, cultures, and hopes of Aboriginal and
Torres Strait Islander peoples of Australia.

Table of Contents

List of Figures

List of Tables

Executive Summary

Coastal wetlands (i.e., mangroves, saltmarshes, and seagrasses) have been recognised as an efficient nature climate solution to help mitigate and adapt to climate change. These ecosystems are also known to provide other ecosystem services to coastal communities, such as coastal hazard mitigation against flooding and erosion, nutrient uptake, fisheries enhancement through the provision of nursery habitat and support biodiversity. Despite their importance in providing ecosystem services and coastal revenues, we still lack information on how to best value these ecosystems and the potential return on investment from coastal management activities.

Here, we aimed to implement the newly minted UN System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA) to develop an ecosystem account for mangroves, saltmarshes, and seagrasses across the entire state of Victoria. Importantly, we wanted to create both a current assessment of the extent, condition, and physical and monetary services, but look at how this could be improved through various management actions. This involved modelling the potential benefits of managing different locations across Victoria's coastline under different management scenarios (e.g., baseline trends, fencing, managed retreat, and levee removal) to identify suitable sites for restoration and their potential return on investment.

We found that:

> Coastal wetlands are distributed within ~80,000 ha along the coastline; 6% are mangroves, 34% are saltmarshes, and 60% are seagrasses. In our assessment of condition, we showed that 8,320 ha of mangroves and saltmarshes have collapsed since their pre-European distribution, while 3,508 ha of mangroves and saltmarshes were identified as highly disturbed, having been impacted by both pasture/grazing and the presence of levees. For seagrasses, we found that 7,031 ha have been stable since the 1960s within the regions of Port Phillip and Western Port bays. In contrast, over 27,000 ha have collapsed since then.

> Overall, we found that the combined benefit (i.e., nitrogen and carbon sequestration, fisheries, and coastal hazard mitigation) provided by existing mangroves, saltmarshes, and seagrasses in Victoria is approximately AUD120.9 billion per year. Our estimates include AUD9.05 million per year for carbon sequestration, AUD281.7 million per year for nitrogen sequestration, AUD2.3 million per year for commercial fisheries, AUD161,000 per year for recreational fisheries, and AUD120.6 billion per year for mitigating coastal hazards. In general, saltmarshes provided the highest combined benefit amongst coastal wetlands, reaching an average AUD3.3 million per hectare per year.

> Due to the potential for erosion, defined by the Victorian Coastal Hazard Assessment (Department of Environment Land Water and Planning 2015) based on projected rates of sea level rise (0.2 m, 0.4 m, 0.8 m, and 1.2 m), wave heights, and coastal geomorphology, we found that 16,492 ha of coastal wetlands would be lost if we consider the erosion high risk (top 20th percentile) areas. The area lost due to erosion increases substantially if we consider the moderate risk (top 50th percentile) areas. In this case, seagrass meadows were the main coastal wetland lost in both erosion scenarios (i.e., approximately 37,000 ha could be lost in the moderate risk areas), followed by saltmarshes (with more than 18,000 ha in moderate risk areas) and mangroves. Therefore, further considerations should be made for management actions that could reduce this erosion risk.

> Considering the management scenarios included in this study, our analysis showed that the most cost-effective management strategies to restore saltmarshes and mangroves in Victoria are fencing and the reintroduction of tidal exchange through the removal of existing levees. Levee removal plus managed retreat is the management option with highest opportunity (~124,000 ha), while fencing only would have the smallest opportunity (~3,400 ha) along Victoria's coastline. Furthermore, levee removal plus managed retreat had the highest cost at AUD7.6 billion; however, it also showed the highest net benefit of AUD134.8 trillion

after 50 years and with a 5% discount rate.

- If areas that were within the past distribution of mangroves and saltmarshes but are currently used for livestock and grazing were fenced, these areas could potentially generate an annual benefit of AUD3.8 billion yr^{-1}. Overall, fencing is the cheapest management action to restore mangroves and saltmarshes while also delivering high returns through the value of ecosystem services. After 50 years and considering a 5% discount rate, if these areas are restored at a large scale, over AUD140 billion could be delivered through carbon and nitrogen sequestration, fisheries, and coastal hazard mitigation.

- Planning for future inundation due to sea level rise is an essential part of planning for future conditions and is likely to play an important role in the restoration and creation of coastal wetlands (i.e., through the newly inundated areas that will be available for their expansion). Our managed retreat scenario showed that the area available for restoration changes depending on the expected inundation extent (i.e., 20 cm by 2040, 47 cm by 2070 and 82 cm by 2100). If these areas become inhabited by mangroves and saltmarshes, we estimate an annual ecosystem service value of approximately AUD1.2 billion yr^{-1} for the areas available from 2040, followed by an annual benefit of AUD664 million yr^{-1} and AUD795 million yr^{-1} from 2070 and 2100, respectively. The scale of opportunity increases when the managed retreat scenarios are combined with the levee removal and fencing strategies.

- We used five different sites that fit this category to understand how the restoration costs and benefits could vary at a local scale. We found that the area available to be restored is the main driver for a restoration project that includes more than two levee removals to be profitable or not. Furthermore, restoration costs at the local scale also play an important role in the overall total benefit provided by the restoration of coastal wetlands at that local scale.

Overall, this study shows that the SEEA EA framework is a powerful approach to help the decision-making process, making a direct contribution to managers by providing the potential value of restored mangroves and saltmarshes in Victoria. Furthermore, it can guide future decisions in the market and financing opportunities that could be applied in the region. Therefore, our results provide encouraging implications of the impacts of actions at local scales.

Keywords: environmental accounting, blue carbon, co-benefits, ecosystem services, coastal hazard mitigation.

Photo: Noyan Yilmaz

Introduction

Coastal wetland ecosystems (i.e., mangroves, saltmarshes, and seagrasses) occur in approximately 36-185 million hectares within the world's coastlines (Macreadie et al. 2021). These ecosystems have been recognised for their role in mitigating and adapting to climate change (Macreadie et al. 2021), while also providing other key ecosystem services to coastal communities, such as coastal hazard mitigation against flooding and erosion, nutrient uptake, fisheries enhancement through the provision of nursery habitat and support biodiversity (Barbier et al. 2011, Himes-Cornell et al. 2018, Carnell et al. 2019, Friess et al. 2020). However, coastal wetlands face a range of threats from land use change, altered hydrology, sea level rise, and declining water quality (Boon et al. 2015, Davidson and Finlayson 2018). Due to these and other factors an estimated 50% of the global extent of coastal wetlands has been lost (Duarte et al. 2013). Despite their importance in providing ecosystem services and coastal revenues, we still lack information on how to best value these ecosystems and the potential return on investment from coastal management activities.

Restoration of marine and coastal ecosystems is still in its infancy when compared to terrestrial ecosystems, with terrestrial ecosystems able to attract more funding opportunities due to their relatively advanced understanding of restoration actions and outcomes (Danovaro et al. 2021). For example, in Victoria (Australia), the State Government has developed a decision support tool to help guide the conservation of terrestrial plants, animals and habitats through land management and action prioritisation (Thomson et al. 2020). In contrast, many marine and coastal management decisions are still made on an ad-hoc basis, including site selection for restoration. The lack of systematic planning for restoration highlights the need for a framework that helps managers identify assess suitable locations for coastal restoration and/or management, estimate the benefits of restoration action on those sites, and identify those that provide the highest return on investment. Environmental accounting frameworks are an approach that can be used to guide decision-making in natural resource management, including in the carbon abatement field (Lohmann 2009, Keith et al. 2017). The United Nations System of Environmental Economic Accounting Ecosystem Accounting is increasingly being adopted worldwide (Hein et al. 2020) and in particular case study areas (Dvarskas 2019, Carnell et al. 2022b) to value ecosystem services provided by existing and restored coastal wetlands and inform where we should act for the greatest benefits.

One particular ecosystem service where this kind of thinking, valuation and approach has been applied, is the conservation and restoration of ecosystems as cost-efficient nature-based solutions to reduce carbon emissions (Macreadie et al. 2021, Costa et al. 2022, Hagger et al. 2022). For example, programs focusing on carbon farming by encouraging land managers to change land use towards practices that reduce carbon emissions (Queensland Government 2019). However, the incorporation of these ecosystems in national and regional policies has been overlooked in the past, with the first blue carbon method in Australia recently released in early 2022 (Clean Energy Regulator 2022a). This new method under the Emissions Reduction Fund will allow managers to collect carbon credits through the restoration of mangroves, saltmarshes, and seagrasses by reintroducing tidal exchange. Despite current evidence on the value of coastal wetlands as carbon sinks (Moritsch et al. 2021, Costa et al. 2022) and additional services (Carnell et al. 2019) of existing ecosystems, we still lack information on the value of the ecosystem services in addition to carbon sequestration provided by restored coastal wetlands.

Australia is one of the wealthiest countries in blue carbon (Bertram et al. 2021), holding 5-11% of global blue carbon stocks (Serrano et al. 2019). Within Australia, the state of Victoria is home to >300,000 ha of coastal wetlands with recent estimates for carbon stocks in the range of ~20-40 Tg C (Serrano et al. 2019, Young et al. 2021). However, the Victorian coastline is still undergoing change through impacts such as coastal development that leads to the degradation of ecosystems (Boon et al. 2015). Furthermore, future changes in environmental conditions (e.g., temperature, solar radiation, rainfall) and increases in sea level rise are also likely to substantially impact coastal wetlands (Finlayson et al. 2013), reducing the future suitability of habitats for supporting these ecosystems and their services (Young et al. 2021). Here, we aimed to implement the newly minted UN System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA) to develop an ecosystem account for mangroves, saltmarshes, and seagrasses across the entire state of Victoria. Importantly, we wanted to create both a current assessment of the extent, condition, and physical and monetary services, but look at how this could be improved through various management actions. This involved modelling the potential benefits of managing different locations across Victoria's coastline under different management scenarios (e.g., baseline trends, fencing, managed retreat, and levee removal) to identify suitable sites for restoration and their potential return on investment. Overall, our analysis will provide key information to land managers and government (local and regional) to understand the net benefits that restoring different sites across the state will have to achieve the greatest return on investment and enable coastal adaptation planning.

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Methods

Principles of the System of Environmental Economic Accounting

Here, we used the United Nations System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA) (UNCEEA 2021) to develop an ecosystem accounting for coastal wetlands (i.e., seagrasses, saltmarshes, and mangroves) in Victoria. The SEEA EA is a spatially based, integrated statistical framework for aligning information about the extent and health of ecosystems and how their contribute to measures of human well-being and economic activity (Figure 1; UNCEEA 2021). The SEEA EA complements the SEEA Central Framework (United Nations 2014), as well as the System of National Accounts (SNA), using accounting principles to integrate environmental and economic information). The SEEA EA is comprised of four main accounts, 1) extent, 2) condition of ecosystems and their resultant 3) physical and 4) monetary ecosystem services (Eigenraam and Obst 2018, UNCEEA 2021).

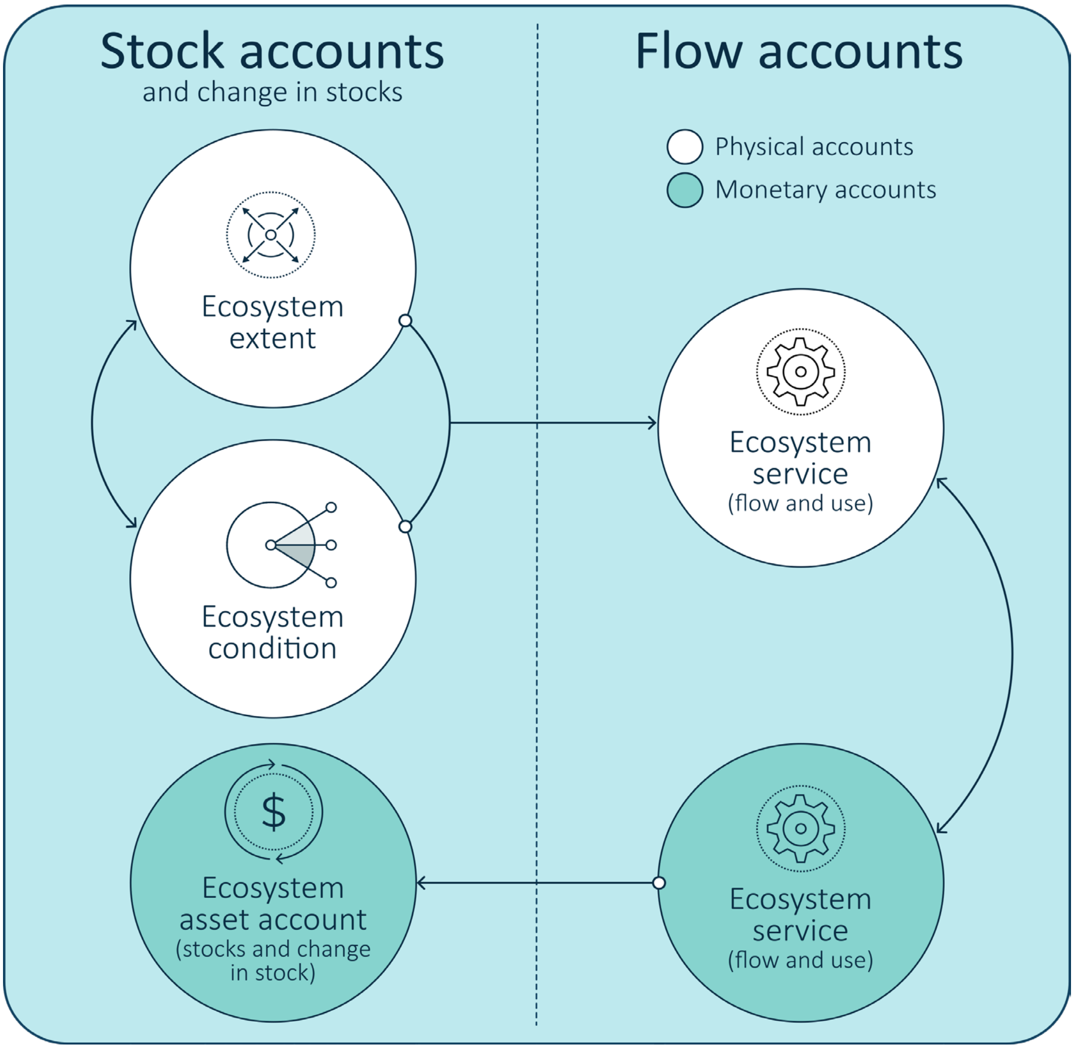

Figure 1. The structure of the UN System of Environmental Economic Accounting, Ecosystem Accounts (source: UNCEEA 2021). This diagram shows the relationship between the ecosystem extent and condition, and how these flows into measures of physical (white) and monetary (green) ecosystem services. In this case study, we have chosen to focus on the flow and use accounts of ecosystem services, rather than ecosystem asset accounts.

We also used the ecosystem accounting approach to add an additional step, which is to evaluate the costs and benefits of undertaking different management actions for mangroves and saltmarsh ecosystems. We focused this section on mangroves and saltmarsh ecosystems as the locations for potential restoration are better known (Sinclair and Boon 2012) and the restoration methods are further developed. We followed the steps described in Figure 2 to identify and quantify ecosystem services provided by existing coastal wetlands. Then, we modelled the potential benefits of managing different locations across Victoria's coastline under different scenarios (e.g., baseline trends, fencing, managed retreat, and levee removal) to identify suitable sites for restoration and their potential return on investment.

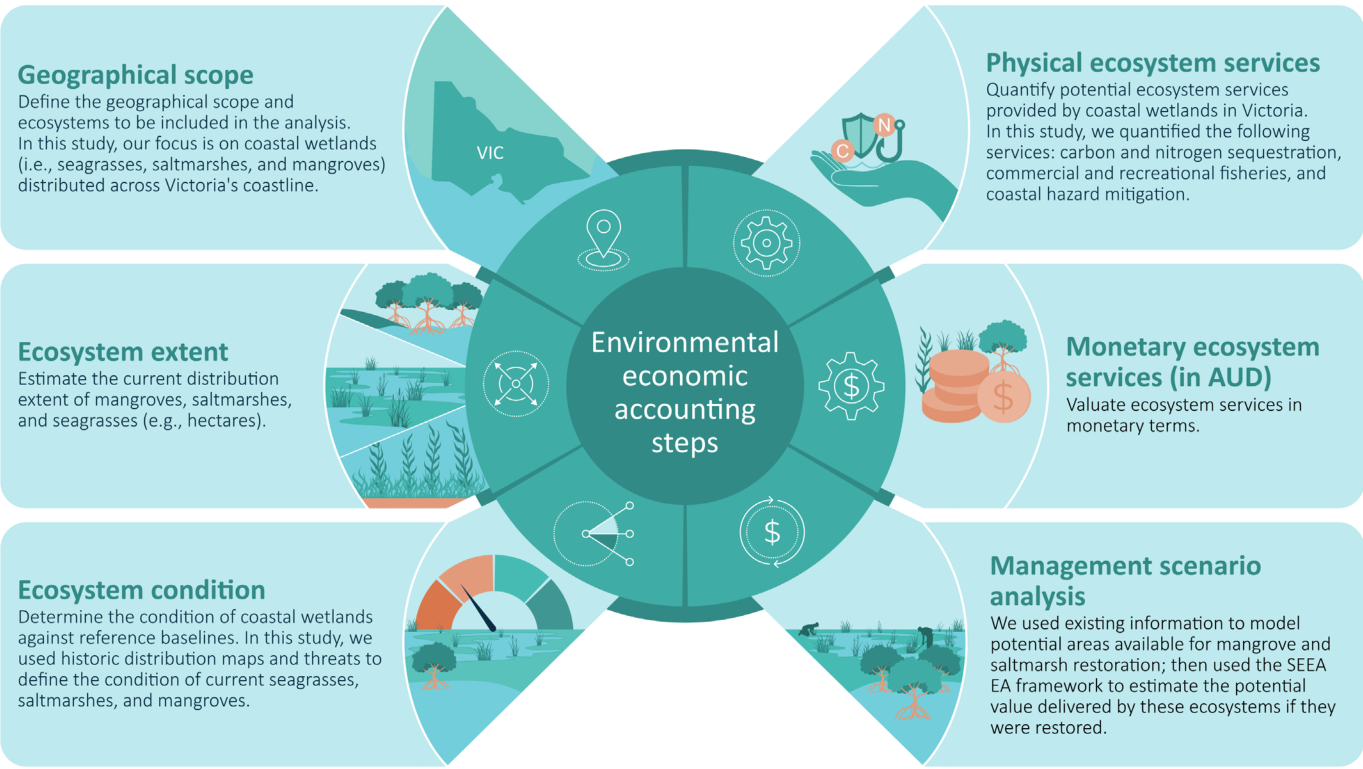

Figure 2. Graphical abstract detailing the description of each step used in the environmental economic accounting used in this study.

Defining condition of coastal wetlands

In this study, we followed the approach implemented by Carnell et al. (2022b) and determined the condition based on the historic distribution of coastal wetlands and threats. For mangroves and saltmarshes, we used the mapped pre-European distribution (Boon et al. 2011), the latest available land use cover (Department of Environment Land Water and Planning 2018a), and the mapped presence of coastal levees (Department of Environment Land Water and Planning 2018b) to classify these ecosystems as collapsed, high disturbance, medium disturbance, low disturbance and natural (Table S1). Land cover information was used to identify known threats to these ecosystems. Sites were considered collapsed if the saltmarsh or mangrove plants were no longer present and are currently under different land use category. Sites that are currently mangroves and saltmarshes were classified into three different conditions based on potential threats (Table S1), while natural ecosystems were identified in areas under conservation or other low-impact activities.

For seagrasses, our analysis was limited to Port Phillip (Lynch 1966, Blake and Ball 2001, Jenkins et al. 2015) and Western Port Bay (Wilkinson et al. 2016) due to the lack of data available on their historical distribution at the state level (Table S2). In this case, we classified the age and last presence of seagrass patches to define seagrass condition. Despite identifying previous seagrass studies in the Corner Inlet region, spatial datasets were not available when conducting this project. In this case, for the Port Phillip and Western Port Bays, we assumed that collapsed seagrasses were those that have not been present for 10-20 years, while seagrasses that were not present in the past 10 years were classified as high disturbance (Table S2). Where seagrasses are currently present, we used their age to determine condition: 1-10 years as medium disturbance, 10-20 years as low disturbance, and >20 years as natural seagrasses. Here, it is important to highlight that temperate seagrass meadows are less ephemeral than tropical seagrasses, and therefore, such time scales are appropriate (Orth et al. 2006). While emerging remote-sensing approaches could help to classify coastal wetland condition (Lymburner et al. 2020, Lee et al. 2021a, Navarro et al. 2021, Murray et al. 2022) such data is not available for all coastal wetland types in Victoria. In this case, the approach used in this study is appropriate and includes key features and indicators to guide our assessment.

Table 1. Detailed description of the two different methods used to estimate carbon sequestration in coastal wetlands across Victoria's coastline.

Method	Description
Coastal Blue Carbon InVEST 3.7.0 model (Sharp et al. 2018)	The Coastal Blue Carbon model is a spatially explicit tool that predicts carbon sequestered in coastal wetlands due to changes in the land cover through time. Overall, the model assumes that carbon sequestration and emission rates are constant over time, and estimates the potential carbon lost to the atmosphere following the disturbance in coastal wetlands. A full description of the model is available in Sharp et al. (2018). In this study, we used the following sequestration rates as input data for our models: A. 0.66 tonnes C ha^{-1} yr^{-1} (2.42 tonnes CO_2 ha^{-1} yr^{-1}) for natural saltmarshes (Ewers Lewis et al. 2020) B. 0.5 tonnes C ha^{-1} yr^{-1} (1.87 tonnes CO_2 ha^{-1} yr^{-1}) for natural seagrasses (Serrano et al. 2019) C. 1.74 tonnes ha^{-1} yr^{-1} (6.38 tonnes CO_2 ha^{-1} yr^{-1}) for natural mangroves (Ewers Lewis et al. 2020) D. 0.54 tonnes ha^{-1} yr^{-1} (1.98 tonnes CO_2 ha^{-1} yr^{-1}) for restored saltmarshes (Gulliver et al. 2020) E. 2.7 tonnes ha^{-1} yr^{-1} (9.9 tonnes CO_2 ha^{-1} yr^{-1}) for restored mangroves (Carnell et al. 2022a) In this case, the outputs of the model show the potential carbon sequestered in each time step included in the model. Therefore, to allow for the calculations of carbon sequestered per year, we followed the assumptions in place in the existing blue carbon method in Australia (Clean Energy Regulator 2022a) and assumed a crediting period of 25 years, which guided the calculations of carbon benefit per year. For the erosion scenarios, we assumed that coastal wetlands located within an embayment would be converted to mudflats and that if located on the open coast, they would be converted to open water (Moritsch et al. 2021, Costa et al. 2022). We assumed that an ecosystem-specific portion of the carbon was lost from the soil following the ecosystem conversion: 50% when transformed to mudflat and 100% when transformed to open waters (Sharp et al., 2018).
Area approach	In this method, we used a simplified method to calculate the potential carbon accumulated per year. In this case, we used the following sequestration rates: A. 0.66 tonnes C ha^{-1} yr^{-1} (2.42 tonnes CO_2 ha^{-1} yr^{-1}) for natural saltmarshes (Ewers Lewis et al. 2020) B. 0.5 tonnes C ha^{-1} yr^{-1} (1.87 tonnes CO_2 ha^{-1} yr^{-1}) for natural seagrasses (Serrano et al. 2019) C. 1.74 tonnes ha^{-1} yr^{-1} (6.38 tonnes CO_2 ha^{-1} yr^{-1}) for natural mangroves (Ewers Lewis et al. 2020) D. 0.54 tonnes ha^{-1} yr^{-1} (1.98 tonnes CO_2 ha^{-1} yr^{-1}) for restored saltmarshes (Gulliver et al. 2020) E. 2.7 tonnes ha^{-1} yr^{-1} (9.9 tonnes CO_2 ha^{-1} yr^{-1}) for restored mangroves (Carnell et al. 2022a) Then, we combined this information with the area for each location.

Valuing ecosystem services

We collated existing information for ecosystem services provided by coastal wetlands in Victoria. In this study, we focused on the following services: commercial and recreational fisheries, carbon and nitrogen sequestration, and coastal hazard mitigation. We recognise that these ecosystems provide additional ecosystem services (such as nature watching, cultural services, biodiversity enhancement, and tourism), however, our analysis was limited to data availability. Below, we provide a detailed description of how we estimated and valued each ecosystem service.

Provisioning services

Commercial Fisheries

To estimate the potential benefit to commercial fisheries, we used available data on the average abundance and biomass enhancement generated by Australian coastal wetlands (Jänes et al. 2020a, 2020b): 19,234 (3,016 - 35,454) individuals ha^{-1} yr^{-1} (or 265 kg ha^{-1} yr^{-1}; ranging from 13.5 - 516.9 kg ha^{-1} yr^{-1}) from mangroves; 1,712 individuals ha^{-1} yr^{-1} (or 64 kg ha^{-1} yr^{-1}; based on only one Australian State) from saltmarshes; and 55,589 (13,375 - 170,946) individuals ha^{-1} yr^{-1} (or 4,064 kg ha^{-1} yr^{-1}; ranging from 530 to 13,800 kg ha^{-1} yr^{-1}) from seagrasses. These estimates are based on 117 fish-specific abundance and biomass data for seagrasses, followed by 23 fish species for mangroves and 8 fish species for saltmarshes (Jänes et al. 2020b).

Then, we used the average production value estimated by Jänes et al. (2020a) for coastal wetlands in Victoria: AUD54.4 ha^{-1} yr^{-1} (ranging from AUD20 to AUD350 ha^{-1} yr^{-1}) for mangroves, AUD7.1 ha^{-1} yr^{-1} (ranging from AUD14.2 to AUD1,082 ha^{-1} yr^{-1}) for saltmarshes, and AUD39 ha^{-1} yr^{-1} (ranging from AUD6.4 to AUD539.8 ha^{-1} yr^{-1}) for seagrasses. Finally, we combined the area of each site with this information to estimate the potential fisheries enhancement and value per year for each blue carbon ecosystem.

Recreational Fisheries

To estimate the potential benefit to recreational fisheries, we used data from fish recreational catch (kg) of finfish and non-fish species for Victoria (total catch = 101,509 kg yr^{-1}; Henry and Lyle 2003). Then, we combined this information with the estimated average contribution from each ecosystem in Victoria (Jänes et al. 2020a): 3% (2-4.5%), 3% (2-4.5%), and 14% (13-32%) for mangroves, saltmarshes, and seagrasses, respectively, and divided by the total distribution of each blue carbon ecosystem in the state (Ewers Lewis et al. 2020). In this case, we estimated that mangroves, saltmarshes, and seagrasses would provide the following benefits in Victoria: 0.52, 0.13, and 0.29 kg ha^{-1} yr^{-1}, respectively. Then, we multiplied this information by the area of each site to estimate the potential benefit per year for each blue carbon ecosystem. We combined the estimated catch per year resulting from the different ecosystems and locations with the price per kg corrected by the Consumer Price Inflation. In this case, we used the average value of AUD8.07 per kg (Jänes et al. 2020a, 2020b).

We also estimated the potential value of the physical services provided by seagrasses to recreational fisheries based on the number of fishing trips per year undertaken in Port Phillips and Western Port Bays (Huang et al. 2020). In this case, we combined the information on the total number of fishing trips in both bays (2 million and 1 million trips in Port Phillip and Western Port Bays, respectively) (Ford and Gilmour 2013) with the spatially-explicit value of fishing trips estimated by Huang et al. (2020). Overall, this value represents a non-market value based on people's preference about where they like to fish. This valuation was limited to the distribution of current ecosystems.

Regulating services

Carbon Sequestration

In this study, we used existing carbon data collected throughout coastal wetlands in Victoria (Serrano et al. 2019, Gulliver et al. 2020, Ewers Lewis et al. 2020). To account for uncertainties in how much carbon is potentially sequestered by coastal wetlands, we estimated carbon sequestration through two different methods (Table 1).

To estimate the carbon value, we used three different carbon prices to account for uncertainties and temporal fluctuations in carbon pricing in Australia:

1. Average carbon price of AUD16.14 per tonne, based on the mean carbon price in Australia in 2020 (Clean Energy Regulator 2020, Moritsch et al. 2021, Costa et al. 2022).
2. Carbon price of AUD47 per tonne, based on the carbon price in Australia in December 2021 (Clean Energy Regulator 2022b).
3. Social Cost of Carbon price, which increases over time (for example, in a range of AUD94.86 – AUD136.17 between 2020 and 2045; Interagency Working Group on Social Cost of Greenhouse Gases 2016, Paul et al. 2017).

Nitrogen Sequestration

Nitrogen plays a key role in water purification services. In this study, we used nitrogen sequestration data collected within mangroves, saltmarshes, and seagrasses within the Port Phillip and Western Port Bays (Carnell unpublished data, Carnell et al. 2022b). Data were collected from three sites in each ecosystem and bay. Samples were then sliced in every 1 cm to conduct 210Pb age dating analysis to allow for the calculation of sediment accretion and sequestration rates. Then, we combined this information (Table S3) with the area of each location to calculate the potential benefit per year.

To estimate the annual value of nitrogen sequestration throughout Victoria's coastline, we assumed a nitrogen price of AUD52 per kg, based on the estimate €32 per kg (assuming a conversion rate at AUD1.61, September 2021) (Liekens et al. 2012). Furthermore, for the Port Phillip Bay region,

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we assumed a one-off payment of AUD8,460 per kg (with a potential range of AUD2,640-AUD12,000) representing the service replacement costs for nitrogen removal from stormwater needed to maintain the good water condition in the bay (Melbourne Water 2021, Carnell et al. 2022b). Considering a 25-year's timeframe and a 7% discount rate, we transformed the one-off payment into an annual value of AUD726 per kg per year, following Equation 1.

$$\textit{Annual value} = \frac{\dfrac{\text{Discount rate}}{\text{Present value}}}{1-(1+\text{Discount rate})^{-years}} \qquad \text{Eq.1}$$

Coastal hazard mitigation

We followed the approach used in Carnell et al. (2019) and used the InVEST Coastal Vulnerability model to estimate the coastal protection value delivered by mangroves, seagrasses, and saltmarshes in Victoria (Arkema et al. 2013, Sharp et al. 2018). In this case, we used the model to develop a first-pass assessment of the potential coastal hazard mitigation generated by coastal wetlands at a large scale. Then, we combine the model outputs on the exposure metrics with the total property value in 2021 within a 1 km distance from coastal wetlands. To transform the asset value (i.e., total property value) into an annual flow value, we assumed a 7% discount rate and a 25-years' timeframe as shown in Equation 1.

Equation 1 was only used to transform an asset value (such as the one-off payment for nitrogen sequestration in Port Phillip Bay or the total property value). In this case, 25 years was used so the timeframe is also compatible with the crediting period of restored ecosystems (as per requirements of the Blue Carbon method released by the Clean Energy Regulator in Australia, Clean Energy Regulator, 2022a); while a 7% discount rate has been used to keep the estimate conservative. Once the asset value was transformed into an annual value, we used it to calculate the net benefits as described further in the 'Management costs' section.

Assessing the costs and benefits from management options

Here, we adapted the approach used by Carnell et al. (2022b) and assessed eight different management scenarios, which are fully described in Table 2. Our scenarios included:

A. two baseline trends scenarios, where we used the mapped erosion high and moderate risk areas to estimate the potential loss of ecosystem services if coastal wetlands were lost to erosion.

B. six management scenarios, including a different combination of fencing, levee removal, and managed retreat, to identify potential areas available for restoration. In this case, we only considered the restoration of mangroves and saltmarshes due to a lack of data and uncertainties regarding seagrass restoration.

Regardless of the restoration scenario, we excluded the land use categories that were assumed as non-amendable to restoration – i.e., areas that are highly unlikely to be converted back to coastal wetlands. To be compatible with previous studies conducted in Victoria (Moritsch et al. 2021), we considered the following categories as amenable for restoration: vacant residential englobo land (102), vacant residential rural (103), separate house and curtilage (111 and 117), miscellaneous building on rural residential land (151), vacant industrial englobo land (301), vacant land mining unspecified (482), native vegetation and agriculture/livestock/in-water aquaculture (500-582), vacant land (600), water catchment area (640), water supply (64), rural and community camps (751), water sports (814, 824), bike track/walking trails (829), culture recreation and sport (837), parks and gardens (844), and protected areas and conservation (900-930, 932-991).

Table 2. Description of each scenario, including rationale, methods, and assumptions, included in this study.

	Scenario	Background, Methods & Assumptions
Baseline trends	Erosion of High-Risk Areas	We used the mapped erosion high-risk areas (top 20^{th} percentile) to identify areas of coastal wetlands that would be lost due to erosion (Department of Environment Land Water and Planning 2015). This scenario represents the blue carbon ecosystem in highest vulnerability risk to be eroded, indicating a more conservative scenario. In this case, we assumed that coastal wetlands located within an embayment would be converted to mudflats and that if located on the open coast, they would be converted to open water (Moritsch et al. 2021, Costa et al. 2022).
	Erosion of Moderate-Risk Areas	We used the mapped erosion moderate risk areas (top 50^{th} percentile) to identify areas of coastal wetlands that would be lost due to erosion (Department of Environment Land Water and Planning 2015). This scenario represents the blue carbon ecosystem in moderate to high vulnerability risk to be eroded, which includes the high-risk areas as well. In this case, we assumed that coastal wetlands located within an embayment would be converted to mudflats and that if located on the open coast, they would be converted to open water (Moritsch et al. 2021, Costa et al. 2022).
Management actions	Fencing	Ungulates (i.e., feral animals and livestock) can cause significant damage to coastal wetlands, causing erosion, preventing recruitment, and reducing the growth of vegetation (Mihailou and Massaro 2021, Waltham and Schaffer 2021). Therefore, substantially impacting the capacity of these ecosystems to deliver benefits (Limpert et al. 2021). Here, we modelled restoration through the fencing of collapsed mangroves and saltmarshes (based on where they existed historically, but do not in their current distribution) that are currently being used as pasture/grazing lands. In this case, we used the most recent land use cover data available for Victoria (Department of Environment Land Water and Planning 2018a) and the pre-European distribution of mangroves and saltmarshes (Boon et al. 2011). The main assumptions of this scenario were: 1. installing a fence around the site perimeter would remove grazing and allow mangroves and saltmarshes to recover over time 2. restoration started in 2022 3. a fence would be deployed in the entire site perimeter since we lack information on the locations of existing fences in Victoria
	Managed Retreat	While sea level rise is likely to trigger the loss of coastal wetlands in several locations along the coastline, it also represents an opportunity to restore historical distribution and expand their distribution in newly inundated areas. Here, we focused on the restoration and creation of saltmarshes and mangroves through the gradual inundation of sea level rise in 2040, 2070, and 2100. In this case, restoration would be based on the pre-European distribution of mangroves and saltmarshes (Boon et al. 2011) under the early signs of sea level rise, while also allowing for additional creation of saltmarshes in areas inundated by sea level rise from 2070 and 2100 (Moritsch et al. 2021, Costa et al. 2022). For that, we used the predicted inundated extent from sea level rise plus storm surge in 2040 (20 cm), 2070 (47 cm), and 2100 (82 cm) (Department of Environment Land Water and Planning 2018c). The main assumptions in this scenario were: 1. restoration would start with early signs of sea level rise in 2040, followed by late signs in 2070 and 2100. 2. Pre-European distribution would be restored in 2040 with the early signs of sea level rise, followed by inundation outside historic distribution from 2070 and 2100 (Department of Environment Land Water and Planning 2018c). 3. All restored sites from 2070 would become saltmarshes. 4. No additional levees or sea wall fortifications were built to limit sea level rise inundation.

Fencing plus Managed Retreat	In this case, we combined the 'Fencing' and 'Managed Retreat' scenarios (including their assumptions) to identify areas that will be inundated through sea level rise that are currently used for pasture and grazing. Therefore, requiring an adaptation plan to allow for the creation of saltmarshes under future sea level rise conditions.
Levee Removal plus Managed Retreat	Restoration of coastal wetlands through the reintroduction of tidal flows has been identified as one of the main management activities with higher potential for blue carbon potential in Australia (Kelleway et al. 2020) and Victoria (Moritsch et al. 2021). This is aligned with the recent blue carbon method released in 2022, which allows for the issuance of Australian Carbon Credit Units (ACCUs) through tidal reintroduction (Clean Energy Regulator 2022a). In this scenario, we considered the restoration of saltmarshes and mangroves through the re-introduction of tidal exchange in combination with the gradual sea level rise. For that, our main assumptions were: 1. Return of tidal exchange will allow for the restoration of mangroves and saltmarshes. 2. The area available for restoration followed the approach used by Moritsch et al. (2021) and Costa et al. (2022) and assumed that areas within 1 km of existing levees with elevation ranging from 0 to 1 m. 3. Altered hydrology does not lead to changes in existing coastal wetlands. 4. Combined the areas available for restoration through levee removal with the 'Managed Retreat' scenario. This scenario represents a potential estimate of areas available for restoration through the removal of levees and is likely to under-or overestimate the inundation extent in certain areas. Therefore, this approach does not replace hydrodynamic modelling and site-specific analysis before undertaking a blue carbon project. Furthermore, this scenario only includes the mapped levees along Victoria's coastline (Department of Environment Land Water and Planning 2018b), which can potentially underestimate the area available for restoration under this scenario.
Fencing, Levee Removal and Managed Retreat	In this scenario, we combined the 'Fencing', 'Levee Removal', and 'Fencing plus Managed Retreat' scenarios to identify sites currently used for pasture and grazing that have levees present, and therefore, would require restoration through both actions. Then, we combined the 'Fencing plus Managed Retreat' scenario, to identify pasture lands that would be inundated through sea level rise.
Complex Hydrological Intervention	This scenario aimed to identify sites with expected complex hydrological interventions. In this case, these sites were based on local knowledge from the region and the assumption that having 2 or more levees present would require complex hydrodynamic modifications on a specific site. In this study, we identified 5 sites (Figure S1): 1. Avalon Saltponds 2. Moolap Saltponds 3. Cheetham Saltponds 4. Werribee sewage treatment ponds 5. Lake Victoria

We estimated benefits derived from restored mangroves and saltmarshes following the same methods and assumptions used to calculate the benefits provided by existing coastal wetlands (described in the 'Valuing ecosystem services section).

To estimate carbon sequestration resulting from each management action, we applied a 5% dicount on the the potential carbon sequestered to account for any loss from the system through time (Clean Energy Regulator, 2022a).

Our main assumption, in this case, was that restored ecosystems would start providing carbon and nitrogen services in year 0 following the management action, while fisheries and coastal hazard mitigation would take 5 and 10 years, respectively. Despite a few studies on the topic (Sasmito et al. 2019, Duarte et al. 2020, Gulliver et al. 2020, Orth et al. 2020, Carnell et al. 2022a), the time taken for restored mangroves and saltmarshes to sequester carbon at the same rate as mature ecosystems is still an open question in blue carbon science (Macreadie et al. 2019). Furthermore, our study did not include the restoration of degraded (low disturbance – high disturbance) ecosystems since we still lack enough data to support our models to estimate the return-on-investment of such improving ecosystem condition, compared to restoring an ecosystem from collapsed state.

Management costs

Costs were estimated based on the approach suggested by Carnell et al. (2022b), which used information from restoration projects developed along Victoria's coastline. This approach allows for the incorporation of local wages and material to be included in the analysis. It is important to highlight that the costs included in the analysis were assumed as a representation of the expected restoration costs for such management actions and do not exclude the need for careful consideration and price estimation before planning and implementing local and/or regional management actions.

Overall, costs were calculated as a function of the management action required and site-specific information (e.g., perimeter, area, levee to be removed). Our cost estimates also include a representation of project management costs, which considers the coordination with landowners, contractors, local government, and researchers to undertake the management action. However, no ongoing maintenance costs were included in the analysis. A full description of how costs were estimated for each management scenario is available in Table 3.

Finally, we estimated the net benefit (i.e., the total benefit provided by restored mangroves and saltmarshes minus total costs) associated with each management scenario. For that, we applied a 5% discount rate to determine the net present value of 50 years of flows from the restored mangroves and saltmarshes. To account for any uncertainties in our calculations, we conducted a sensitivity analysis considering different discount rates (i.e., 1%, 3%, 7%, 11%) and timeframes (20 and 100 years).

Photo: Getty Images

Table 3. Detailed description on how costs were calculated for each management scenario included in the study.

Scenario	Cost Description
Fencing	Total costs were comprised by a combination of variable and fixed costs. **Variable cost** $V_c = P_f * Perim$, where, P_f is the price per unit of fencing (AUD15 per meter) and Perim is the distance around each area amenable for restoration (i.e., perimeter in meters) **Fixed cost** Stay= AUD100 Gate= AUD200 Material transportation= AUD100 **Project Management** < 10 ha= AUD20,000 10-50 ha= AUD40,000 50-200 ha= AUD80,000
Managed Retreat	We considered a cost per year to represent community and Traditional Owners engagement, monitoring, and science projects for 5 years to prepare landowners to adapt to future sea level rise conditions: < 10 ha= AUD100,000 10-50 ha= AUD200,000 50-200 ha= AUD400,000 > 200 ha= AUD500,000
Fencing plus Managed Retreat	For this scenario, we combined the costs used in the 'Fencing' and 'Managed Retreat' scenarios.

Levee Removal plus Managed Retreat	At locations where levees needed to be removed, total costs for removing levees were a combination of variable and fixed costs. **<u>Variable cost</u>** $V_{cik} = P_{BW} * BW_k * W_{ik}$ where, P_{BW} is the price per unit of levee removed (AUD6 per m^3), BW_k is the volume of levee k (which equals to half of the length of the levee multiplied by the width and height, where width and height were assumed as the average value from levee characteristics in the region – i.e., width defined as 11 meters and height as 3 meters). Length was estimated from the mapped levees map available for Victoria (Department of Environment Land Water and Planning 2018b). Wik is the area i available for restoration following the levee removal. **<u>Fixed cost</u>** **Project Management** < 10 ha= AUD20,000 10-50 ha= AUD40,000 50-200 ha= AUD80,000 > 200 ha= AUD100,000 **Hydrological Assessment** < 10 ha= AUD30,000 10-50 ha= AUD50,000 50-200 ha= AUD100,000 > 200 ha= AUD120,000 **Bathymetry Modification** < 10 ha= AUD60,000 10-50 ha= AUD150,000 50-200 ha= AUD300,000 > 200 ha= AUD600,000 Then, we combined the costs from the ‘Managed Retreat’ scenario to the sites that would be restored through the gradual inundation due to sea level rise.
Fencing, Levee Removal and Managed Retreat	For this scenario, we combined the costs from the 'Fencing' with the 'Levee Removal plus Managed Retreat' scenarios.

Complex Hydrological Intervention	For this scenario, costs followed the same approach ad assumptions as the one used in the 'Levee Removal plus Managed Retreat' scenario. Furthermore, we used a recent detailed quote estimated to restore Avalon to improve our costings for project management and planning. Therefore, the costs at local scale were estimated as: **Variable cost:** same approach used in the 'Levee Removal plus Managed Retreat' scenario **Fixed cost** AUD1.2 million for project management and planning AUD120,000 for hydrological assessment AUD600,000 for bathymetry modification **NOTE**: The Lake Victoria region has been extensively modified in the past years; however, no earth wall has been mapped in the area. In this case, for the purpose of this study, we assumed that the variable cost was half of the variable cost estimated for Moolap Saltponds. A full detailed hydrological assessment is needed for all sites before planning an on-ground restoration project.

Photo: Noyan Yilmaz

Results

Existing coastal wetlands

Extent and condition

Based on the existing distribution maps available for Victoria, coastal wetlands are distributed within ~80,000 ha along the coastline (Figure 3, Table 4). From this total area, 6% are mangroves, 34% are saltmarshes, and 60% are seagrasses (Table 4). Our results also showed that 8,320 ha of mangroves and saltmarshes have collapsed since their pre-European distribution (Figure 4, Table S1). Furthermore, 3,508 ha of mangroves and saltmarshes were identified as highly disturbed, having been impacted by both pasture/grazing and the presence of levees (Figure 4, Table S1). A total of 3,488 ha was classified as medium disturbed, while 8,603 ha were identified as low disturbed ecosystems (Figure 4, Table S1). Finally, our analysis showed that 16,546 ha of saltmarshes and mangroves are under natural conditions along Victoria's coastline (Figure 4, Table S1).

For seagrasses, we found that 7,031 ha have been stable since the 1960s within the Port Phillip and Western Port Bays (Figure 4, Table S1). In contrast, over 27,000 ha have collapsed since then. We also estimated that 2,178 ha of seagrasses have recently been lost, and therefore, classified as highly disturbed (Figure 4, Table S1). Furthermore, we identified that approximately 6,215 ha and 4,069 ha of seagrasses are classified as medium or low disturbed, respectively (Figure 4, Table S1). Despite no historic spatial data was available for seagrasses in Corner Inlet, in 2016, it has been estimated that the cover of subtidal seagrass was the lowest in the past 48 years (8,530 ha), declining at a rate of 50 ha^{-1} yr^{-1} (Ford et al. 2016).

Value of ecosystem services

Here, we present the results considering the carbon price at AUD47 per tonne to represent the current carbon prices in Australia under the Emissions Reduction Fund. Results for other scenarios tested in this study are available in the Supplementary Material. Overall, we found that the combined benefit provided by existing mangroves, saltmarshes, and seagrasses in Victoria is approximately AUD120.9 billion per year (Table 4). Our estimates include AUD9.05 million per year for carbon sequestration, AUD281.7 million per year for nitrogen sequestration, AUD2.3 million per year for commercial fisheries, AUD161,000 per year for recreational fisheries, and AUD120.6 billion per year for mitigating coastal hazards (Table 4). In general, saltmarshes provided the highest combined benefit amongst coastal wetlands, reaching AUD3.3 million per hectare per year (Table 4).

We found that regardless of the scenario tested, coastal hazard mitigation and nitrogen sequestration are the main ecosystem services driving the total benefit value from coastal wetlands in Victoria (Figure 5, Table 4). Furthermore, as expected, the total estimated benefits vary substantially along the coastline, with areas inhabited by saltmarshes and mangroves providing the highest benefits (Figure 5).

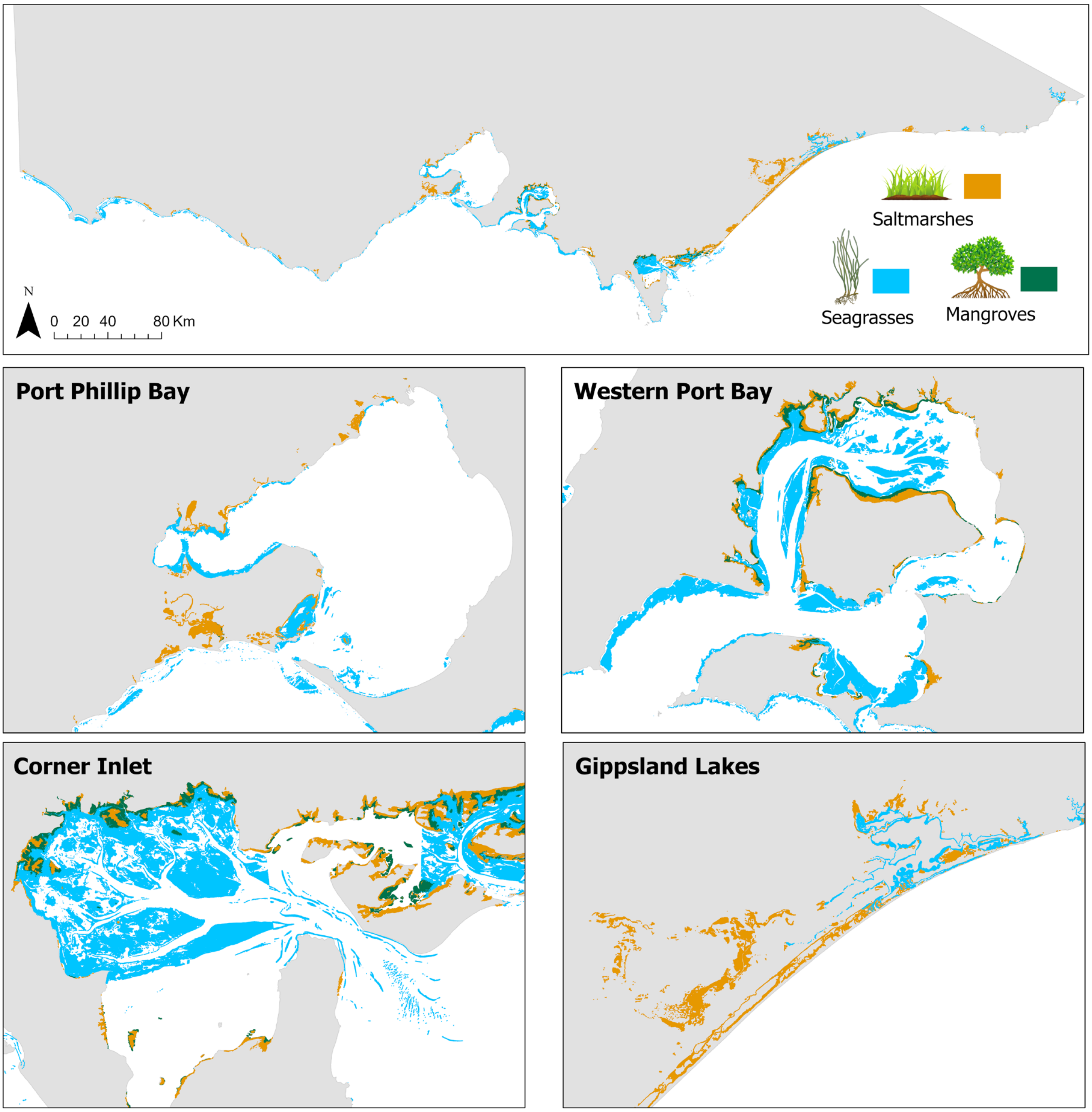

Figure 3. Current distribution of mangroves, saltmarshes, and seagrasses along Victoria's coastline, based on existing distribution maps (Boon et al. 2011, Lucieer et al. 2019).

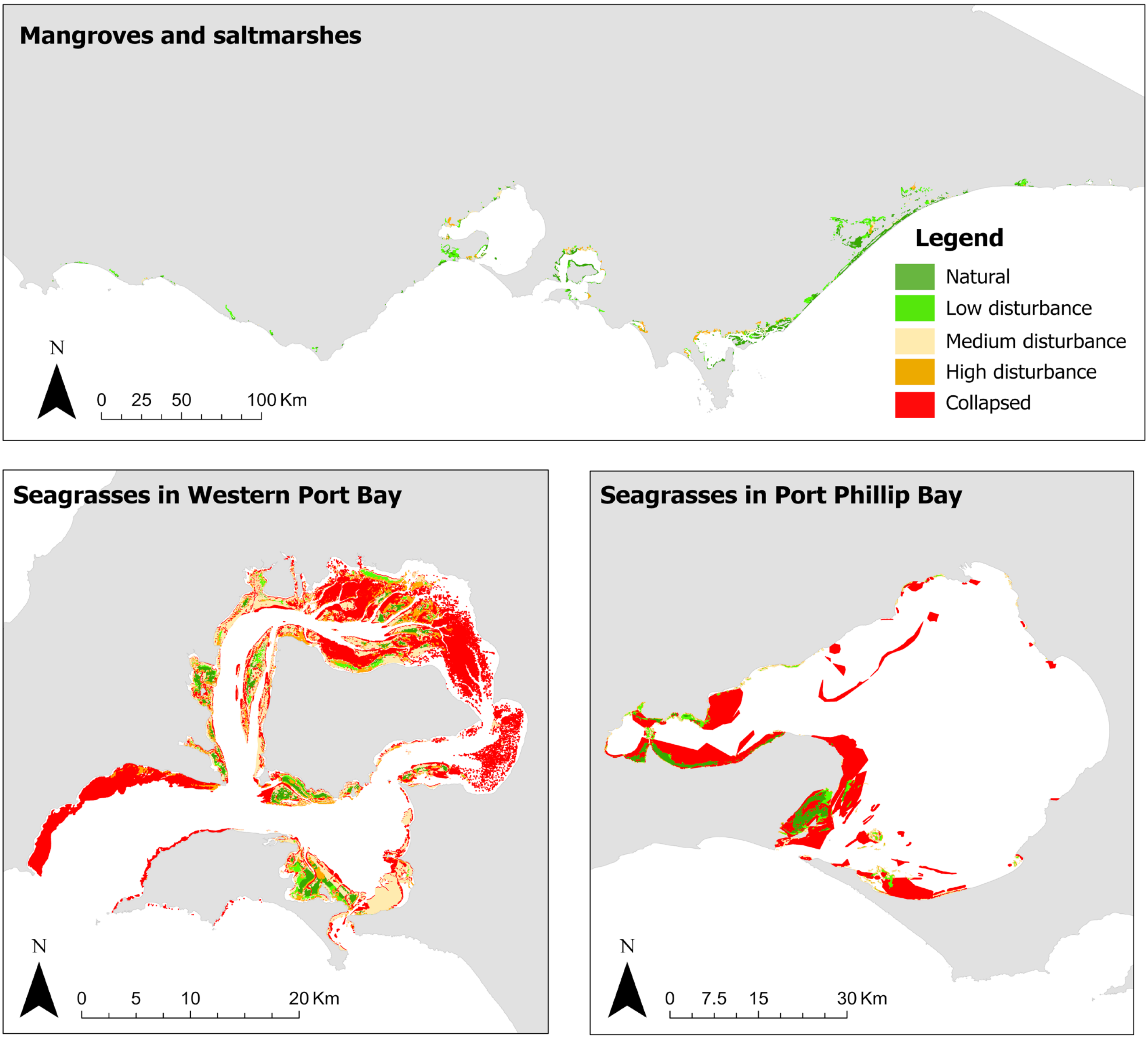

Figure 4. Condition of mangroves, saltmarshes, and seagrasses along Victoria's coastline based on existing information on their distribution (Boon et al. 2011, Lucieer et al. 2019) and land use data (Department of Environment Land Water and Planning 2018a). The condition analysis for seagrasses was limited to the region of Port Phillip and Western Port bayes due to data availability.

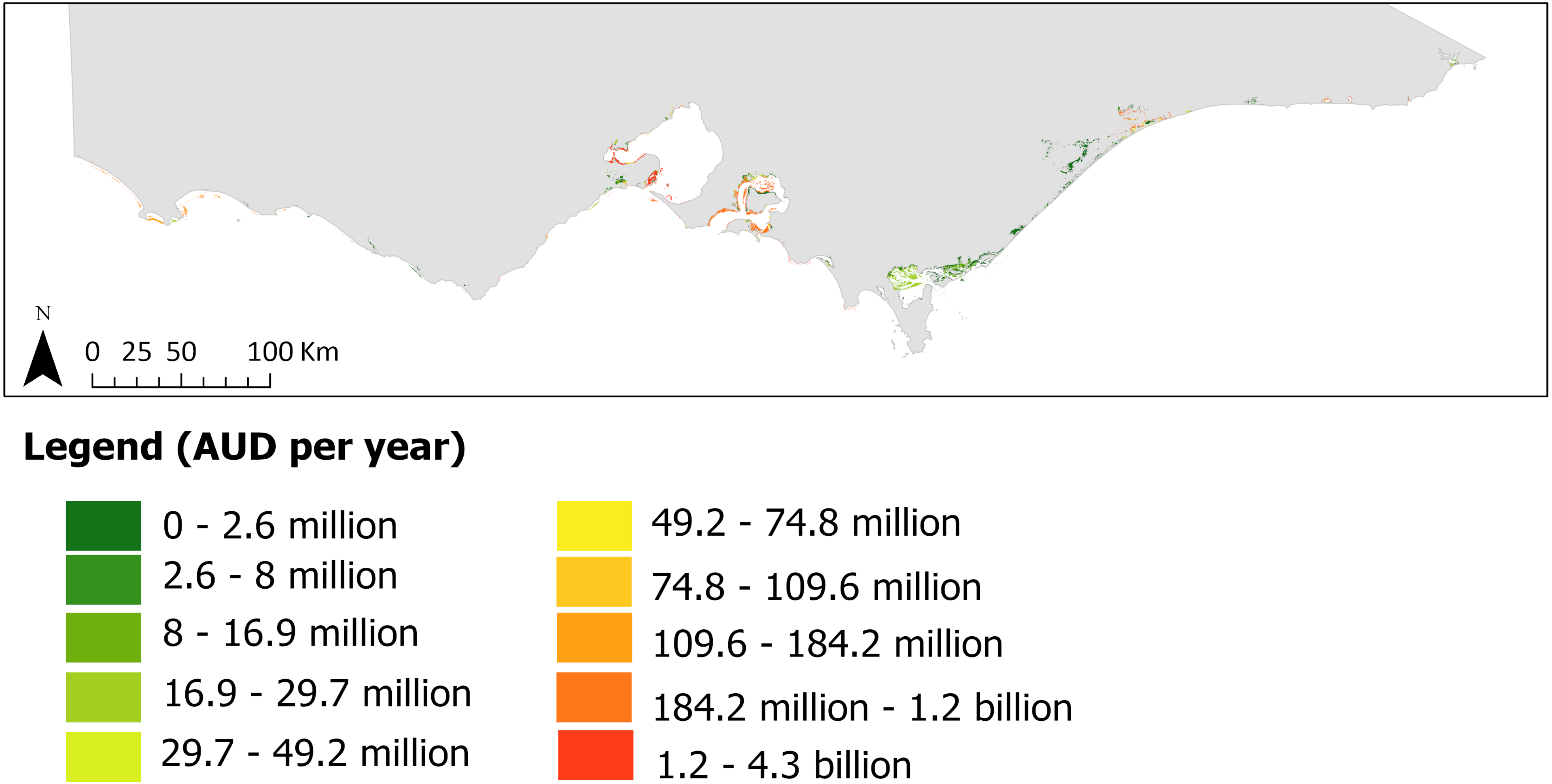

Figure 5. Estimated total benefits (combining annual valuation for carbon and nitrogen sequestration, commercial and recreational fisheries, and coastal protection) for mangroves, saltmarshes and seagrasses distributed throughout Victoria's coastline. Results presented in this figure are from the scenario considering carbon sequestration modelled in the InVEST Coastal Blue Carbon Model and carbon price at AUD47. Annual coastal protection value was estimated based on the total value of properties in 2021 within 1 km distance from coastal wetlands. Values for each ecosystem service provided by existing coastal wetlands in Victoria are available in Figures S2 to S7.

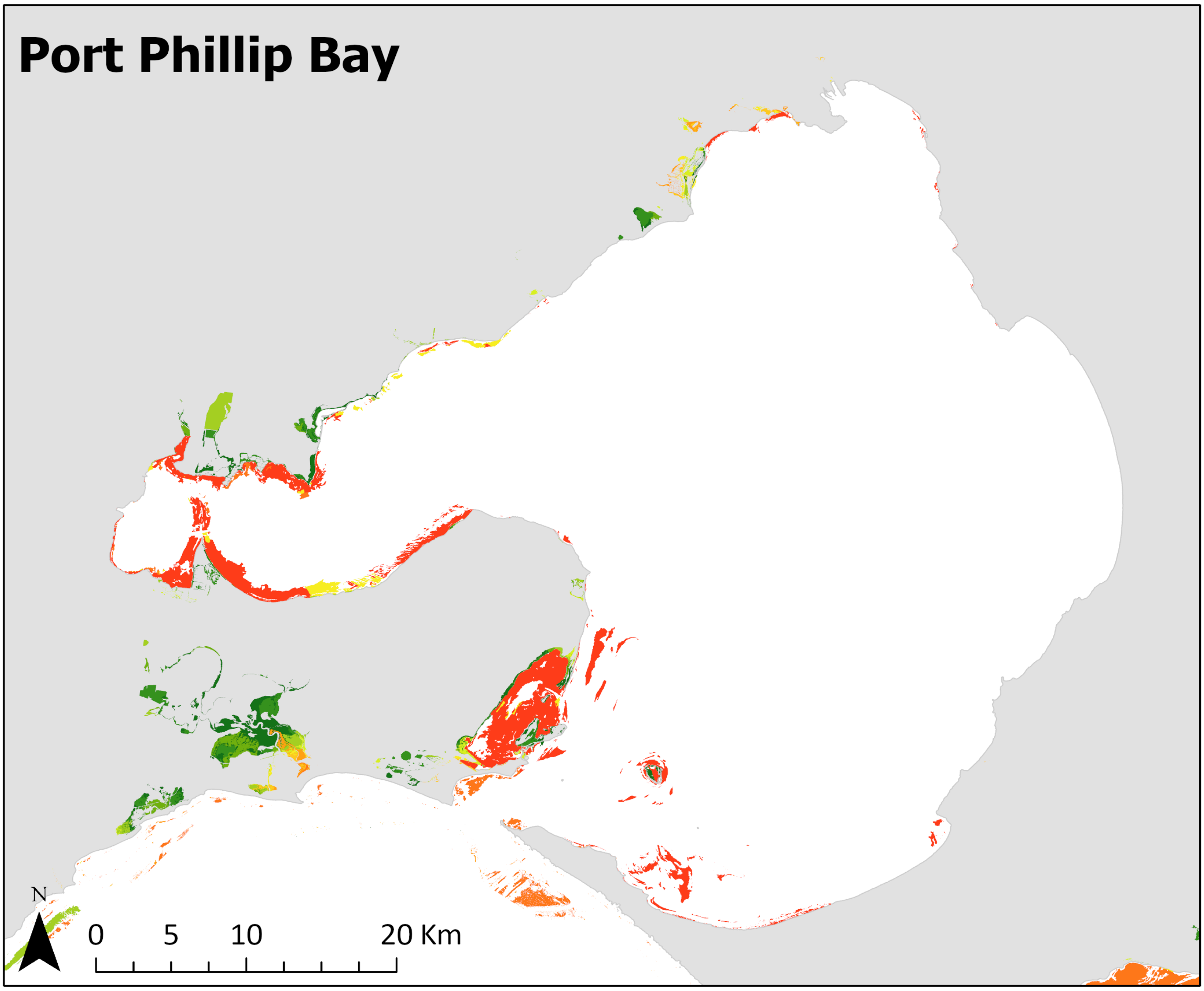

Figure 5. Continuation.

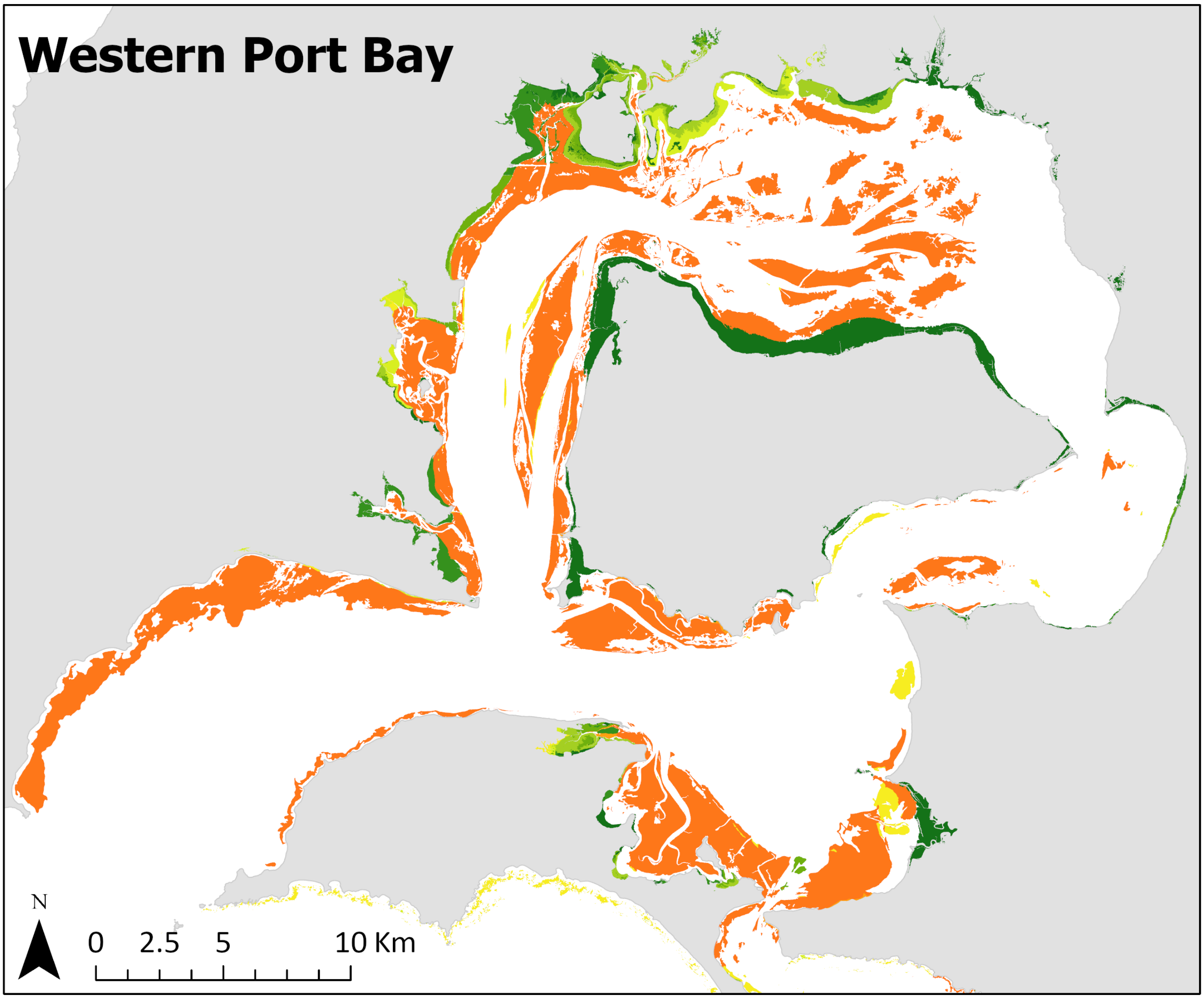

Figure 5. Continuation.

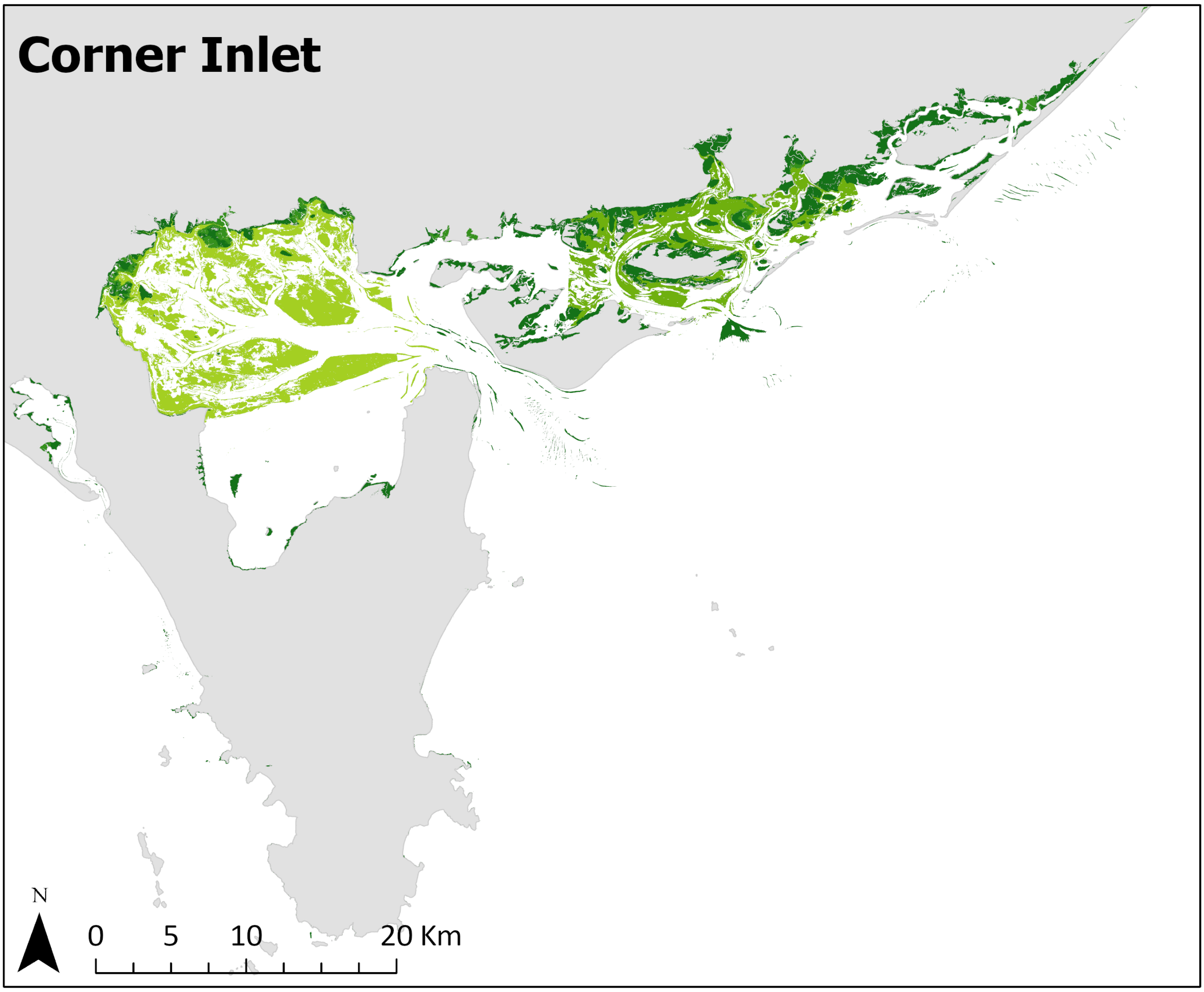

Figure 5. Continuation.

Table 4. Detailed results on ecosystem services and their associated values on a per-year basis for mangroves, saltmarshes, and seagrasses along Victoria's coastline. Results presented in this table are from the scenario considering carbon sequestration modelled in the InVEST Coastal Blue Carbon Model and carbon price at AUD47 per tonne. Annual coastal protection value was estimated based on the total value of properties in 2021 within a 1 km distance from coastal wetlands. Recreational fisheries value is the combination of the estimated catch value with the fishing trip value. Other scenarios are available in Tables S4 to S8. *Values were rounded to the nearest integer. **This value is a representation only and assumes the carbon stock may be lost if coastal wetlands are disturbed. Values from carbon stocks in existing mangroves, saltmarshes and seagrasses were extracted from Ewers Lewis et al. (2020).

Ecosystem Services		Coastal Wetlands		
		Mangroves	Saltmarshes	Seagrasses
		5,196 ha	26,949 ha	47,368 ha
Stocks				
Carbon stocks	tonnes	255,034	1.1 million	943,357
	AUD**	12 million	52.4 million	44.3 million
Flows				
Soil carbon sequestration	tonnes yr^{-1}	33,999	69,913	88,614
	AUD yr^{-1}	1.6 million	3.3 million	4.2 million
Nitrogen soil sequestration	tonnes yr^{-1}	325	2,253	461
	AUD yr^{-1}	17.5 million	185.4 million	78.7 million
Commercial fisheries	kg yr^{-1}	1.4 million	1.7 million	192.5 million
	AUD yr^{-1}	282,661	191,340	1.8 million
Recreational fisheries	kg yr^{-1}	2,702	3,503	13,737
	AUD yr^{-1}	21,804	28,273	110,912
Coastal hazard mitigation	Number of properties	154,631	1,644,684	292,544
	Total property value	93.6 billion	1 trillion	261 billion
	AUD yr^{-1}	8 billion	90.1 billion	22.4 billion
TOTAL	**AUD yr^{-1}**	**8.05 billion**	**90.3 billion**	**22.5 billion**
AVERAGE	**AUD ha^{-1} yr^{-1}**	**1.5 million**	**3.3 million**	**474,884**

Baseline trends

We considered two scenarios to estimate the potential benefits that could be potentially lost if coastal wetlands would be lost due to erosion. In this case, we found that 16,492 ha of coastal wetlands would be lost if we consider the erosion high risk (top 20^{th} percentile) areas. The area lost due to erosion increases substantially if we consider the moderate risk (top 50^{th} percentile) areas (Figure 6). In this case, seagrass meadows were the main coastal wetland lost in both erosion scenarios (i.e., approximately 37,000 ha could be lost in the moderate risk areas), followed by saltmarshes (with more than 18,000 ha in moderate risk areas) and mangroves.

Here, we present the results considering the carbon price at AUD47 per tonne to represent the current carbon price in Australia under the Emissions Reduction Fund. Results for other scenarios tested in this study are available in the Supplementary Material (Tables S9 - S18). The potential services lost due to erosion are described in Tables 5 and 6, showing that regardless of the erosion scenario, the loss of coastal wetlands in Victoria can lead to substantial loss of

ecosystem services provided by seagrasses, saltmarshes, and mangroves. We also found that the estimated total value of services did not change substantially, regardless of the scenario tested (Tables 5, 6, S8-S17). The main changes between scenarios were related to the potential soil carbon lost, which is explained by the two different methods used in this study. For example, the Coastal Blue Carbon model accounts for the different magnitude of CO_2 release depending on the type of vegetation conversion and level of disturbance (Sharp et al. 2018).

Table 5. Detailed results on ecosystem services and their associated values on a per-year basis for coastal wetlands that could be **lost due to erosion in high-risk areas** (represented by negative symbols below) along Victoria's coastline. Results presented in this figure are from the scenario considering carbon sequestration modelled in the InVEST Coastal Blue Carbon Model and carbon price at AUD47 per tonne. Annual coastal protection value was estimated based on the total value of properties in 2021 within a 1 km distance from coastal wetlands. Other scenarios are available in Tables S9-S13. Recreational fisheries value is the combination of the estimated catch with the fishing trip value. *Values were rounded to the nearest integer.

Ecosystem Services		**Coastal Wetlands**		
		Mangroves	**Saltmarshes**	**Seagrasses**
		-295 ha	-4,342 ha	-11,864 ha
Soil carbon sequestration	tonnes yr^{-1}	-3,101	-71,211	-159,322
	AUD yr^{-1}	-145,748	-3.3 million	-7.5 million
Nitrogen soil sequestration	tonnes yr^{-1}	-16	-356	-114
	AUD yr^{-1}	-925,863	-30.2 million	-15.8 million
Commercial fisheries	kg yr^{-1}	-78,157	-277,915	-48.2 million
	AUD yr^{-1}	-16,044	-30,831	-462,318
Recreational fisheries	kg yr^{-1}	-153	-564	-3,438
	AUD yr^{-1}	-1,238	-4,556	-83,228
Coastal hazard mitigation	Number of properties	-11,131	-152,934	-46,838
	Total property value	-7.9 billion	-71.2 billion	-37.2 billion
	AUD yr^{-1}	-680 million	-6.1 billion	-3.2 billion
TOTAL	**AUD yr^{-1}**	**-681 million**	**-6.1 billion**	**-3.2 billion**
AVERAGE	**AUD ha^{-1} yr^{-1}**	**-2.3 million**	**-1.4 million**	**-270,518**

Table 6. Detailed results on ecosystem services and their associated values on a per-year basis for coastal wetlands that could be **lost due to erosion in moderate-risk areas** (represented by negative symbols below) along Victoria's coastline. Results presented in this figure are from the scenario considering carbon sequestration modelled in the InVEST Coastal Blue Carbon Model and carbon price at AUD47 per tonne. Annual coastal protection value was estimated based on the total value of properties in 2021 within a 1 km distance from coastal wetlands. Other scenarios are available in Tables S14 to S18. Recreational fisheries value is the combination of the estimated catch with the fishing trip value.*Values were rounded to the nearest integer.

Ecosystem Services		Coastal Wetlands		
		Mangroves	Saltmarshes	Seagrasses
		-5,050 ha	-18,262 ha	-37,054 ha
Soil carbon sequestration	tonnes yr^{1}	-56,165	-264,245	-502,925
	AUD yr^{1}	-2.6 million	-12.4 million	-23.6 million
Nitrogen soil sequestration	tonnes yr^{1}	-320	-1,539	-360
	AUD yr^{1}	-17.2 million	-137.2 million	-68.7 million
Commercial fisheries	kg yr^{1}	-1.3 million	-1.2 million	-150.6 million
	AUD yr^{1}	-274,703	-129,658	-1.4 million
Recreational fisheries	kg yr^{1}	-2,626	-2,374	-10,746
	AUD yr^{1}	-21,190	-54,223	-260,151
Coastal hazard mitigation	Number of properties	-20,250	-352,611	-92,921
	Total property value	-13.4 billion	-209.2 billion	-81.4 billion
	AUD yr^{1}	-1.1 billion	-17.9 billion	-6.9 billion
TOTAL	AUD yr^{1}	-1.2 billion	-18.1 billion	-7.08 billion
AVERAGE	AUD ha^{-1} yr^{1}	-233,353	-991,377	-191,246

Figure 6. Estimated area of coastal wetlands to be lost due to erosion along Victoria's coastline (Department of Environment Land Water and Planning 2015). Coastal erosion risk areas were defined by the Victorian Coastal Hazard Assessment (Department of Environment Land Water and Planning 2015) based on projected rates of sea level rise, wave heights, and coastal geomorphology.

Photo: Getty Images

Management scenarios

In this study, we evaluated the benefit of managing mangroves and saltmarshes at a large scale by estimating the change in the value of ecosystem services provided by these ecosystems and the potential costs to restore them (Figure 7 and Table 7). Here, we present the results considering the carbon price at AUD47 per tonne to represent the current carbon price in Australia under the Emissions Reduction Fund in combination with a 50-years' time horizon and a 5% discount rate. This scenario has been chosen to align with the terrestrial Strategic Management Prospects developed to help the decision-making process to conserve and restore terrestrial species in Victoria. Our analysis showed that the most cost-effective management strategies to restore saltmarshes and mangroves in Victoria are fencing and the reintroduction of tidal exchange through the removal of existing levees (Table 7). Table 8 shows the detailed results for each ecosystem service and management action included in this study.

Overall, the analysis showed that the area available for restoration varies substantially based on the management action (Figure 7, Tables 7 and 8). From all management actions tested in this study, levee removal plus managed retreat is the management option with highest opportunity (~124,000 ha), while fencing only would have the smallest opportunity (~3,400 ha) along Victoria's coastline (Table 7). Furthermore, levee removal plus managed retreat had the highest cost at AUD7.6 billion; however, it also showed the highest net benefit of AUD134.8 trillion after 50 years and with a 5% discount rate (Table 7).

Furthermore, if areas that were within the past distribution of mangroves and saltmarshes but are currently used for livestock and grazing were fenced, these areas could potentially generate an annual benefit of AUD3.8 billion yr^{-1} (Table 7). Overall, fencing is the cheapest management action to restore mangroves and saltmarshes while also delivering high returns through the value of ecosystem services (Table 7). For example, after 50 years and considering a 5% discount rate, if these areas are restored at a large scale, over AUD140 billion could be delivered through carbon and nitrogen sequestration, fisheries, and coastal hazard mitigation (Table 7).

Our results also showed that planning for future inundation due to sea level rise is an essential part of planning for future conditions and is likely to play an important role in the restoration and creation of coastal wetlands (i.e., through the newly inundated areas that will be available for their expansion). In this case, our managed retreat scenario showed that the area available for restoration changes depending on the expected inundation extent (i.e., 20 cm by 2040, 47 cm by 2070 and 82 cm by 2100) (Table 7). If these areas become inhabited by mangroves and saltmarshes, we estimate an annual ecosystem service value of approximately AUD1.2 billion yr^{-1} for the areas available from 2040, followed by an annual benefit of AUD664 million and AUD795 million from 2070 and 2100, respectively (Table 7). The scale of opportunity increases when the managed retreat scenarios are combined with other management strategies such as levee removal and fencing (Figure 7 and Table 7).

Finally, some sites are known to need complex hydrological interventions to be able to restore saltmarshes and/or mangroves within their limits. We used five different sites that fit this category to understand how the restoration costs and benefits could vary at a local scale. In this case, we found that the area available to be restored is the main driver for a restoration project that includes more than two levee removals to be profitable or not (Tables 7 and 8). Furthermore, restoration costs also play an important role in the overall total benefit provided by the restoration of coastal wetlands at local scale. In this case, all five sites included in this analysis showed the potential to deliver a positive net present value if they were restored (Tables 7 and 8).

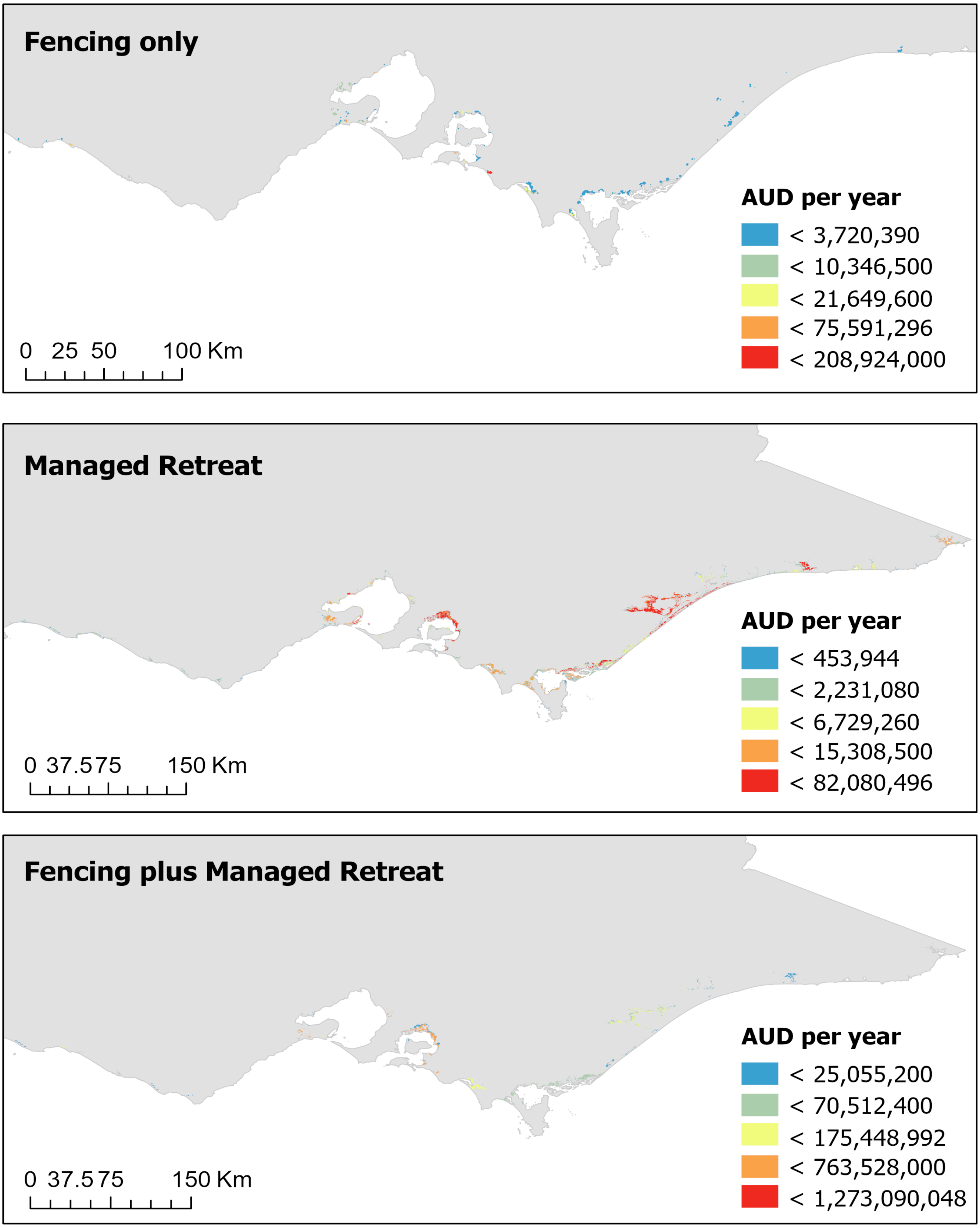

Figure 7. Potential annual benefits from restoring mangroves and saltmarshes along Victoria's coastline via different management strategies. Results presented in this figure are from the scenario considering carbon sequestration modelled in the InVEST Coastal Blue Carbon Model and carbon price at AUD47. The scenarios 'Levee Removal plus managed Retreat' and 'Fencing, Levee Removal plus Managed Retreat' are represented without the areas amenable for restoration under future conditions to highlight the areas available for restoration under current conditions. Results for other scenarios are available in Table S19.

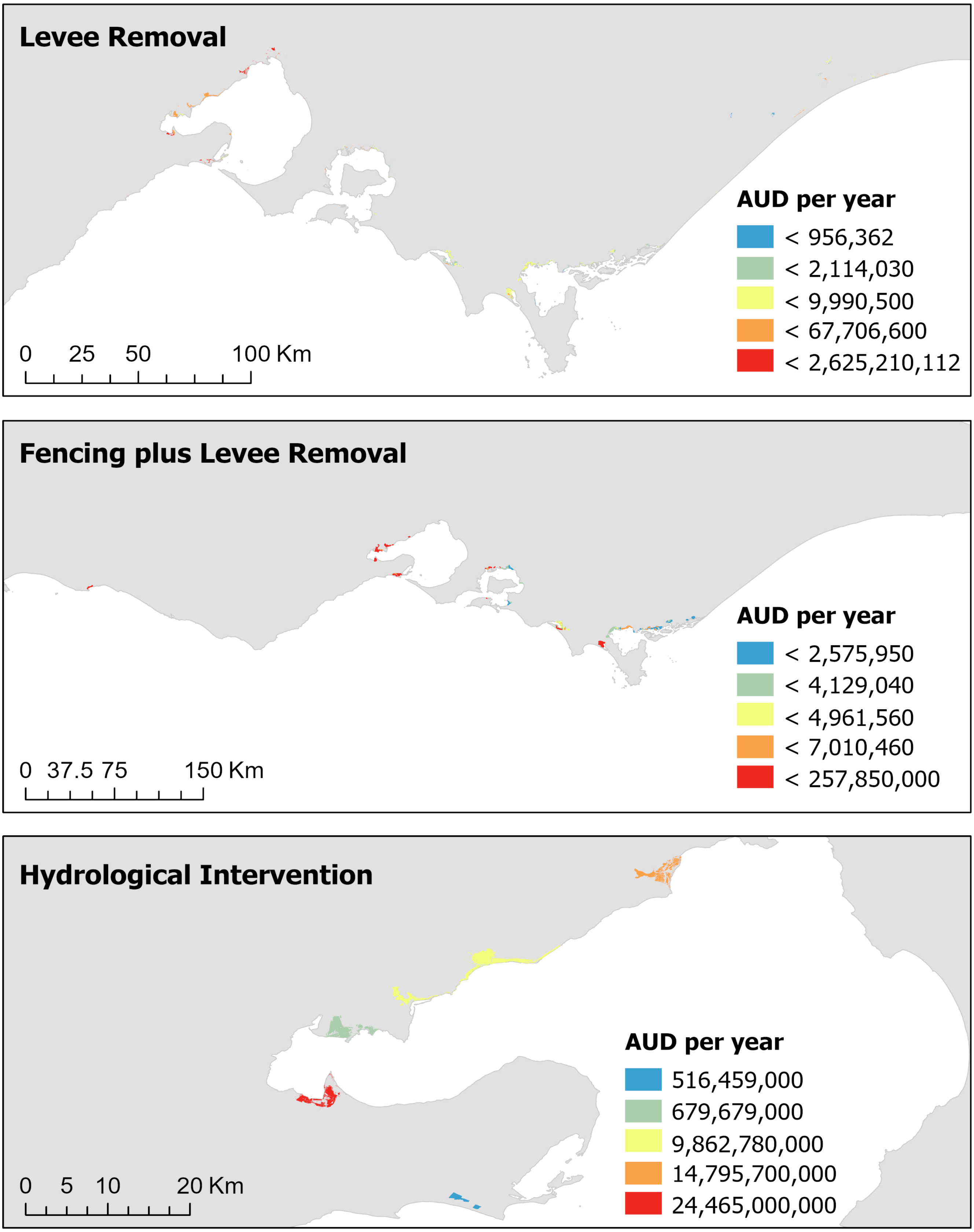

Figure 7. Continuation.

Table 7. Estimated area available for restoration in each management scenario, total costs, net benefits over 50 years and 5% discount rate. Results presented in this figure are from the scenario considering carbon sequestration modelled in the InVEST Coastal Blue Carbon Model and carbon price at AUD47. Other scenarios are available in Table S19. For the scenarios including the gradual inundation due to sea level rise, the results are correspondent to the restoration area available in each time step (i.e., 2040, 2070, 2100). *Indicates restoration for saltmarshes only.

Scenario	Area (ha)	Total Cost (million AUD)	Total Benefit (billion AUD yr^{-1})	Net Benefit (billion AUD)
Fencing	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**
	3,190	19.9	3.6	138.3
	Mangroves:	**Mangroves:**	**Mangroves:**	**Mangroves:**
	208	2	0.18	7
Managed Retreat				
2040	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**
	85,754	511.5	1.2	49.7
	Mangroves:	**Mangroves:**	**Mangroves:**	**Mangroves:**
	362	6.9	0.005	219.8
2070*	14,974	437.1	0.67	26
2100*	15,258	356.8	0.79	31.1
Fencing plus Managed Retreat				
2040*	22,680	221	0.079	3,000
2070*	6,498	210.8	0.08	3,200
2100*	7,705	217.5	10.6	404.4
Levee Removal plus Managed Retreat				
2022	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**
	7,970	6,200	3,500	134,700
	Mangroves:	**Mangroves:**	**Mangroves:**	**Mangroves:**
	271	131.6	0.47	17.8
2040*	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**	**Saltmarshes:**
	85,754	511.5	0.001	49.7
	Mangroves:	**Mangroves:**	**Mangroves:**	**Mangroves:**
	362	6.9	0.005	0.22
2070*	14,974	437.1	0.67	26
2100*	15,258	356.8	0.79	31.1

Table 7. Continuation.

Fencing, Levee Removal and Managed				
2022*	4,809	1,200	12.3	464.1
2040*	22,680	221	0.079	3,000
2070*	6,498	210.8	0.08	3,200
2100*	7,705	217.5	10.6	404.4
Hydrological Intervention				
1. Avalon	471	578.7	0.68	25.4
2. Moolap	360	561.9	24.5	929.2
3. Cheetham	392	465.8	14.8	561.9
4. Werribee	901	3.7	9.9	371.4
5. Lake Victoria	210	281.9	0.52	19.4

Table 8. Detailed results on ecosystem services and their associated values on a per-year basis for each management action included in this study. Results presented in this table are from the scenario considering carbon sequestration modelled in the InVEST Coastal Blue Carbon Model and carbon price at AUD47 per tonne. Annual coastal protection value was estimated based on the total value of properties in 2021 within a 1 km distance from coastal wetlands. *Values were rounded to the nearest integer. The results for the scenarios that include sea level rise include the total benefit considering all three years in the analysis (i.e., 2040, 2070, 2100), while the results for the hydrological interventions scenarios show the total value of ecosystem services if all five sites were restored.

		Management actions					
Ecosystem services		Fencing	Managed Retreat	Fencing plus Managed Retreat	Levee Removal plus Managed Retreat	Fencing, Levee Removal and Managed Retreat	Hydrological Intervention
Area (ha)		3,399	116,348	36,883	124,589	41,692	2,244
Soil carbon sequestration	tonnes yr^{1}	7,986	836,141	54,149	854,329	63,679	4,134
	AUD yr^{1}	375,361	39.3 million	2.5 million	40.1 million	2.9 million	194,318
Nitrogen soil sequestration	tonnes yr^{1}	283.4	9,826	3,321	10,432	3,697	114
	AUD yr^{1}	21.8 million	795.2 million	204.6 million	928 million	261.7 million	83.1 million
Commercial fisheries	kg yr^{1}	259,307	7.5 million	2.4 million	8.1 million	2.4 million	143,642
	AUD yr^{1}	33,962	843,224	261,783	914,582	620,073	15,935
Recreational fisheries	kg yr^{1}	523	15,267	4,795	16,444	5,518	292
	AUD yr^{1}	4,220	123,202	38,694	132,703	44,530	2,355
Coastal hazard mitigation	No. of properties	36,679	99.7 million	3.4 million	153.4 million	3.5 million	739,582
	Total Property $	44.2 billion	7.5 trillion	2 trillion	48.8 trillion	2.06 trillion	585.4 billion
	AUD yr^{1}	3.8 billion	1.8 million	174.2 billion	3.5 trillion	186.4 billion	50.2 billion
TOTAL	**AUD yr^{-1}**	**3.8 billion**	**2.6 billion**	**174.4 billion**	**3.5 trillion**	**186.6 billion**	**50.3 billion**
AVERAGE	**AUD ha^{-1} yr^{-1}**	**1.1 million**	**22,704**	**4.7 million**	**28.5 million**	**4.5 million**	**22.4 million**

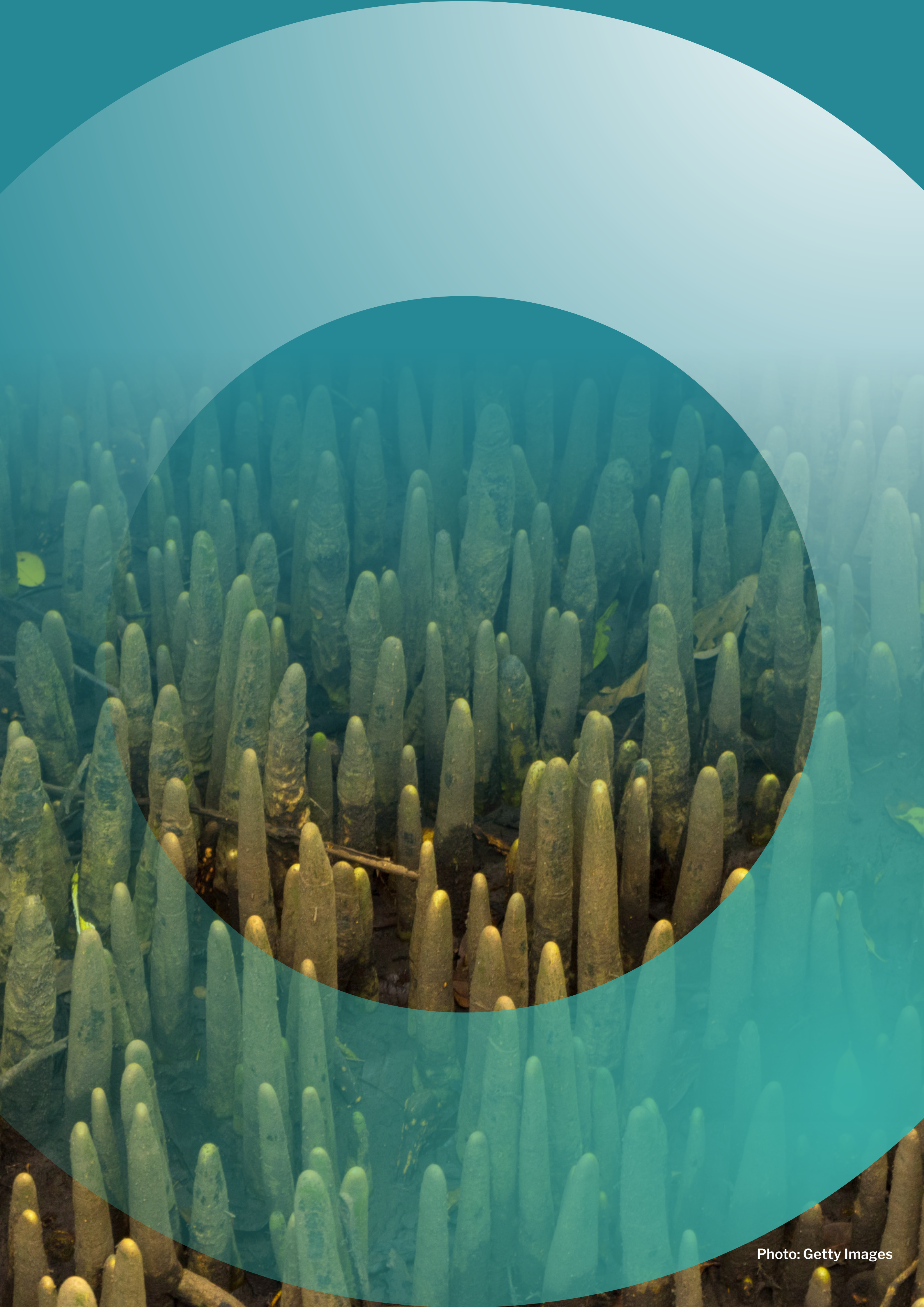

Photo: Getty Images

Discussion

Coastal wetlands in Victoria hold a large potential to deliver multiple ecosystem services, with management and restoration representing an opportunity to help managers mitigate and adapt to climate change. Overall, this project aimed to: 1) undertake a first pass assessment of current, and potential future blue carbon ecosystems along the Victorian coastline; 2) identify feasible areas for the restoration or expansion of blue carbon ecosystems through different management options; and 3) identify likely priority areas for restoration or expansion of blue carbon ecosystems based on environmental-economic analyses. This study showed that the UN System of Environmental Economic Accounting Ecosystem Accounting (SEEA EA) is a valuable framework to help decision-makers understand the current and future (based on management actions) net benefits generated by these ecosystems (Keith et al. 2017, Carnell et al. 2022b). Therefore, suggesting a new approach to support initial identification of cost-effective management actions in priority areas for restoration.

We showed that annual benefits (i.e., carbon and nitrogen sequestration, fisheries, and coastal hazard mitigation) vary substantially throughout Victoria's coastline with existing mangroves, saltmarshes and seagrasses having a combined value of AUD120.9 billion per year across their entire distribution. If mangroves and saltmarshes were to be restored at large-scale, fencing and levee removal are the most cost-effective management actions. Overall, we found that the area available for restoration changes substantially based on the management action, with fencing alone expected to deliver AUD 3.8 billion per year and AUD145.3 billion after 50 years. While our analysis only partially represents the ecosystem services provided by coastal wetlands and the costs involved in coastal restoration, our results provide key spatially explicit information to guide future investments in coastal management.

Erosion driven by projected rates of sea level rise, wave heights, and coastal geomorphology, is expected to cause major losses in coastal wetlands along Victoria's coastline (Moritsch et al. 2021). Our results showed that over 16,000 ha could be lost in the most conservative scenario (top 20th percentile representing the high-risk erosion areas) with seagrasses being the most impacted ecosystem. Despite the lack of information on the historic distribution of seagrasses at the State level, we showed that approximately 7,000 ha of seagrasses in Port Phillip and Western Port Bays have been stable through time since 1960. In contrast, ~27,000 ha has collapsed since then. Considering these trends, we suggest that future studies should focus on the long-term mapping of coastal wetlands, including seagrasses. Our ability to monitor coastal wetland condition (Boon et al. 2011) and losses and gains over time (Murray et al. 2022), has increased significantly in recent years, and these approaches should be employed across the state of Victoria. This information can then be fed directly into environmental-economic accounts, and state of the environment reporting. Such studies will generate valuable information that could be used not only in environmental accounting frameworks but also to guide the implementation of future restoration projects and the return of ecosystem services (Bullock et al. 2011, Orth et al. 2020).

Coastal ecosystem restoration is still in its infancy when compared to terrestrial ecosystems (Saunders et al. 2020) with fewer examples of projects aiming for the delivery of ecosystem services and collection of credits (Canning et al. 2021, Duncan et al. 2022). In Victoria, this study upscales the analysis conducted by Carnell et al. (2022b), which also applied the SEEA EA framework to develop spatially explicit environmental accounting for coastal wetlands in Port Phillip and Western Port Bays. Apart from the geographical scale, the other main difference between this study and Carnell et al. (2022b) is the inclusion of coastal protection values in the restoration scenarios. Regardless, both studies found fencing as the cheapest management option to restore mangroves and saltmarshes, while levee removal would provide overall larger net benefits due to large areas available for restoration. Furthermore, our study also showed the importance of planning for future sea level rise, with these areas likely to provide a value of AUD1.2

billion yr^{-1} from 2040 if inhabited by coastal wetlands. It is important to highlight that while sea level rise is expected to trigger the loss of some coastal wetlands along the coastline, there is also the opportunity to expand their distribution in newly inundated areas at larger scale. These results are in agreement with other studies modelling potential areas for restoration under sea level rise scenarios (Moritsch et al. 2021, Costa et al. 2022). In this case, providing the opportunity to develop managed retreat as a new blue carbon method.

Regardless of the management scenario tested, the potential for coastal hazard mitigation and nitrogen sequestration were the ecosystem services providing the highest benefits. This means, while the blue carbon market is the most developed nowadays (Ullman et al. 2013, Wylie et al. 2016, Vanderklift et al. 2019), if restoration projects are aiming to achieve a net benefit, this will be difficult based on carbon markets alone, with our results showing that the opportunities increase substantially if these other ecosystem services can be verified. While we still face many uncertainties in the valuation of ecosystem services provided by coastal wetlands (Himes-Cornell et al. 2018, Friess et al. 2020), a number of new methods for verifying these other ecosystem services in site-specific approaches are increasing (VERRA 2010, Smart et al. 2020, Canning et al. 2021). For example, standards developed and released by VERRA to demonstrate and verify co-benefits for carbon projects, such as coastal protection at project scale (VERRA, 2010); or the Queensland's Government Land Restoration Fund Co-Benefits Standard, which supports the verification of environmental, socio-economic and First Nations co-benefits (Queensland Government, 2021). Furthermore, we are also developing a guide for verifying ecosystem services provided by restored blue carbon ecosystems within Australia; while the full guide is expected to be released in July 2023, detailed information on the project will be available at https://www.bluecarbonlab.org/our-research/ecosystem-services/ from September 2022.

Our results showed high spatial variability in costs and net benefits, regardless of the management scenario tested. That said, even for expensive management actions (such as levee removal), it is expected that the provision of ecosystem services is likely to overweigh the investment costs in the long term (de Groot et al. 2013, Wylie et al. 2016, Vanderklift et al. 2019). The main limitation to large-scale restoration is the lack of funding, with coastal restoration usually facing very restricted budgets. In this case, our study can be used to help in the decision-making process to guide managers in the site selection process. Future studies could improve our results for mangroves and saltmarshes by integrating our spatially explicit outputs with decision support tools (such as Marxan) to understand the spatial priorities and irreplaceability in the delivery of multiple ecosystem services at a minimum cost (Ball et al. 2009, Adame et al. 2015, Atkinson et al. 2016, Strassburg et al. 2020). It was not possible to include seagrasses and kelp forests in this current project, as across the state we lack the information to identify areas for restoration at large-scale and have high uncertainty (due to lack of case studies) of the approaches and costs to restore these ecosystems. Once these knowledge gaps are addressed, opportunities for restoration of seagrasses and kelp forests will be able to be included in future accounts.

The substantial value of ecosystem services provided by coastal wetlands is a major asset for Victoria, which can be increased by the implementation of restoration projects aiming to expand their distribution. Our spatially explicit results at a large scale can help underpin future projects by providing baseline information that is crucial for investment. However, understanding the limitations and caveats about valuing ecosystem services and their potential net benefits is key to improving the implementation of restoration projects. The application of the SEEA EA framework to valuate coastal wetlands at this large spatial-scale, is a significant step-forward in the contribution to this field, with an opportunity to systematically plan for long-term monitoring programs that align with the framework implementation (Keith et al. 2017, UNCEEA 2021). Furthermore, demonstrating the economic value resulting from the conservation and restoration of coastal wetlands can guide the necessary changes in management and policies over time (Barbier 2019).

Overall, one of the main limitations of this study is that all scenarios considered that management actions were taken at a large scale, which while suitable for identifying optimal locations for action, can over- or underestimate the area amenable for restoration and their potential return on investment (Costa et al. 2022). Therefore, future restoration projects must also consider the current local conditions and local benefits provided to resident species (for example, essential freshwater habitats to migratory bird species, which were created when tidal barriers/levees are constructed) (Heimhuber et al. 2021, Waltham et al. 2021, Costa et al. 2022). There are other limitations that may over- or underestimate the potential net benefit generated by restored coastal wetlands. For example, limitations of this study that are likely underestimating the potential benefits include: 1) inclusion of only mapped ecosystems (Boon et al. 2011) and levees (Department of Environment Land Water and Planning 2018b); and 2) inclusion of only five potential benefits generated by coastal wetlands due to data availability (e.g., social benefits or non-market recreational fisheries have not been included). In contrast, certain limitations are likely to overestimate the potential net benefits, such as 1) project costs do not include additional costs (e.g., strategies to manage additional threats to biodiversity such as feral animals) that may be relevant to implement at local scale; and 2) limitations on estimating coastal hazard mitigation at large scale, including no consideration of the spatial variability of wave attenuation along the coastline (Lee et al. 2021b). Finally, there are limitations, such as the uncertainties on the time for restored mangroves and saltmarshes to deliver ecosystem services, that remain unclear and which is also likely to vary depending on the service (Su et al. 2021, Carnell et al. 2022b). For example, in this study, our assumptions were made based on previous studies summarised in Carnell et al. (2022b) we assumed that mangroves and saltmarshes would start providing co-benefits at different timeframes after the restoration action has taken place (e.g., carbon and nitrogen sequestration at 0 years, fisheries after 5 years, and coastal hazard mitigation after 10 years). However, the time needed for restored coastal wetlands to provide co-benefits can vary substantially depending on the project site location, which reinforces the need for long-term monitoring of restoration activities. In this case, our results are useful to identify cost-effective options at landscape scale with site-specific restoration studies still required before any levee removal or sea level rise restoration projects should proceed. Furthermore, future studies or local assessments should also consider these uncertainties during the planning stage so on-ground projects can help answer these uncertainties.

The growing interest in blue carbon markets has driven increasing interest in conservation and restoration of coastal wetlands. In Australia, the Federal Government has released the first blue carbon method that enables the issuance of

Australian Carbon Credit Units to restore coastal wetlands through the removal of levees and consequent reintroduction of tidal flows (Clean Energy Regulator 2022a), with new methods expected to be developed in the near future. That said, blue carbon markets still face several challenges, from legal uncertainties in the legislation context (Bell-James and Lovelock 2019, Bell-James et al. 2022), risks in the carbon permanence to high implementation costs (Macreadie et al. 2022). A recent study summarised the existing barriers (and potential solutions) to operationalise blue carbon projects, which include 1) social (i.e., improve stewardship by incorporating indigenous knowledge and values), 2) governance (i.e., improve policy and legal arrangements, clarifying property rights), 3) financial (i.e., improve financial approaches), and 4) technological (i.e., use of accounting tools to incorporate co-benefits, development of low-cost technological solutions for measuring carbon sequestration, and resolving knowledge gaps in blue carbon cycles) (Macreadie et al. 2022). The possibility of having higher payments for ecosystem services if additional ecosystem services are verified (such as the Land Restoration Fund program developed in Queensland, https://www.qld.gov.au/environment/climate/climate-change/land-restoration-fund/co-benefits/overview) is a great opportunity to increase the return on investment and to increase the financial amenability of land holders towards blue carbon projects.

This study shows that the SEEA EA framework is a powerful approach to help the decision-making process, making a direct contribution to managers by a case to judge the return on investment for the restoration of mangroves and saltmarshes in Victoria. Here, we showed that coastal wetlands deliver significant returns. This can guide future decisions in the market and financing opportunities that could be applied in the region. Overall, our results provide a good indication of where different management actions would provide the best returns on investment. The implementation of coastal wetland restoration projects is also dependent on the uptake of local communities, land holders, and stakeholders. Here, we showed that coastal wetlands deliver significant returns. Our results can guide future decision making in financing opportunities and management actions at local scales.

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