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Estimating blue carbon sequestration under coastal management scenarios

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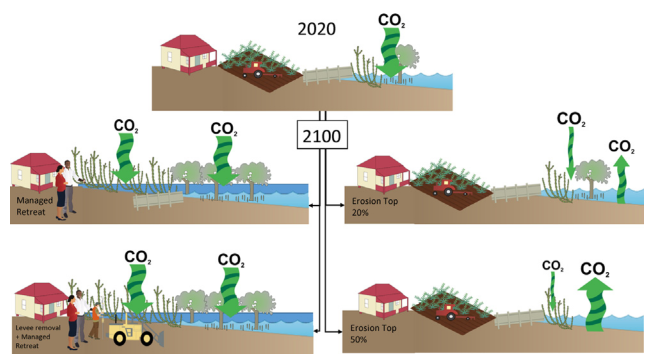
HIGHLIGHTS

- Erosion of soils in blue carbon ecosystems is a large carbon emissions threat.
- Managed retreat sequestered 7 to 17 million Mg CO_2 more than no-action alternative.
- Levee removal had similar sequestration compared to managed retreat but began sooner.
- Protecting and restoring blue carbon ecosystems can help reduce carbon emissions.

GRAPHICAL ABSTRACT

Conceptual diagram presenting scenarios as individual scenes of coastal land use and blue carbon ecosystems. Downward green arrows represent carbon sequestration. Upward green arrows represent carbon emissions. Not to scale.



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ABSTRACT

Restoring and protecting "blue carbon" ecosystems - mangrove forests, tidal marshes, and seagrass meadows - are actions considered for increasing global carbon sequestration. To improve understanding of which management actions produce the greatest gains in sequestration, we used a spatially explicit model to compare carbon sequestration and its economic value over a broad spatial scale (2500 km of coastline in southeastern Australia) for four management scenarios: (1) Managed Retreat, (2) Managed Retreat Plus Levee Removal, (3) Erosion of High Risk Areas, (4) Erosion of Moderate to High Risk Areas. We found that carbon sequestration from avoiding erosion-related emissions (abatement) would far exceed sequestration from coastal restoration. If erosion were limited only to the areas with highest erosion risk, sequestration in the non-eroded area exceeded emissions by 4.2 million Mg CO_2 by 2100. However, losing blue carbon ecosystems in both moderate and high erosion risk areas would result in net emissions of 23.0 million Mg CO_2 by 2100. The removal of levees combined with managed retreat was the strategy that sequestered the most carbon. Across all time points, removal of levees increased sequestration by only an additional 1 to 3% compared to managed retreat alone. Compared to the baseline erosion scenario, the managed retreat scenario increased sequestration by 7.40 million Mg CO_2 by 2030, 8.69 million Mg CO_2 by 2050, and 16.6 million Mg CO_2 by 2100. Associated economic value followed the

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same patterns, with large potential value loss from erosion greater than potential gains from conserving or restoring ecosystems. This study quantifies the potential benefits of managed retreat and preventing erosion in existing blue carbon ecosystems to help meet climate change mitigation goals by reducing carbon emissions.

1. Introduction

Globally, net zero greenhouse gas emissions must be reached by 2035 to limit warming to 1.5 °C (Rogelj et al., 2018). Removing carbon dioxide (CO_2) from the atmosphere through biosequestration is one method to help mitigate the consequences of global climate change (Griscom et al., 2017). Nature-based solutions address both the causes and consequences of climate change, and more specifically blue carbon initiatives are aimed at protecting, restoring, and managing coastal ecosystems. To meet emissions reductions goals, many governments are evaluating strategies to reduce national emissions and adapting to the impacts of climate change. Carbon sequestration through the conservation or restoration of natural habitats represents one of the actionable steps for a country to achieve net carbon reductions (Herr and Landis, 2011). To achieve this, some nations are engaging in debt for nature swaps and establishing other innovative financing mechanisms to fund blue carbon projects.

Coastal "blue carbon" ecosystems, mainly mangrove forests, tidal marshes, and seagrass meadows, can sequester carbon in their soils at rates up to an order of magnitude greater than terrestrial forests, giving them an important role in biosequestration strategies (Alongi, 2012; Chmura et al., 2003; Mcleod et al., 2011; Murdiyarso et al., 2015). Their comparatively small total area and lack of data have historically led to their exclusion from landscape-level carbon storage assessments. However, soils of these ecosystems can store carbon for millennia, representing an avenue for climate mitigation and an ecosystem service to the global human population (Barbier et al., 2011; Macreadie et al., 2017b; Mateo et al., 2006; Simard et al., 2019). Protection and restoration of blue carbon ecosystems have recently gained international recognition as strategies for effective carbon sequestration (Herr and Landis, 2016).

Anthropogenic activities such as land conversion for agricultural production and urban expansion threaten blue carbon ecosystems (Craft et al., 2009; Davis et al., 2016). Land-use change, including conversion of mangroves to aquaculture (Adame et al., 2018; Arifanti et al., 2019; Kauffman et al., 2014) or conversion of tidal marshes to coastal development and agriculture (Howe et al., 2009), can disturb the carbon-rich soil and release tons of soil carbon to the atmosphere (Lovelock et al., 2017). If allowed to migrate further inland, these ecosystems may retain their capacity to sequester carbon (Adams et al., 2012; Meyer et al., 2008; Rogers et al., 2019). However, landward ecosystem migration is often restricted by human development or coastal protection structures such as levees and seawalls, resulting in ecosystem loss as sea levels rise, unless vertical accretion of soils is rapid enough to keep pace with rising water levels (Craft et al., 2009; Nicholls and Cazenave, 2010). Removal of these structures to actively restore tidal inundation has gained attention as a strategy that can reduce losses from sea level rise and improve carbon sequestration capacity for blue carbon ecosystems (Macreadie et al., 2017a,b). Even without levee removal, maintaining carbon sequestration as sea levels rise by creating or allowing space for ecosystem migration will play an important role in sustaining carbon sequestration (Rogers et al., 2019) as well as reducing coastal hazards (Hino et al., 2017). Sea level rise and increasing wave energy may also erode soils (Passeri et al., 2015), presenting a challenge for taking advantage of restored tidal inundation. Successful management of these ecosystems to promote carbon sequestration will require balancing tidal inundation and exposure to erosive forces such as strong currents and waves (Fagherazzi et al., 2007).

Along with many other regions of the world, Australia has a growing interest to include blue carbon ecosystems in carbon markets and government emissions reductions plans (Serrano et al., 2019). The Australian government created the Climate Solutions Fund (CSF; formerly the Emissions Reduction Fund) as part of its plan to reduce emissions by 26 to 28% below 2005 levels (Vanderklift et al., 2018). The CSF pays for activities that would deliver carbon sequestration that would not otherwise occur. For example, sequestering carbon as a result of breaching coastal defenses and restoring tidal inundation would be eligible for CSF credits, while ongoing sequestration in existing blue carbon ecosystems would not be eligible. A reverse auction determines the unit price of carbon. Carbon sequestration also has value to society outside of markets, as sequestration is an ecosystem service that stabilizes the global climate and reduces damages associated with climate change (e.g. increasingly severe floods, droughts, wildfires, and hurricanes), known as the Social Cost of Carbon (SCC; Interagency Working Group on Social Cost of Carbon, United States Government, 2010). The CSF reflects the cost of government payments to conserve blue carbon ecosystems, while the SCC approximates the value of sequestration benefits derived by conserving them.

Complementing the national carbon market, regional scale management plans are important for the protection or restoration of these resources. In the Australian state of Victoria, the comprehensive Marine and Coastal Policy (Department of Environment, Land, Water and Planning, 2020) recognizes that blue carbon ecosystems provide many services, including carbon sequestration, and outlines several management options to address threats to them, such as managed retreat and erosion control. Selecting which land management options to apply and where requires understanding of the value of potential blue carbon opportunities under different management scenarios. This information is currently lacking, limiting the ability to include blue carbon ecosystems into emissions reduction strategies (Lovelock et al., 2017; Macreadie et al., 2017a; Rogers et al., 2018). To assess the impact of varying management activities, we used an ecosystem services model to estimate carbon sequestration in soils of mangrove, tidal marsh, and seagrass ecosystems using a spatially explicit modeling approach in Victoria.

We evaluated net sequestration between 2020 and 2100 under four scenarios of ecosystem restoration or loss. We compare the economic value of CO_2 sequestered (and emitted) in each of the five scenarios using two pricing methods, modeling their CSF value and the SCC value. These results can directly be applied to prioritize areas for restoration and conservation and provide estimates of potential economic benefits from the presence and planning for blue carbon ecosystems.

2. Methods

2.1. Study area

The state of Victoria in southeast Australia (Fig. 1a) is a cool temperate region that supports extensive blue carbon ecosystems. Tidal marsh is highly diverse (131 species), and comprised of multiple communities ranging from tall shrubs dominated by *Tecticornia arbuscula*, to low groundcover dominated by *Sarcocornia quinqueflora* (Boon et al., 2011). Victoria's mangroves are the most southern in the world and are comprised of one species, *Avicennia marina* subsp. *australasica* (Boon et al., 2011). Seagrass is mainly found in low-energy bays and estuaries. Species include *Zostera muelleri, Zostera nigracaulus, Posidonia*

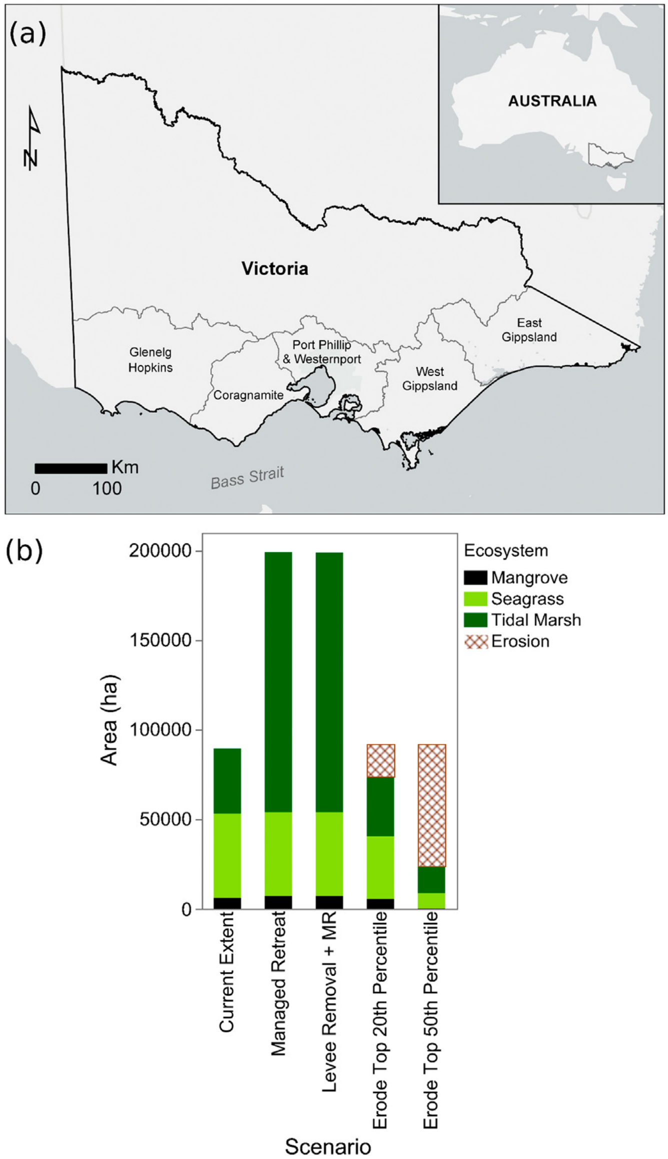

Fig. 1. (a) Catchment Management Authority boundaries of coastal Victoria, Australia. (b) Area of Victoria's blue carbon ecosystem types in each scenario. Area of the current blue carbon ecosystems is provided for reference. Area that can be eroded is distinguished from area of existing blue carbon ecosystems with the crosshatch pattern. 'MR' indicates Managed Retreat.

australis, Ruppia spp., and *Lepilanea marina* (Ewers Lewis et al., 2018). This area of Australia is expected to experience many of the deleterious impacts of climate change and is located in a climate change "hot spot," where these impacts are likely to be exacerbated (Ridgway, 2007). Sea levels are expected to rise 45 to 82 cm before the end of the century (CSIRO and Bureau of Meteorology, 2015), and storm surge events are increasing in frequency (Colberg and McInnes, 2012; Young and Ribal, 2019). The combined effects of these climate change impacts could affect the distribution and resulting carbon sequestration capacity of coastal ecosystems.

2.2. Blue carbon model overview

We evaluated future carbon sequestration into soils using the Coastal Blue Carbon Model (v3.7, The Natural Capital Project) from the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) open source tool suite (Sharp et al., 2019; www.naturalcapitalproject.org). This tool combines existing regional data on average annual carbon accretion rates for unique land cover classes and government-provided maps of land cover (Victoria Department of Economic Development, Jobs, Transport and Resources, 2018) to create spatially explicit estimates of carbon sequestration under different management scenarios and timeframes (Supplemental Material, Section 1). We focused on modeling soil carbon because it is typically the largest carbon pool in blue carbon ecosystems (Donato et al., 2011; Fourqurean et al., 2012; Saintilan et al., 2013) and because of its ability to sequester carbon for long time scales (Mcleod et al., 2011). The model assigns value to the net carbon sequestration according to either market price or the Social Cost of Carbon (Table S1) (Sharp et al., 2019), which is the global average cost of climate-related damages that society must bear for each additional metric ton of CO_2 in the atmosphere (Interagency Working Group on Social Cost of Greenhouse Gases, US Government, 2016). The model places value on change in total carbon stock instead of the amount of carbon stocks themselves, as most carbon market payment systems, including Australia's, focus on change in greenhouse gas balances (Supplemental Material, Eqs. (1)–(3)). Maintaining existing carbon stock is not eligible for payments, but sequestration or avoided emissions count toward determining market value.

We modeled carbon sequestration from 2020 to 2100 under different future scenarios for Victoria's blue carbon ecosystems:

1. Managed Retreat: Restoration by reintroduction of tidal flow through gradual sea level rise (no levee removal)
2. Levee Removal Plus Managed Retreat: Restoration by the reintroduction of tidal flow through levee removal, beginning in 2020, plus the reintroduction of tidal flow by gradual sea level rise
3. Erosion of Top 20th Percentile: Erosion of blue carbon ecosystem in Victoria's top 20% of coastal erosion risk areas (high risk), defined by the Victorian Coastal Hazard Assessment (Department of Environment, Land, Water and Planning (DELWP), 2015)
4. Erosion of Top 50th Percentile: Erosion of blue carbon ecosystem in Victoria's top 50% of coastal erosion risk areas (moderate to high risk), defined by the Victorian Coastal Hazard Assessment (DELWP, 2015)

While each of these scenarios were modeled across the Victorian coast as a whole, pieces of these scenarios can be spatially combined based on local conditions and sea level rise planning goals.

We used blue carbon ecosystem extent polygons for tidal marsh, mangroves, and seagrass as the starting state of ecosystems for all scenarios from a national compilation of marine habitat extents (Lucieer et al., 2019). We did not include polygons for the seagrass species *Amphibolis antarctica* in this study since it generally grows on a base of hard substrate in this region and therefore does not have the same carbon sequestration capacity (Ewers Lewis et al., 2018). While mudflats also store carbon in their soils, their carbon sequestration dynamics are poorly understood, and therefore we did not include mudflat ecosystems in this study.

Ecosystem polygons were converted to 100 × 100 m resolution rasters to serve as the ecosystem extents for 2020, the initial time step of our model. We selected this resolution to match the resolution of existing carbon stock maps of 1 m depth (Carnell et al., 2019; www.maps.oceanwealth.org). We used the Cell Centers method in ArcGIS 10.6 to reduce overestimation of area from conversion, particularly for locations where blue carbon ecosystems are patchy (Supplemental Material, Sections 1.2–1.5). Because climate change will alter ecosystem distribution before 2100 (Rogers et al., 2014; Saintilan and Williams, 1999), we assumed that some blue carbon ecosystems would be lost if no action was taken. We represented this as loss of the ecosystems in the Erosion of the Top 20th Percentile (high risk of erosion) scenario. We treated this erosion scenario as the baseline. Carbon sequestration in alternative scenarios was measured as gains or losses against this scenario.

We assumed the rate of carbon sequestration for each ecosystem was constant for the entire period. While there is mixed evidence for whether soil carbon sequestration rates will change with rising sea levels and changing temperature and rainfall, the overall effects of interactions between temperature, microbial activity, oxygen exposure, and soil moisture are difficult to predict (Lewis et al., 2014; Macreadie and Hardy, 2018; Macreadie et al., 2019; Trevathan-Tackett et al., 2015). Incorporating predictions of changes in sequestration rates and future species distributions was beyond the scope of this study. We used average carbon sequestration rates and standard deviations for mangrove (4.93 Mg CO_2 ha^{-1} yr^{-1} $\pm$ 0.47), tidal marsh (1.49 Mg CO_2 ha^{-1} yr^{-1} $\pm$ 1.02), and seagrass (1.87 Mg CO_2 ha^{-1} yr^{-1} $\pm$ 1.63) from core samples in temperate blue carbon ecosystems from Victoria and New South Wales (Serrano et al., 2019).

2.3. Managed Retreat scenario

Sea level rise presents opportunities to restore historical blue carbon ecosystems, if tidal waters are allowed to advance. The Victorian Department of Environment, Land, Water and Planning (2020) recognizes managed retreat as a climate adaptation option. To model restoration of coastal vegetation on the coastal plain from managed gradual return of tidal connectivity to historical habitat and low-lying areas with sea level rise, we combined existing blue carbon ecosystem extents, with extents estimated from the inundation due to sea level rise plus storm surge in 2040, 2070, and 2100 (DELWP, 2018). We assumed that low-lying areas at or below the average elevation encompassed by the sea level rise at each particular time would become inundated (Supplemental Material, Section 1.4). A key assumption of restoring blue carbon ecosystems via managed retreat is that no additional levees or sea wall fortifications would be built to limit future inundation extent (Table 1).

In these scenarios, we assumed ecosystems between 0 and 20 years post-restoration (tidal reconnection) sequester carbon at a fraction of the rate of an undisturbed ecosystem (Table S2; Craft, 2001; Marbà et al., 2015; Osland et al., 2012). We assigned sequestration rates to restored ecosystems (Table S2) at the appropriate intervals corresponding to the years since a given 100 × 100 m square of landscape became inundated. This produced a staggered progression of newly restored ecosystems with lower carbon sequestration rates, 10-year-old restored ecosystems with intermediate sequestration rates, and ≥20 year-old ecosystems with the same sequestration rate as their original counterparts (Table S3). Sea level rise can also increase rates of carbon sequestration with increasing inundation depth (Morris et al., 2002; Rogers et al., 2019), but this is not included in the model due to high levels of uncertainty in the relationship between levels of inundation and carbon sequestration in the study region, and thus our sequestration rates are likely conservative.

Another assumption was that areas with historical mangrove presence could be restored to mangroves (Boon et al., 2011), while all other restored areas would become tidal marsh. Here the term restoration can also include creation of blue carbon ecosystems in areas where they did not historically occur. Based on historical data, it is uncertain how far mangroves will encroach into tidal marshes as the climate warms (Saintilan and Williams, 1999). Seagrass meadows may also occupy former mangrove habitat as sea levels rise (Neil Saintilan and Williams, 1999; Whitt et al., 2020). However, we did not model seagrass restoration because historical data on seagrass extent was limited, and seagrasses are dynamic in their coverage due to conditions that are harder to predict (Rasheed et al., 2014; York et al., 2015), causing us to limit their use in scenarios to their present-day extent. We used government land cover maps to categorize which areas were compatible with blue carbon restoration. Land cover was broadly categorized into the following categories: residential, commercial, industrial, mining, agriculture, water catchment, camps and recreation, and nature reserves and preserves. Categories were further subdivided into classes of public versus private ownership and types of use (including vacant land). We excluded areas with land uses that are incompatible with restoration such as urban development, extractive industrial use, or any other land use involving permanent hard structures (Supplemental Material, Section 1.3) based on land use classifications (Victoria Department of Economic Development, Jobs, Transport and Resources, 2018). The newly-inundated area would increase mangrove extent by approximately 1000 ha and increase tidal marsh extent by 109,000 ha (Fig. 1b). Seaward losses of ecosystems were addressed in the erosion scenarios (below). Details on geospatial processing and methods for creation of

Table 1
Assumptions for future land use/land cover and coastal land management for each blue carbon ecosystem scenario.

Scenario	Land use/land cover assumptions	Management assumptions
Managed Retreat	• Return of tidal inundation will facilitate restoration and expansion of blue carbon ecosystems • Altered hydrological patterns do not cause losses of blue carbon ecosystems • The extent and carbon sequestration rates of currently existing mangroves, tidal marshes, and seagrasses remain the same through 2100	• Policies for managed retreat allow inland migration of ecosystems to grazing and other non-urban land-uses • No additional coastal fortifications alter area affected by sea level rise • Existing coastal levees remain in place
Managed Retreat Plus Levee Removal	• Return of tidal inundation will allow restoration and expansion of blue carbon ecosystems (mangroves and tidal marshes) • The extent and carbon sequestration rates of currently existing mangroves, tidal marshes, and seagrasses remain the same through 2100 • Altered hydrological patterns do not cause loss of blue carbon ecosystems • Levee removal does not include possible inundation by storm surge	• Policies for managed retreat allow inland migration of ecosystems to undeveloped land • No additional coastal levees or sea wall fortifications alter the area affected by sea level rise
Erosion of Top 20th Percentile (High risk areas)	• Erosion will be limited to the areas within the top 20th percentile of erosion risk • Eroded blue carbon ecosystems will convert to mudflat if in a sheltered area and will convert to open water if located on the open coast • Blue carbon ecosystems will not spread beyond their current extent	• No additional coastal fortifications alter area affected by sea level rise or erosion • No restoration of eroded blue carbon ecosystems takes place • No redeposition of lost sediment
Erosion of Top 50th Percentile (Moderate to high risk areas)	• Erosion will be limited to the areas within the top 50th percentile of erosion risk • Eroded blue carbon ecosystems will convert to mudflat if in a sheltered area and will convert to open water if located on the open coast • Blue carbon ecosystems will not spread beyond their current extent	• No additional coastal fortifications alter area affected by sea level rise or erosion • No restoration of eroded blue carbon ecosystems takes place • No redeposition of lost sediment

maps for each time step of InVEST modeling are provided in the Supplemental Material (Section 1).

2.4. Levee Removal Plus Managed Retreat scenario

Breaching coastal levees to restore tidal connectivity is one approach that allows the return of historical blue carbon ecosystems and expansion of existing ecosystems into nearby low-lying areas or freshwater wetlands (Howe et al., 2009; Macreadie et al., 2017a; Rogers et al., 2014). Earlier restoration of tidal connectivity would allow carbon sequestration (and other ecosystem services) to return sooner than waiting for gradual sea level rise to overtop levees, thus increasing the attractiveness of this option to managers or land owners wishing to participate in the CSF. To model ecosystem restoration by breaching coastal structures such as levees, we extended the footprint of existing blue carbon ecosystems to include the projected area gained by the reinstatement of tidal flow. We assumed that levee breaching or removal activities starting in the present could begin sequestering carbon by this time. As a proxy for the footprint of tidal reintroduction, we combined the footprint of historical (pre-1750's) tidal marsh and mangroves (Sinclair and Boon, 2012) with areas within 1 km of the breached structure that were ≤1 m in elevation above mean sea level (i.e., a 'bathtub' approach to inundation) extracted from coastal LiDAR data. The mean elevation of the historical extent of tidal marsh and mangrove was 0.98 m, so we used the heuristic 1.0 m threshold as the envelope for possible restoration via levee removal. We used the same land use classifications to define areas that could and could not be restored that we used for the Managed Retreat scenario. In addition to area inundated by levee removal, we also estimated area inundated by sea level rise and storm surge (using the same methods as described for the Managed Retreat scenario). Where managed retreat and levee removal inundated the same locations, levee removal was given priority because this action would happen before gradual inundation by sea level rise through managed retreat. While levees were built to hold back tidal inundation, there was substantial overlap between areas that could be re-inundated with levee removal and areas that projected sea level rise would inundate even with current levees in place. It is possible that levee removal could result in the return of blue carbon ecosystems in the newly inundated area while causing losses elsewhere through changes in current speed, sediment delivery, turbidity, sudden flooding, or other factors (Cabaço et al., 2008; Wasson et al., 2012). However, due to the tradeoff between maintaining certainty in local processes and maintaining broad spatial coverage (Craft et al., 2009; Rezaie et al., 2020), we did not model ecosystem area or sediment deposition changes from these processes. Newly inundated area by 2100 was similar to that of the Managed Retreat scenario, but areas affected by levee removal became inundated sooner (Fig. 1).

2.5. Coastal Erosion scenarios

The Department of Environment, Land, Water and Planning (2020) recognizes erosion as a threat to coastal ecosystems. Modeling erosion of blue carbon ecosystems used risk scores from the Victoria Coastal Hazard Assessment (DELWP, 2015) to identify locations with high risk (in the top 20th percentile) and moderate and high risk (in the top 50th percentile) for coastal erosion based on projected rates of sea level rise, wave heights, and coastal geomorphology. Loss of high risk areas removed 600 ha of mangroves, 12,000 ha of seagrass, and 3000 ha of tidal marsh. Loss of moderate and high risk areas combined removed 6000 ha of mangroves, 38,000 ha of seagrass, and 21,000 ha of tidal marsh (Fig. 1). We modeled the loss of carbon that would occur if blue carbon ecosystems within these high risk areas converted to mudflat or low wave energy subtidal (if sheltered within the bounds of an estuary) or high wave energy open water (if exposed to the open ocean). An ecosystem-specific percentage of carbon stock was released from each location across the landscape during the conversion (Table S4). We used spatially explicit carbon stock maps for coastal blue carbon in Victoria (Carnell et al., 2019; www.maps.oceanwealth.org). The fate of eroded sediment and its associated carbon is a large source of uncertainty in estimations of carbon budgets in blue carbon ecosystems (Pendleton et al., 2012). We assumed that 100% of eroded carbon would eventually become CO_2 (Davis et al., 2016; Kirwan et al., 2010; Lovelock et al., 2017) and that the eroded sediment would not be deposited elsewhere in a way that was beneficial to carbon sequestration (e.g., redeposition onto adjacent marsh or formation of a sheltering mudflat downcurrent). Assumptions for each scenario are presented in Table 1.

2.6. Estimating the value of carbon sequestration

We estimated the economic value of carbon sequestration from each of these scenarios using two carbon pricing methods:

1. September 2020 CSF auction price: USD 11.02 Mg^{-1} CO_2, 1.5% discount rate (Clean Energy Regulator, 2020; Reserve Bank of Australia, 2019)
2. SCC price: Price of carbon (USD) increases over time (USD 50 to 150), 2.5% discount rate (Interagency Working Group on Social Cost of Greenhouse Gases, U.S. Government, 2016; Sharp et al., 2019)

For the CSF auction price, we chose a discount rate equal to Australia's 1.5% cash rate (the federal government's interest rate for overnight loans) from August 2016 to May 2019 (Reserve Bank of Australia, 2019). As the CSF is government-funded, using the rate at which the government can borrow was appropriate (Treasury, 2019). The 2.5% discount rate for the Social Cost of Carbon (SCC) represents a general rate appropriate for developed countries and allows for a more global comparison of the conservation value of sequestration (Treasury, 2019). CSF value is calculated based on *additional* carbon sequestration beyond what a baseline no-action scenario would sequester. Using this pricing method, carbon sequestered or lost in the baseline scenario has no value, though prevention of erosion that would have otherwise occurred does have value. The Erosion of the Top 20th Percentile scenario served as our baseline.

To estimate uncertainty in the CSF price, we used prices ($N = 11$) from all past auctions (Clean Energy Regulator, 2020) to find the 95% confidence interval (CI) of values awarded for the average price per ton. Because prices were not normally distributed, we used bootstrapping with replacement ($N_{runs} = 1000$) to find the mean of the resampled distribution and distance between CI's and the mean. We found the upper and lower CI's for the most recent auction price by adding to and subtracting these respective distances (−0.79, +0.74) from the current price, assuming that future auction prices would stay within these bounds.

The SCC approximates the economic value of damages avoided by removing CO_2 from the atmosphere (Interagency Working Group on Social Cost of Greenhouse Gases, U.S. Government, 2016). Because blue carbon ecosystems sequester carbon and thereby provide an ecosystem service to society irrespective of carbon market accounting rules, carbon sequestered has value when using the SCC regardless of additionality. To estimate uncertainty in SCC value, we used data from Ricke et al. (2018), which explored how combinations of Representative Concentration Pathways (RCPs) and socioeconomic development will influence the costs of climate change damages by country. We selected scenarios where SCC was not set to 0 by default ($N = 244$ scenarios). Again, because these data were not normally distributed, we used bootstrapping with replacement ($N_{runs} = 1000$) to find the upper and lower CI's and distance from the mean SCC (−0.40, +0.44). We added and subtracted these distances from the mean projections of SCC values supplied by InVEST (Sharp et al., 2019).

Using ArcMap 10.6.1, economic values of Victoria's blue carbon sequestration were summed within state boundaries (including coastal waters) and within the boundaries of coastal Catchment Management

Authorities (CMAs), the state's primary natural resource management districts (Fig. 1). All economic values are reported in U.S. dollars (USD) using the average exchange rate from the 2019 calendar year (1 Australian dollar = 0.70 USD). Economic values are reported on a per hectare basis to facilitate direct comparison between the different management scenarios.

2.7. Model limitations

Our scenarios were designed to bracket best and worst case futures (e.g., all loss, all gain) for blue carbon ecosystems in Victoria and compare them, rather than to make projections on likely spatial combinations of gains and losses. Climate change will raise annual minimum temperatures, allowing further mangrove encroachment into tidal marshes (Rogers et al., 2005; Saintilan and Williams, 1999). Because mangroves have higher sequestration rates than tidal marshes (Serrano et al., 2019), this will likely increase their future contributions to sequestration (Kelleway et al., 2016). This study does not take into account how changes to soil temperature, oxygen, and microbial activity will affect sequestration rates (Macreadie et al., 2019; Trevathan-Tackett et al., 2017), or how interactions between climate-related increases in temperature, wind, and waves will affect the persistence of these ecosystems (Reguero et al., 2019; Young et al., 2011).

Changes in blue carbon ecosystem distributions will likely be a mosaic of ecosystem gains and losses, dependent on sea level rise adaptation policy, blue carbon restoration initiatives, and erosion management. The restoration scenarios presented here represent an optimistic estimation of future sequestration, while the erosion scenarios are pessimistic estimations. It is unlikely that a single scenario will occur across the entire Victorian coast. Maximizing sequestration will require actions to address erosion and provide a path for inland migration. Our maps are intended to estimate the opportunity for blue carbon sequestration at broad spatial scales (thousands of kilometers of coast), serving as a spatial framework to target a combination of management scenarios for coastal land use planning. The use of suitability models and migration models for future blue carbon ecosystem distributions can aid in refining spatial predictions of future sequestration under a warmer climate (Geselbracht et al., 2015; Kirwan and Megonigal, 2013; Zhou et al., 2016). Site-level models, while necessary for detailed planning, require hydrological modeling, feasibility assessments, land tenure evaluation, and are not trivial when scaling up to extents as large as the Victorian coast. This is not to say that site-level models are not necessary. Our analysis can provide guidance for spatially prioritizing development of more time- and data-intensive site-level assessments.

3. Results

In the baseline scenario, Erosion of the Top 20th Percentile, net loss of carbon resulted from erosion in 2030. Decades of carbon sequestration in the remaining blue carbon ecosystems gradually reversed these emissions. 5.68 million and 2.57 million Mg CO_2 were emitted in 2030 and 2050 respectively, but by 2100, positive sequestration of 4.22 million Mg CO_2 occurred. In the managed retreat scenario, the combination of sequestration and lack of emissions from avoided erosion resulted in a difference of 7.40 million Mg CO_2 relative to the baseline erosion scenario by 2030. This grew to 8.69 million Mg CO_2 by 2050 and 16.6 million Mg CO_2 by 2100 (Fig. 2), approximately a 4-fold increase over the baseline sequestration for the same year. The Levee Removal Plus Managed Retreat scenario followed a similar pattern with approximately 50 to 200 thousand Mg CO_2 additional sequestration at any given time step compared to Managed Retreat alone (Figs. 2, 3a–f). While the Levee Removal Plus Managed Retreat scenario had the greatest gains in carbon sequestration at all time points, its relative increase over Managed Retreat alone was marginal at the scale of the Victorian coast, at only 3% higher in 2030 and 2050 and 1% higher in 2100 (Fig. 2). Earlier timing of flooding associated with levee breaching or removal were responsible for this early advantage in sequestration (Supplemental Material, Section 2; Fig. S1), but sea level rise

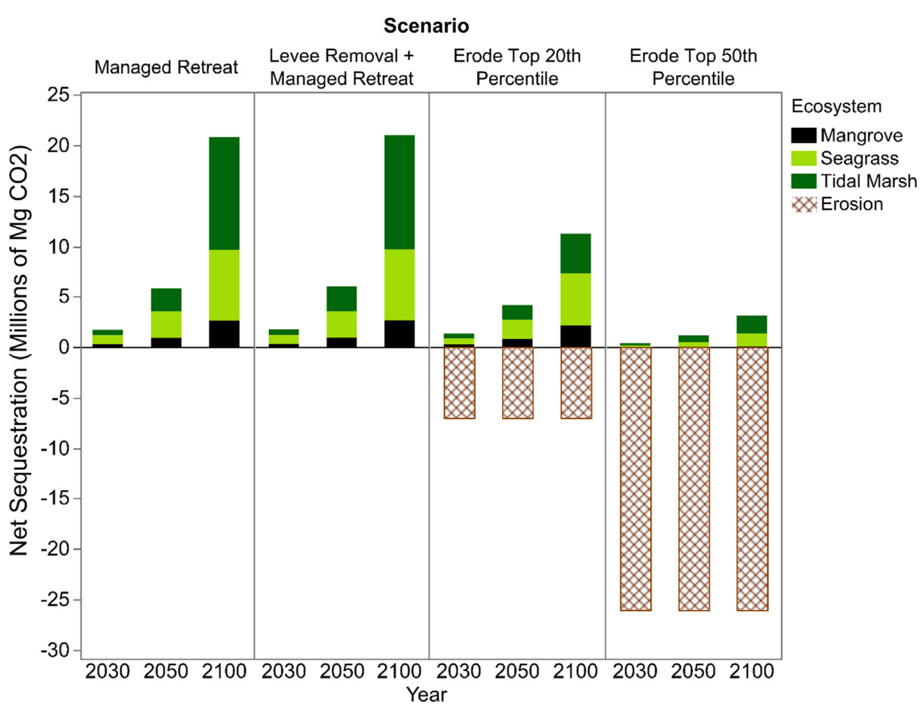

Fig. 2. Total net carbon sequestration in soils of blue carbon ecosystems by scenario. Values above zero represent carbon sequestered from the atmosphere. Values below zero represent carbon emissions (negative sequestration) from soils. Carbon sequestration was modeled using the InVEST Coastal Blue Carbon model with maps of different potential future ecosystem distributions for each scenario.

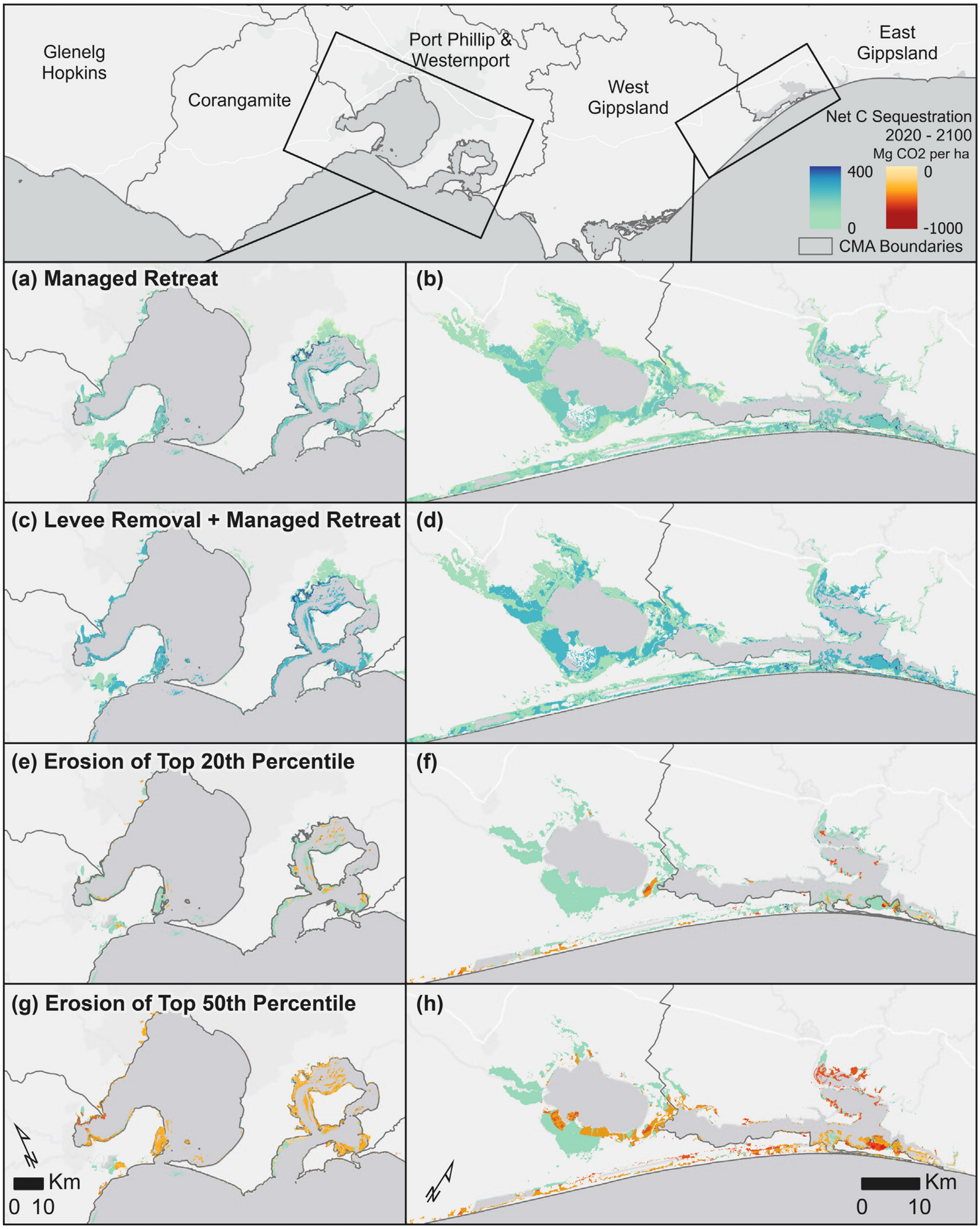

Fig. 3. Map of InVEST models for total net carbon sequestration (Mg CO_2 equivalent ha^{-1}) from 2020 to 2100 in the Port Phillip (left) and Westernport area (right) for the (a, b) Managed Retreat scenario, (c, d) Managed Retreat Plus Levee Removal scenario, (e, f) Erosion of Top 20th Percentile risk areas scenario, and (g, h) Erosion of Top 50th Percentile risk areas scenario. Full-color interactive maps for the whole Victoria coast are available at https://maps.oceanwealth.org. Within the map viewer, select Regional Planning > Regional Datasets > Australia > Blue Carbon to see individual layers.

ultimately inundated greater area over time. In the Erosion of the Top 50th Percentile scenario, sequestration in the low remaining area of blue carbon ecosystems (Fig. 1b) was not enough to offset erosion-related emissions, and net sequestration was negative for the entire study period. This resulted in net emissions of 23.0 to 25.6 million Mg CO_2 at any given time (Figs. 2, 3g–h), which equated to a total loss of 27.2 million Mg CO_2 by 2100 compared to the baseline scenario. More than one hectare of restoration was required to offset losses from one hectare of erosion (Fig. S1).

On a per hectare basis, original blue carbon ecosystems had the highest CSF and SCC value compared to their restored counterparts (Fig. 4a–d, Fig. S1), regardless of how early the restoration began. Overall CSF and SCC value for restoration were higher when restoration was started earlier, such as with near-term levee removal, which maintained at least 80% of the CSF and SCC value of corresponding original ecosystems by 2100. Restoration that started later, due to waiting for sea level rise for inundation, had lower overall carbon sequestration (Fig. S1) and therefore lower CSF and SCC values compared to

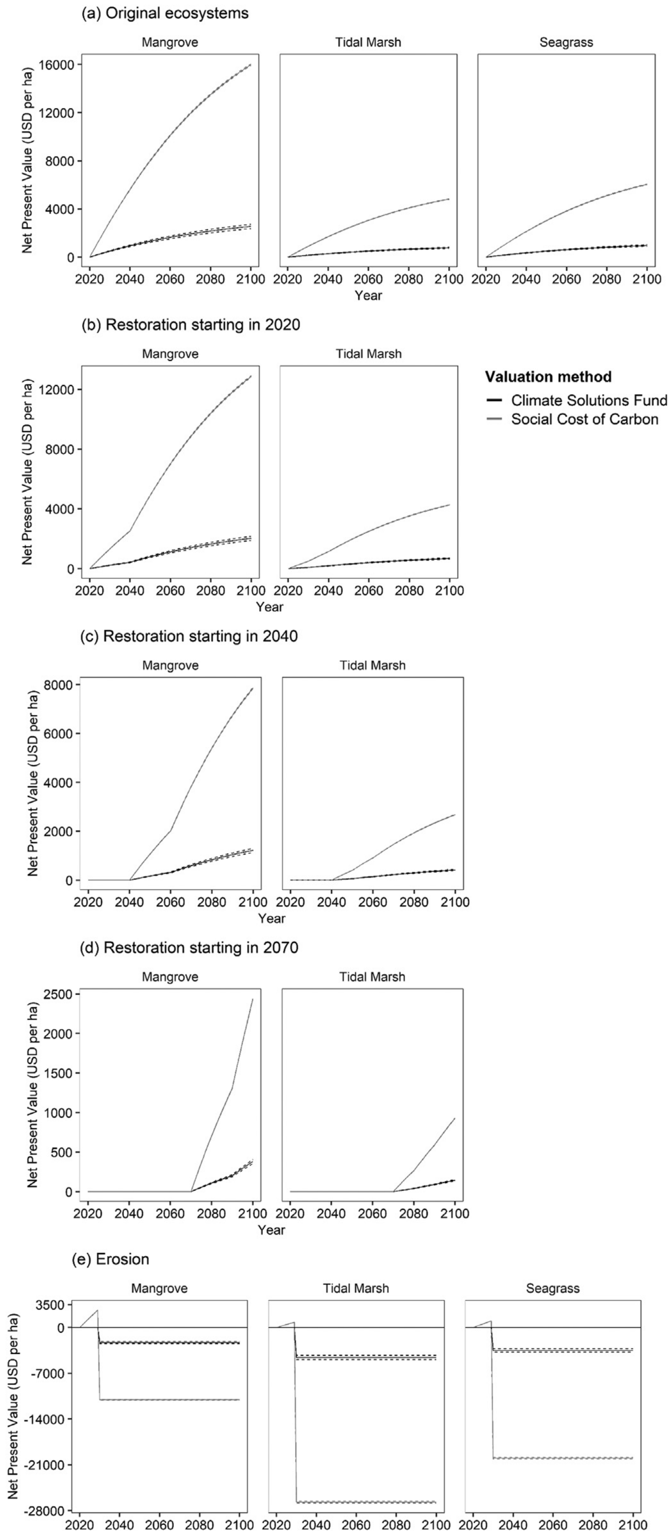

Fig. 4. Comparison of the net present value of equivalent carbon payments from the Climate Solutions Fund (black lines) and Social Cost of Carbon (grey lines) for each ecosystem state found in the different management strategies: (a) original ecosystems (undisturbed), (b) restoration starting in 2020 from levee removal, (c) restoration starting in 2040 from managed retreat from sea level rise, (d) restoration starting in 2070 from managed retreat from sea level rise, and (e) erosion of blue carbon ecosystems. Seagrass restoration was not modeled. Dashed lines (- -) represent 95% confidence intervals. Values presented reflect carbon sequestration or emissions that satisfy conditions for additionality (i.e., sequestration or emissions that would not have happened anyway).

restoration from levee removal. For example, mangroves and tidal marshes where restoration started with inundation in 2070 would earn less than 20% of what original ecosystems would earn (Fig. 4d) by 2100. For original ecosystems and ecosystems restored before 2070, the rate of value gain slowed over time due to the effects of discounting on net present value in later years. This pattern was not observed for ecosystems restored in 2070 (Fig. 4d), where the timing of increase in post-restoration sequestration rates coincided with timing when discounting had the greatest reductions on value of future gains.

Erosion-related value losses were greatest in tidal marshes and lowest in mangroves. By 2100, lost potential CSF payments were USD ha^{-1} 2294 for mangroves, USD ha^{-1} 4597 for tidal marshes, and USD ha^{-1} 3508 for seagrasses (Fig. 4f), with CI's spanning 159 to 320 USD on either side of the mean estimate (Fig. S2). Climate damages (SCC values) for eroded ecosystems were 4.8 to 5.8 fold larger in magnitude (more negative) than estimated CSF value (Fig. 4f). Restoration of one hectare of mangroves or tidal marshes could not compensate for the loss of CSF or SCC value from one hectare of erosion, regardless of restoration start date. Only original mangroves left intact could sequester enough carbon to offset emissions and associated value loss from equivalent area of eroded mangroves (Fig. 4a, e; Fig. S1). Because carbon sequestrations or emission has social impacts regardless of additionality, sequestration prior to erosion slightly offsets negative SCC values (Fig. 4e). However, due to additionality requirements, this sequestration did not qualify for CSF value.

The SCC value of carbon sequestration was greater in both positive and negative extremes than the CSF value at all time points. Projected SCC values typically varied from tens to hundreds of dollars per hectare. Projected variation in CSF value was larger and more frequently hundreds of USD ha^{-1} (Fig. S2).

Across all CMAs, erosion posed the greatest risk to carbon sequestration and its value and outweighed potential gains from restoration. In both erosion scenarios, West Gippsland CMA and Port Phillip and Westernport CMA experienced the most significant losses of carbon sequestration (Fig. S3). Erosion risk was most prevalent in the southern part of Gippsland Lakes, the western edge of Port Phillip Bay, and along the islands in Western Port Bay (Fig. 3e–h). Glenelg Hopkins CMA had the lowest total starting area of blue carbon ecosystems and the lowest gains in carbon sequestration in the restoration scenarios. Glenelg Hopkins was the only CMA to attain positive net sequestration in both erosion scenarios by 2050 (Fig. S3), as this portion of Victoria had relatively little erosion-prone area overlapping with blue carbon ecosystems. In all other CMAs, erosion of high risk areas resulted in net emissions at 2050 and did not become net positive sequestration until later years. Erosion of moderate and high risk areas combined never resulted in net sequestration in these CMAs.

West Gippsland CMA gained the most sequestration from managed retreat-driven restoration compared to other CMAs, with restoration areas concentrated in Gippsland Lakes and Corner Inlet (Fig. 3b, d). Sequestration gains from managed retreat were second highest in East Gippsland CMA and similar in Corangamite CMA and Port Phillip and Western Port CMA. In Corangamite CMA, this was concentrated along the coastal fringe and entrance of Port Phillip Bay, while in East Gippsland CMA, gains were concentrated in Gippsland Lakes (Fig. 3a, b). Highest sequestration gains from levee removal were located in West Gippsland CMA, followed by Port Phillip and Western Port CMA (Fig. 3c, d). Gains from levee removal were relatively minor in all other CMAs. Areas flooded by levee removal often overlapped with areas that would later be flooded under the Managed Retreat scenario.

4. Discussion

Sequestration of carbon in soils represents an important strategy for achieving climate mitigation goals at state, national, and global scales (Clean Energy Regulator, 2020; Vermeulen et al., 2019). The scenario-based evaluations presented in this study can guide spatial planning decisions for the state's Marine and Coastal Policy and CSF target areas by evaluating where carbon could accumulate or be lost under different strategies for restoration and what the value of these changes are. For example, active restoration by returning tidal inundation via levee removal yielded additional sequestration by 2030 in limited areas (Fig. 2, 3). Meanwhile, setting aside open space for ecosystem migration with sea level rise (Managed Retreat scenario) produced greater sequestration that will not be realized in appreciable quantities until 2050 or later (Figs. 2, 3), an action which may incur management costs. The Levee Removal Plus Managed Retreat scenario shows managers that the combination of rapid and gradual restoration allows for earlier monetary gains from the CSF and the greatest potential carbon sequestration in the future.

Our results highlight that erosion in this landscape poses a major risk of releasing centuries worth of soil carbon stocks and therefore reducing the carbon sequestration services of the region. For example, carbon lost in one hectare of tidal marsh erosion was greater than what one hectare of marsh restoration could replace within the modeling period (Fig. S1). Exposure of old, deeply buried carbon to oxygen triggers microbial remineralization and increases carbon turnover (Macreadie et al., 2019). Preventing further ecosystem loss is important to overall carbon sequestration, as well as more cost-effective for climate mitigation compared to the restoration of degraded ecosystems (Fig. 4). Conservation of existing ecosystems maintains higher carbon sequestration rates compared to restored ecosystems, avoiding the missed sequestration opportunity that is inherent in decades of reduced sequestration rates of newly restored ecosystems (Figs. 2, 4, S1). Erosion control efforts could target locations that we have identified as losing the most carbon should they erode (Fig. 3e–h), if technically feasible and cost effective.

4.1. Relevance of carbon pricing methods

The total value of carbon sequestration through the current CSF price was consistently lower than the cost of damages associated with leaving the same amount of carbon in the atmosphere. This value difference suggests that the amount the Australian government pays private parties to proactively sequester carbon is considerably lower than what it would pay to address direct climate impacts if that carbon were to remain in the atmosphere. This represents a gap between the cost of avoiding climate damages and the cost of responding to climate damages once they occur. Since no Australian government agency currently pays the SCC value, the SCC is less relevant to individual parties conducting sequestration activities, though it remains important to both the government and residents of Australia, who could bear the full impacts of missed sequestration opportunities.

The CSF price is unlikely to remain static over the entire modeling period, but traditional approaches to projecting its change over time such as Brownian motion models (Zarate-Barrera and Maldonado, 2015) are not yet feasible with this fund due to the sporadic timing of auctions, which have historically occurred once or twice a year. However, over the past five years, the price has been trending upward (Clean Energy Regulator, 2020). If this overall trend continues, our projected CSF values will be underestimates of what the Australian government would pay for carbon sequestration projects.

4.2. Comparison to costs of restoration

Restoration of blue carbon habitats has many direct and indirect costs that must be weighed against the total benefit. Per hectare costs of restoration are highly variable depending on whether levee removal and physical regrading of elevation profiles are required versus if tidal connectivity will naturally return with sea level rise. Transplantation of shoots, direct planting, or methods for passive propagule dispersal create tradeoffs in labor costs, effort, and efficacy (Vanderklift et al., 2018). Even within Australia, restoration costs vary considerably by ecosystem: USD 11,400 ha^{-1} for mangrove, USD 202,000 $ha^{-1}$for seagrass, and USD 26.7 million ha^{-1} for tidal marsh (Bayraktarov et al., 2016).

Private land tenure of potential restoration sites may create additional challenges for restoration. The cost of buying out property owners in Victoria in the zone of potential restoration (DELWP, 2019; Rural Bank Australia, 2020), based on a 2019 median price of USD ha^{-1} 84,105, was highest price per unit area for rural residential, vacant industrial, and nature reserve land use categories (Table S5). In 2100, existing tidal marshes, mangroves, and seagrass had SCC values at least 5-fold lower than the median buyout price (Fig. 4a). Restoration SCC values were by default lower due to their later start date for carbon sequestration, suggesting buyouts would be a prohibitively expensive strategy. For eroded ecosystems, the estimated lost 2100 SSC values were at least 3-fold lower than the median buyout cost (Fig. 4e), also highlighting the relative expense of buyouts. The cost of buyouts could decline in future decades as sea levels rise. Repeated coastal flooding during storms reduces property values of residential parcels and increases annual costs of insurance. Saltwater intrusion in coastal agriculture stresses crops, reducing germination and growth (Athukorala et al., 2018; Beltrán et al., 2019; Grattan et al., 2002; Nhung et al., 2019).

Buyouts are not the only tool available to for encouraging restoration. Conservation easements or land swaps for rural land owners can incentivize setting aside land for future tidal inundation (Young, 2018; Georgetown Climate Center, 2020). Incorporating farms and livestock operations into carbon payment programs such as the CSF can allow land owners to transition from growing crops to growing “carbon plantations” without entirely foregoing revenue. Agricultural operations already qualify for CSF payments for growing certain trees, though CSF payments would need to increase to between USD 26 and 35 per Mg CO_2 for longer-term economic viability (Regan et al., 2020). Expanding CSF payments to blue carbon sequestration on former agricultural land represents another potential strategy.

4.3. Implications for blue carbon planning and policy

While CSF payments for carbon sequestration are attached to a specific location, the benefits of a more stable climate are globally shared. The SCC measures the ecosystem service of carbon sequestration alone, though the total economic benefits of blue carbon ecosystems are higher because they provide services beyond climate mitigation (Barbier et al., 2011; Reddy et al., 2015). For example, in storm events, coastal vegetation dissipates wave energy and root networks reduce sediment erosion, protecting people and infrastructure from the forces of strong waves (Arkema et al., 2013; Hochard et al., 2019; Narayan et al., 2017). Restoration-related increases in production of commercial fish create economic benefits on an annual basis. In one case study, reconnection of a tidal marsh in the Clarence River estuary, New South Wales, increased fishery production value by USD 14,000 ha^{-1} yr^{-1} (Creighton et al., 2019).

To allow blue carbon ecosystems to expand with sea level rise (Managed Retreat scenario) would require considerable planning and rezoning. This process could entail relocating existing coastal activities farther inland to allow nature-based coastal defenses (so-called “green” infrastructure) and preventing construction of additional hard fortification structures (“grey” infrastructure) to maintain these ecosystems' ability to migrate inland, potentially incurring management costs (Kirwan and Megonigal, 2013; Reiblich et al., 2019; Reiblich et al., 2017; Young, 2018).

Conserving blue carbon ecosystems would also strongly benefit from management measures to prevent coastal erosion, which might include nature-based engineering techniques to slow water movement and promote sediment deposition. For example, installations of oyster reefs have demonstrated the ability to improve sediment trapping in North America (Morris et al., 2018; Rodriguez et al., 2014), while hollow submerged concrete modules (“reef balls”) protect sediment banks on higher-energy shorelines and provide space for settlement of mangroves (Harris, 2006; Krumholz and Jadot, 2009). Ultimately, these decisions are frequently made by weighing the costs and benefits of coastal defense or managed retreat utilizing policy frameworks such as the United Nations System of Environmental Economic Accounting (United Nations, 2012). Here, natural capital accounting approaches can evaluate alternative scenarios for the current and future extent and condition of ecosystems, and the provision of services and benefits (Hein et al., 2015; Keith et al., 2017).

Blue carbon ecosystems store and sequester considerable carbon, and thus represent a tool for fighting climate change in coastal landscapes. Conversely, loss of their rich carbon stocks is detrimental to progress toward global sequestration targets. In southeastern Australia, the areas at high risk of erosion also have adjacent areas that have significant potential for restoration, making them locations ideal for focusing marine and land-based spatial planning efforts. When faced with discussions of protecting or restoring blue carbon ecosystems, consideration of the carbon gained and lost from management actions is central to evaluating the landscape's ability to contribute to climate mitigation. Erosion results in more carbon loss than can be negated by restoration, making effective protection of existing ecosystems critical for maintaining sequestration. While existing ecosystems incrementally sequester carbon each year, erosion can potentially erase centuries of carbon gains in the span of years to decades. As opportunities arise to return tidal inundation to additional areas through levee breaching or managed retreat from sea level rise, blue carbon sequestration and provision of other ecosystem services can be further enhanced, improving the ability of governments to meet climate mitigation targets through biosequestration.

Data accessibility

Data (GIS map files) are available at doi:https://doi.org/10.6084/m9.figshare.12362552. Full-color interactive maps for the whole Victoria coast are available at https://maps.oceanwealth.org. Within the map viewer, select Regional Planning > Regional Datasets > Australia > Blue Carbon to see individual layers.

CRediT authorship contribution statement

Monica M. Moritsch: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Mary Young:** Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Paul Carnell:** Data curation, Writing – review & editing. **Peter I. Macreadie:** Conceptualization, Investigation, Writing – review & editing, Project administration, Funding acquisition. **Catherine Lovelock:** Writing – review & editing. **Emily Nicholson:** Writing – review & editing, Funding acquisition. **Peter T. Raimondi:** Resources, Writing – review & editing, Project administration, Funding acquisition. **Lisa M. Wedding:** Writing – review & editing. **Daniel Ierodiaconou:** Conceptualization, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.145962.

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