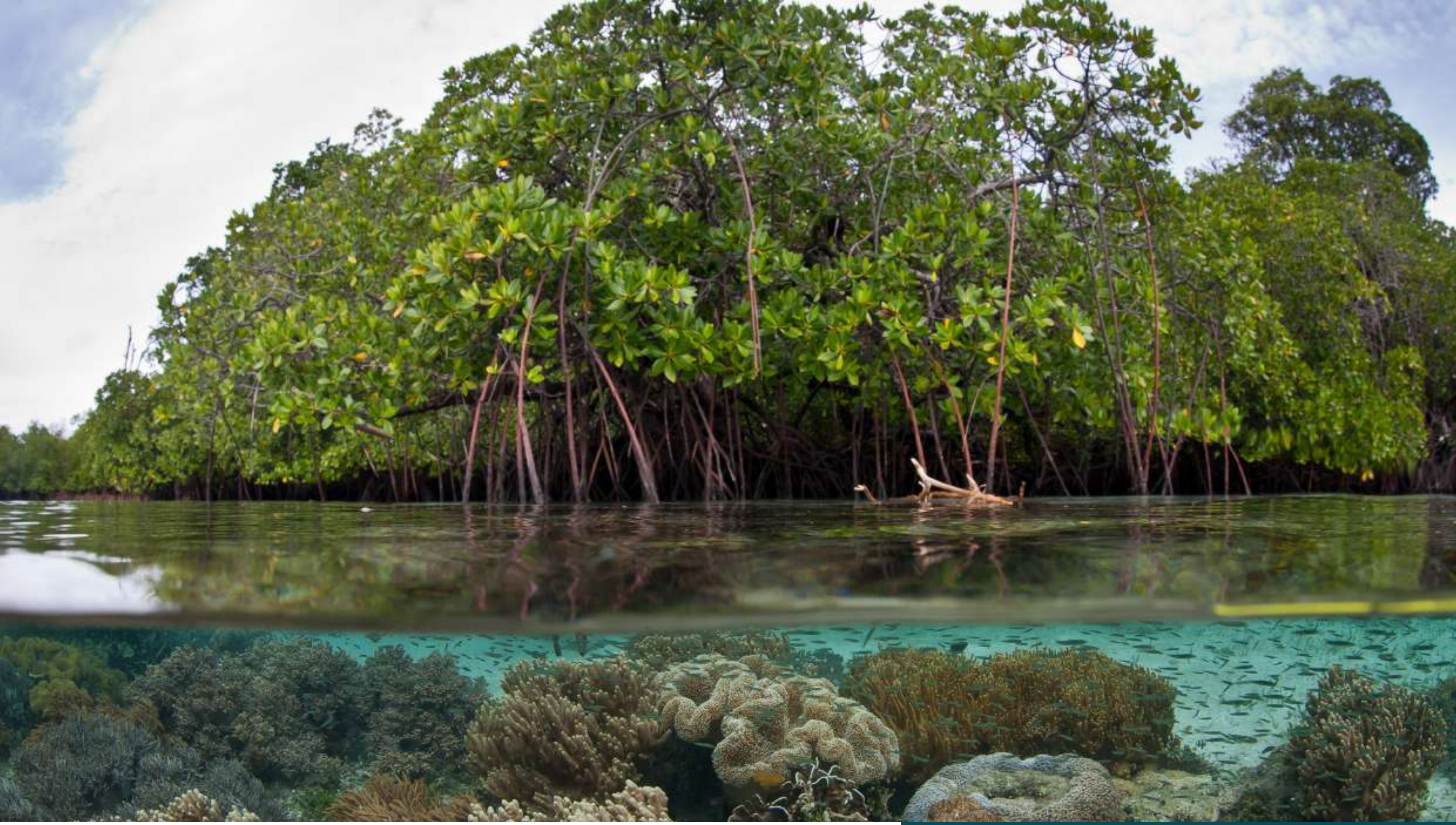

BLUE CARBON OPPORTUNITIES IN QUEENSLAND:

How much and where?

Deakin University (Lead), Queensland Government, The University of Queensland, James Cook University, CSIRO, GreenCollar Group, North Queensland Dry Tropics, Australian Government Department of Industry, Science, Energy and Resources, Qantas, HSBC, Great Barrier Reef Foundation

BLUE CARBON OPPORTUNITIES IN QUEENSLAND:

How much and where?

This report is funded by the Queensland Government as part of the Pilot Projects Program of the Land Restoration Fund

May 2020

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Queensland Government

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EXECUTIVE SUMMARY

Coastal **blue carbon ecosystems** (seagrass meadows, saltmarshes and mangrove forests) are among the most efficient natural carbon sinks. These ecosystems capture and store carbon 30-50 times faster than terrestrial forests, locking away carbon in the ground for millennial time-scales, thereby reducing atmospheric carbon concentrations that contribute to global warming. However, their capacity to sequester and store carbon is threatened by coastal development and climate change.

Given the importance of blue carbon ecosystems for the wide range of ecosystem services they provide, there is a need to determine how management actions affect current and future blue carbon stocks. This project aims to answer one of the most critical question underpinning further investments in blue carbon in the Land Restoration Fund context - how big is the **opportunity for blue carbon** in Queensland **(focusing in the Great Barrier Reef catchments)** and **where to act?**

The components of the study included:

- Reviewing available data on blue carbon stocks and drivers, assembled and recorded for the Great Barrier Reef catchments;
- Modelling soil carbon stocks throughout the distribution of mangrove forests and seagrass meadows within the Great Barrier Reef catchments;
- Development of a first-pass blue carbon stocks heatmap for the Great Barrier Reef catchments;
- Modelling carbon sequestration under a range of potential management scenarios.

Major findings:

- Mangrove forests and seagrass meadows within the Great Barrier Reef catchments hold a blue carbon stock of over **111 million tonnes**, which is equivalent to the annual emissions of **~87 million cars.**
- These ecosystems would **sequester ~251 million tonnes CO_2 equivalent by 2100**.
- **Six Local Government Areas hold almost 70% of all the blue carbon** in the Great Barrier Reef catchments. The top six blue carbon hotspots include the Cook Shire, Livingstone Shire, Gladstone Regional, Burdekin Shire, Isaac Regional and Whitsunday Regional.
- If considering the Natural Resource Management (NRM) regions, **Cape York and Fitzroy regions hold more than 60%** of the predicted carbon stocks.

In terms of opportunities for carbon credits generation through land restoration, we found that:

- Total net sequestration of **~256 million tonnes of CO_2** equivalent draw down (increase of ~5 million tonnes of CO_2 equivalent compared to the no net change scenario) if we reinstated tidal exchange in ~**90,000 ha** throughout the Great Barrier Reef catchments. Fitzroy, Burdekin and Mackay Whitsunday NRM regions have large areas of land behind tidal barriers, and consequently, if tidal exchange is restored, would have the greatest blue carbon opportunities. For example, carbon sequestration would increase by **6%, 2.4% and 2%**, respectively, by 2100 when compared to the no net change scenario (i.e. baseline scenario - assuming the distribution of blue carbon ecosystems and their carbon sequestration rates remain the same through time).

- When combining the reinstatement of tidal exchange with sea level rise predictions, which increase the area available for coastal wetlands, carbon sequestration could increase by ~**19%**, **10% and 20%** in the Fitzroy, Burdekin and Mackay Whitsunday NRM regions, respectively, by 2100 when compared to the no net change scenario.
- Wet Tropics and Burnett Mary NRM regions could also have great opportunities, with a potential increase in carbon sequestration of **~20% and 9%**, respectively. This increase is due to their large area (~130,000 ha combined) of pre-clearing distribution of coastal wetlands that were assumed to be gradually inundated and restored with sea level rise.

Interactive maps showing our results are available in a Story Map.

Planning for future sea level rise and erosion management could also bring benefits for carbon sequestration:

- In this case, there is an opportunity to increase total carbon sequestration by ~12% (~**30 million Mg CO_2 equivalent**) by 2100 if investments are made towards land use planning for sea level rise (i.e. landward migration). Fitzroy, Mackay Whitsundays and Wet Tropics NRM regions would have the greatest opportunities in this scenario.
- The loss of blue carbon ecosystems through erosion could lead to a **decrease of 30-47%** of total net carbon sequestration when compared to the no net change scenario. In this case, Fitzroy and Wet Tropics would be the NRM regions with greatest loss of blue carbon ecosystems within erosion prone areas.

One of the major limitations in this project was the gap in blue carbon data for saltmarshes (i.e. only 1 sampling point for saltmarsh against 60 and 89 for seagrass meadows and mangrove forests, respectively), which was identified early in the project. Saltmarshes encompass an area approximately equivalent to mangrove forests within the GBR catchments (~207,000 ha), therefore, results presented in this report are likely conservative, since saltmarshes are not represented.

There are some major caveats when upscaling restoration projects at the GBR catchments scale. For example, net sequestration and economic values presented here do not account for the crediting period (i.e. 25 years for sequestration projects and 7 years for emission avoidance projects) required by the Australian Government's Emission Reduction Fund or the natural loss of carbon and emissions resulting from undertaking (e.g. additional vehicle or electricity use) a restoration project (more details on pages 23-25). In addition, all the scenarios modelled in this project considered that actions would have been taken at the scale of the Great Barrier Reef catchments. Here, we aimed to develop a first-pass assessment of additionality opportunities at large-scale to guide future blue carbon projects. The removal of tidal exclusion structures (e.g. levees, bund walls) has been considered as the main strategy for restoration of mangrove forests and saltmarshes in Australia, and we showed that such management activity can increase carbon sequestration within the Great Barrier Reef region. However, future blue carbon projects must consider local conditions and ecosystem services provided by freshwater wetlands created due these structures, and consequently, the costs and benefits of restoration projects.

In this sense, we suggest future work focuses on:

- Evaluating how future environmental conditions are likely to influence blue carbon stocks in the Great Barrier Reef catchments.
- Exploring case studies for local changes in management strategies along the Great Barrier Reef catchments.
- Executing a field campaign to collect core samples from saltmarshes along the Great Barrier Reef coastline.
- Evaluating the imapct of erosion on CO_2 emissions (i.e. is the carbon redeposited in the marine environment or is it mineralized to CO_2?).
- Mapping tidal exclusion structures and the impacts of their removal at finer scale.
- Evaluating the biogeochemical consequences of reintroducing tidal flow in freshwater ecosystems.
- Evaluating the role of the Queensland Government's Land Restoration Fund Co-Benefits Standard if applied in blue carbon projects.

Queensland is in a strong position to be at the forefront of national and international efforts to capitilise on blue carbon opportunities, and consequently, help mitigate climate change.

BACKGROUND

Coastal blue carbon ecosystems (seagrass meadows, saltmarshes and mangrove forests) are among the most efficient natural carbon sinks, but their capacity to sequester and store carbon is threatened by coastal development and climate change (including sea level rise). This project will help put Queensland at the forefront of international efforts to incorporate coastal carbon within CO_2 mitigation strategies, thereby helping to mitigate climate change while also enhancing natural capital, and contributing to jobs, economic growth and community well-being. Our multi-sector R&D collaboration – comprising academia, project developers, and industry – will answer the most critical question underpinning further consideration and investment in blue carbon within the context of the Land Restoration Fund: how big is the opportunity for blue carbon (e.g. how many tonnes of CO_2 could be offset per annum?) in Queensland and where to act? This information is essential for informing potential future investments in blue carbon through the Land Restoration Fund.

AIMS

The overall aim of this project is to develop a first-pass assessment of potential land area amenable to blue carbon projects, which will be achieved via the following objectives:

Objective 1:
Review, synthesise, and map blue carbon stocks and sequestration rates for the Great Barrier Reef (GBR) catchments.

Objective 2:
Identify ecological, geomorphological and anthropogenic predictors of blue carbon in the GBR catchments.

Objective 3:
Develop a predictive model of blue carbon in the GBR catchments under different management scenarios.

OBJECTIVE 1

Review and synthesis of blue carbon data

The review and synthesis on blue carbon soil stocks and sequestration rates for the GBR catchments was completed on July 2019. Our initial dataset comprised soil carbon data carbon stock in (Mg C ha^{-1}) collected by the Carbon Cluster Program (Kelleway et al., 2017; Serrano et al., 2019). During this phase, we contacted over twenty blue carbon experts in Australia and overseas to check if their data had been included in our initial dataset. With that, we gathered the following information for seagrass meadows and mangrove forests: 60 and 89 study sites within the GBR catchments with data on carbon stocks in the top 1 m (Figure 1). Surprisingly, we discovered a gap in blue carbon data within saltmarshes, with only one sampling point within the GBR region. With that, this report focuses only in the blue carbon soil stocks from mangrove forests and seagrass meadows, reducing the soil carbon stocks estimates in the GBR since saltmarshes encompass an approximately equivalent area as mangrove forests within the GBR catchments (~207,000 ha). This project focused only on the blue carbon soil stocks and plant biomass was assumed at steady state in existing forests since the majority of carbon sequestered by coastal wetlands is stored in their soils.

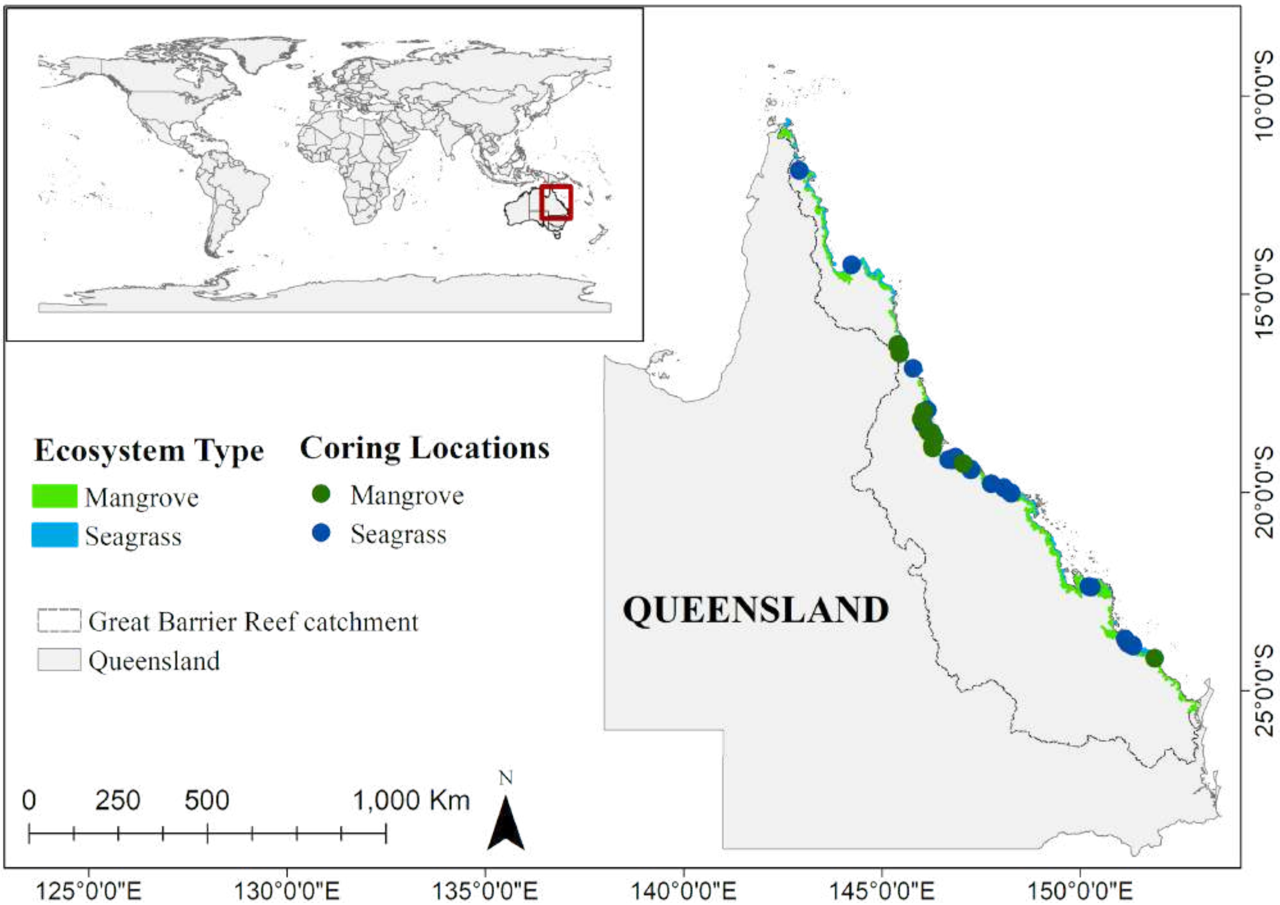

Figure 1: *Soil carbon samples collected in seagrass meadows and mangrove forests that were included in the models.*

OBJECTIVE 2

What drives the distribution of blue carbon in the coastal wetlands within the GBR catchments?

We used the compiled dataset of soil carbon sampled across mangrove forests and seagrass meadows to model soil carbon stocks in the GBR catchments. We combined this information with spatially explicit data on seventeen biophysical and anthropogenic predictors known to influence carbon distribution in coastal wetlands (Table S1) to understand what drives the variability in blue carbon soil stocks, and create a heat map of blue carbon soil stocks within the GBR catchments. Spatial layers were projected to the same coordinate system (WGS 1994 Australian Centre for Remote Sensing Lambert) and converted to 15 m resolution. Layers that were coarser than 15 m were downscaled using Inverse Distance Weighted interpolation while layers at a finer resolution were resampled to 15 m in ArcGIS 10.5.1 (ESRI, 2011) . We extracted the suite of predictors data for each blue carbon sampling location (Figure 1) within the GBR catchments.

We used Boosted Regression Trees (BRTs) (Elith et al., 2008) to examine the blue carbon soil stocks in relation to biophysical and anthropogenic predictors (Table A1). This method is a machine learning approach and ensemble method for modelling the relationship between response (i.e. blue carbon soil stocks) and explanatory variables (i.e. blue carbon predictors, Table A1). Once the final model was identified for each blue carbon ecosystem, we used the BRT to predict blue carbon soil stocks across the GBR catchments. Further details about the modelling approach is available in the Appendices.

We found that the final combination of variables explained 78% and 51% of the variation in soil organic carbon stocks in mangrove forests and seagrass meadows, respectively, across the GBR catchments. Partial dependency plots show the models prediction for soil carbon for each explanatory variable in the model (Figure 2). Climatic variables, such as temperature, rainfall and solar radiation, showed a strong contribution (8.8% - 38%) in accounting for variation in soil carbon in mangrove forests (Figures 2 and 3). In this case, annual average temperature showed a positive relationship with soil carbon stocks up to around 23.8°C where there was a decrease in soil carbon stock followed by a dramatic increase in stocks at 26°C (Figure 2). Rainfall was also positively related to soil carbon (11.7%) up to around 2000 mm followed by another peak at around 3000 mm, while solar radiation (8.8%) displayed a negative relationship with soil carbon stocks (Figure 2). Soil carbon stocks from terrestrial ecosystems was also influential (11.4%) with a negative relationship with soil carbon stocks in mangrove forests. Population at the Local Government Area, current speed and distance from the closest estuary and elevation accounted for the remaining 29.7%. Population showed a variable response (7.7%) in the variation of soil carbon in mangrove forests, which corresponds to the complexity of the processes associated with human-related activities. Current speed showed a negative relationship with soil stocks up to around 0.15 m/s followed by a positive relationship with soil stocks. Distance to the closest estuary accounted for 7.3% of the variability and showed an overall tendency of decrease in carbon stocks as distance to the estuary increases. Elevation also influenced soil carbon in mangrove forests (7.1%) with soil carbon increasing at higher elevations.

In contrast, our BRT models for seagrass meadows showed that soil type accounted for most of the variability (47.8%) of soil carbon (Figure 3) with higher stocks in areas influenced by kandosols (i.e. associated with mulga vegetation that support sheep and cattle grazing on native pastures) and sodosols (i.e. highly erodible) (Figure 3). Climatic variables, such as solar radiation (14.8%), temperature (7.3%) and rainfall (3.6%) also contributed to explain the variability of soil carbon stocks in seagrass meadows. Similar to mangrove forests, solar radiation showed a negative relationship with soil stocks, while the relationship between soil carbon and temperature and rainfall was relatively neutral. Slope (7.6%) was also influential with a negative/neutral relationship with soil carbon stocks in seagrass meadows. Distance from the closest estuary explained 7% of the variation and showed an overall tendency of increase in carbon stocks as distance to the estuary increases. Current speed accounted for 5.2% of the variability and showed a positive/neutral relationship as current speed increases. Elevation (1.7%), wave energy (1.4%), tidal range (1%) and wave height (0.2%) also contributed to explain the variability of our BRT model for seagrass meadows, although their relationship with soil carbon stocks was not strong.

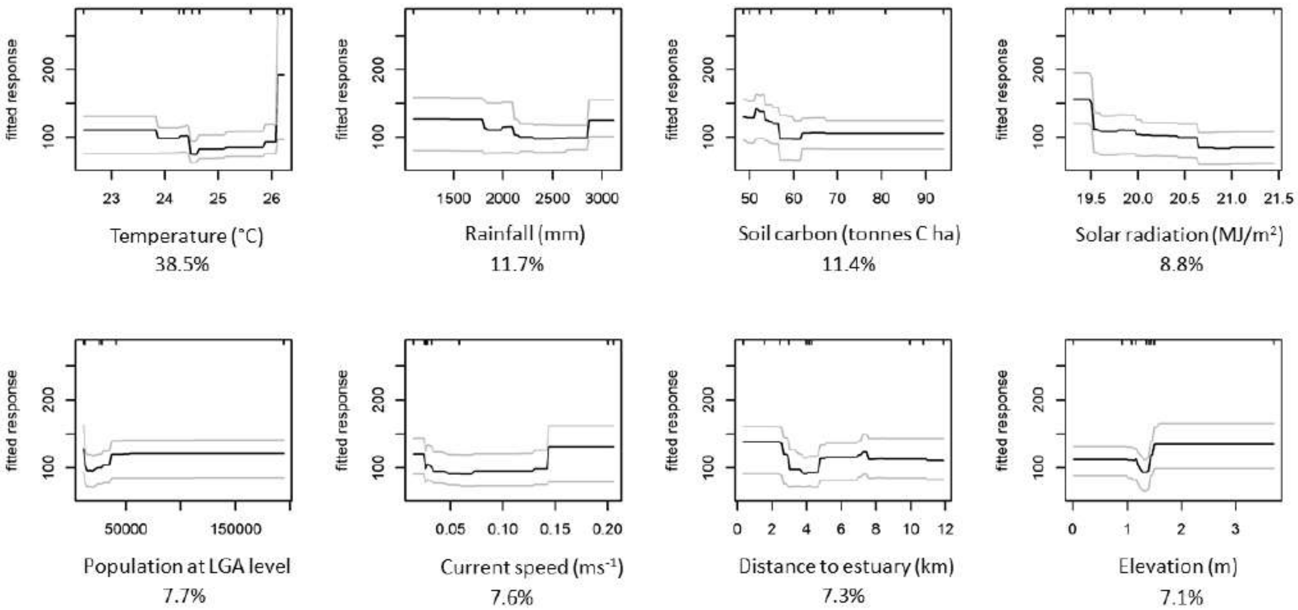

Figure 2: *Partial dependency plots with 95% confidence intervals for each variable used to explain the variability of soil carbon stocks in mangrove forests. The plots show the effect of a given predictor on the soil carbon stock of mangrove forests while keeping all other variables at their mean. Relative influence of each predictor is reported below each plot. Black tick marks across the top of each plot indicate observed data points.*

From our predictive map, we estimated the total soil organic carbon stocks at approximately **111.8 Tg C** (+/- 31.9 Tg C) within mangrove forests and seagrass meadows across the GBR catchments (Figure 4). We also evaluated the total amount of soil organic carbon stocks for each Local Government Area (LGA) within the GBR catchments (Figure 5). We found that Cook Shire, Livingstone Shire, Gladstone Regional, Burdekin Shire, Isaac Regional and Whitsunday Regional are the LGAs that hold the blue carbon hotspots (> 5 Tg) within the region (Figure 5). If considering the Natural Resource Management (NRM) regions, Cape York and Fitzroy regions hold more than 60% of the predicted carbon stocks (Figure 5). Such information is crucial to inform future investments in carbon farming within Queensland and can underpin restoration strategies at the local scale.

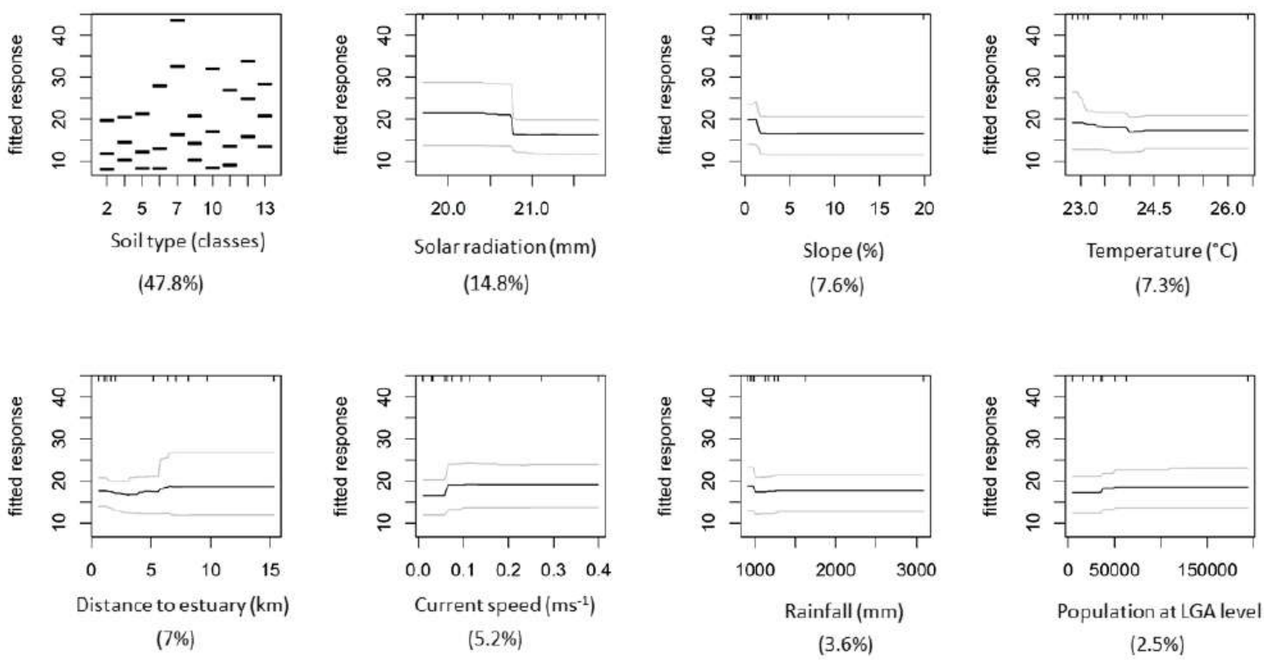

Figure 3: *Partial dependency plots with 95% confidence intervals for each variable used to explain the variability of blue carbon stocks in seagrass meadows. The plots show the effect of a given predictor on the blue carbon stock of an ecosystem while keeping all other variables at their mean. Relative influence of each predictor is reported below each plot. Black tick marks across the top of each plot indicate observed data points. Soil type are as follow: 2-calcarosols, 4-dermosols, 5-ferrosols, 6-hydrosols, 7-kandosols, 9-organosols, 10-podosols, 11-rudosols, 12- sodosols, and 13-tenosols. Tidal range and wave height data represent a classification based on the maximum tide range and the mean wave height in a site. Elevation (m), wave energy (Pa), tidal range (m) and wave height (m) were not included in the plot since their relationship with soil carbon stocks in seagrass meadows was not strong.*

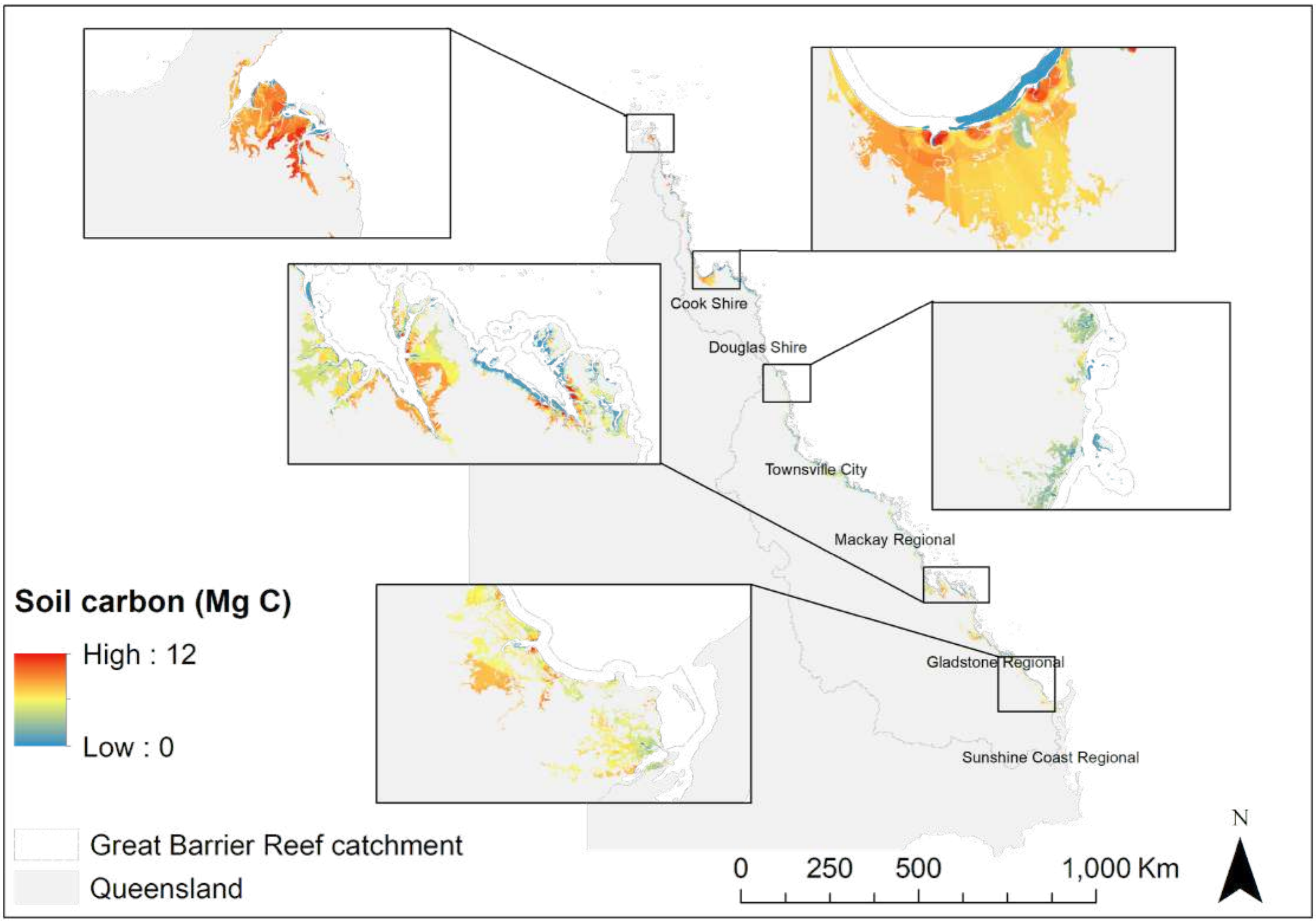

Figure 4: *Distribution of soil organic carbon stocks (Mg C ha^{-1}) for the top meter of soil across the GBR catchments at 15 m resolution (pixel area= 0.0225 ha). Note saltmarshes were not included in this study, reducing the soil carbon stocks estimates in this region. Detailed map is available here.*

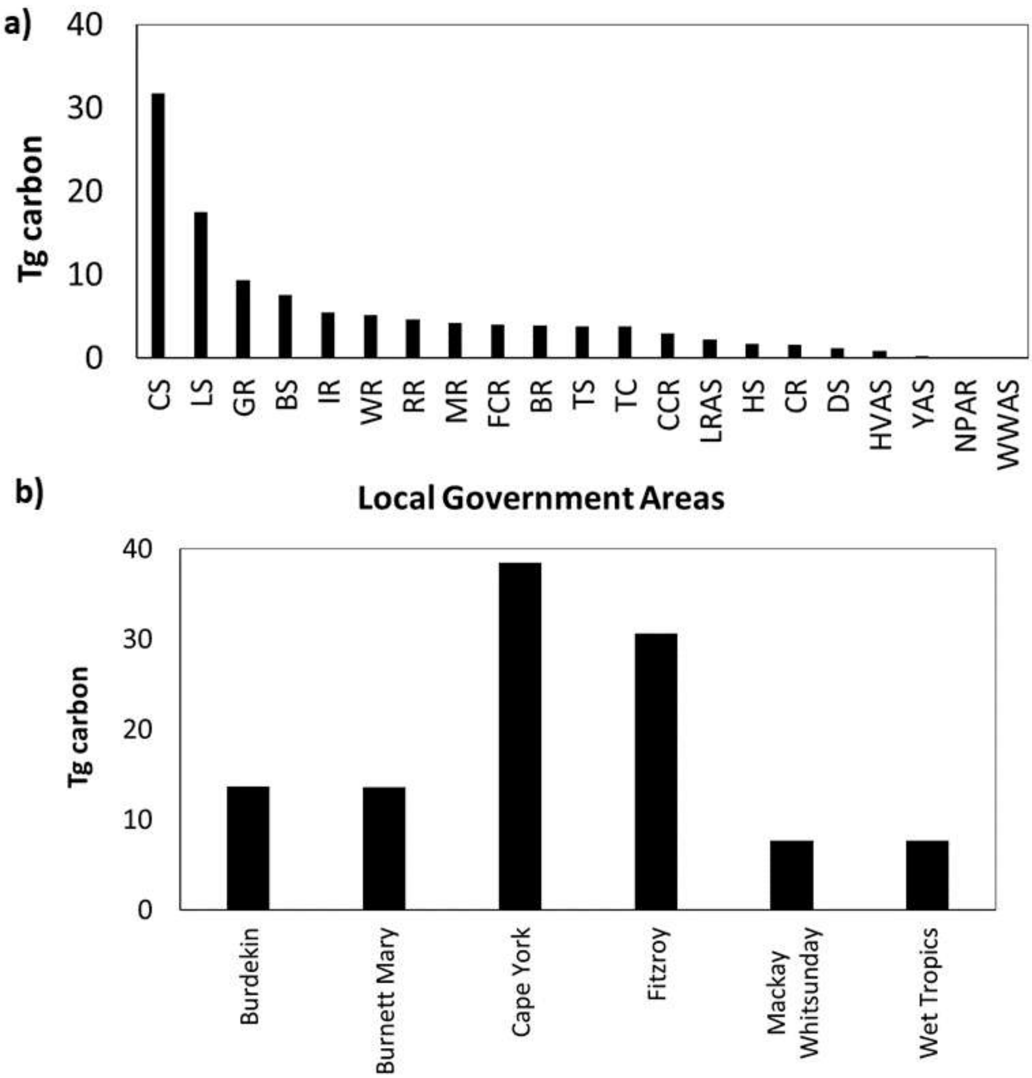

Figure 5: *Current total soil organic carbon stocks (in Teragrams, Tg, which 1 Tg = 1 million tonnes) within each (a) Local Government Areas (LGA, i.e. third tier of government in Australia) and (b) Natural Resource Management (NRM) regions located across the GBR catchments. Note saltmarshes were not included in this study, causing incomplete the soil carbon stocks estimates for each LGA and NRM regions. (**CS**: Cook Shire, **LS**: Livingstone Shire, **GR**: Gladstone Regional, **BS**: Burdekin Shire, **IR**: Isaac Regional, **WR**: Whitsunday Regional, **RR**: Rockhampton Regional, **MR**: Mackay Regional, **FCR**: Fraser Coast Regional, **BR**: Bundaberg Regional, **TS**: Torres Shire, **TC**: Townsville City, **CCR**: Cassowary Coast Regional, **LRAS**: Lockhart River Aboriginal Shire, **HS**: Hinchinbrook Shire; **CR**: Cairns Regional, **DS**: Douglas Shire, **HVAS**: Hope Vale Aboriginal Shire, **NPAR**: Northern Peninsula Area Regional).*

OBJECTIVE 3

Blue Carbon additionality under different management scenarios

We used the Coastal Blue Carbon InVEST 3.7.0 model (Sharp et al. 2018) to estimate future net sequestration carbon in blue carbon ecosystems and its monetary value under different management strategies within the GBR region. This model is a spatially-explicit tool that predicts carbon sequestered in soils between time points due to changes in land cover (Sharp et al. 2018). The model assumes that the carbon accumulation and emission rates for a specific ecosystem type is constant through time points. Based on spatial layers of land use changes between time points, the model estimates the carbon lost to the atmosphere over time when a blue carbon ecosystem is disturbed or the carbon gained through restoration (Sharp et al. 2018).

The model requires an initial value for blue carbon stocks and sequestration rates for each ecosystem type considered in the analysis. In our case, we used the Regional Ecosystems (RE) Mapping (Department of Environment and Science, 2019) to extract the ecosystem types to be included in the model (i.e. each RE category that included a blue carbon ecosystem within the GBR catchments was considered an ecosystem type in the model). For all scenarios, sequestration rates for each ecosystem type were derived from Serrano et al. (2019) (seagrass: 0.36, saltmarsh: 0.39, and mangrove: 1.26 Mg C ha^{-1} y^{-1}) while initial blue carbon soil stocks were derived from the spatially-explicit raster at 15 m resolution created in the **Objective 2** (initial stocks for RE that contains saltmarshes are underestimated since this ecosystem was not included in the models for carbon stocks). Both sequestration rates (Mg C ha^{-1} y^{-1}) and carbon stocks (Mg C ha^{-1}) were transformed into Mg CO_2 equivalent ha^{-1} by multiplying by 3.67 (i.e. conversion factor that represents the molecular weight ratio of CO_2 to C). We followed the carbon stocks data resolution, and modelled future carbon sequestration at 15 m from 2020 to 2100. All spatial files were converted from polygons to 15 m resolution rasters. Here, we focused on the restoration of saltmarshes and mangrove forests. Detailed information on the modelling approach is available in Sharp et al. (2018).

We assumed that carbon sequestration rates of restored ecosystems will be the same mature ecosystems after 20 years (Craft, 2001; Osland et al., 2012; Marbà et al., 2015), with ecosystems between 0-20 years since restoration sequestering carbon at a lower rate compared to mature ecosystems. Therefore, we used a percentage of carbon sequestration in mature ecosystems as sequestration rates for recently restored (45% and 56% for mangroves and saltmarshes, respectively) and 10-years-old (45% and 80% for mangroves and saltmarshes, respectively) restored ecosystems (Craft et al., 1999; Meyer et al., 2008; Adams et al., 2012; Osland et al., 2012; Marbà et al., 2015). The methods used in this study were adapted from Moritsch et al. (submitted).

Scenarios

We modelled carbon sequestration under different scenarios. First, we considered a **no net change scenario**, where distribution of blue carbon ecosystems remains the same through time. This scenario was used to compare the changes in carbon sequestration as a result of a restoration project. We considered two restoration scenarios, where blue carbon ecosystems were restored by **tidal restoration through the removal of tidal exclusion structures** (when a project is proposed with no consideration of sea level rise predictions) and a combination of **tidal restoration through the removal of tidal exclusion structures + sea level rise.** Finally, we modelled carbon sequestration/emissions due to **sea level rise** and **erosion** within the GBR catchments. We recognise that land use planning for sea level rise and erosion management at the level of the GBR catchments might not be feasible at large scale, but the objective here is to evaluate for the first time where such activities and/or feasibility studies should be considered in the future.

NO NET CHANGE SCENARIO

We used the current distribution of blue carbon ecosystems within the GBR catchments and assumed that their distribution and sequestration rates would remain the same from 2020 to 2100.

TIDAL RESTORATION THROUGH THE REMOVAL OF TIDAL EXCLUSION STRUCTURES

The installation of tidal exclusion structures is one of the main human impacts on intertidal wetlands. To model wetland restoration by re-introducing tidal flow in areas impacted by the construction of tidal exclusion structures, we combined the current distribution of blue carbon ecosystems with the projected area that could be restored. We buffered all the mapped land that is protected from tidal inundation (classes H2M3 and H2M3P available in the Queensland Wetlands dataset - Department of Environment and Science, 2019) within the GBR catchments by 1 km (i.e. 1 km radius semi circle around each tidal exclusion structure) to estimate the projected area flooded if such structure is removed. Then, we combined this layer with the pre-clearing distribution of saltmarshes and mangrove forests (Department of Environment and Science, 2018) so the area available for restoration includes historic mangrove and saltmarsh within 1 km of a tidal exclusion structure with no consideration of sea level predictions. Here, we assumed that restored land would be converted back to saltmarshes. It is important to highlight here that our objective was to develop a first-pass estimate of potential carbon gains at large scale and that this approach is likely to under- or overestimate the inundation extent in some areas. In this sense, this approach is not meant to replace future hydrodynamic modelling and/or site-specific analyses (Abbott et al., 2020).

TIDAL RESTORATION THROUGH THE REMOVAL OF TIDAL EXCLUSION STRUCTURES PLUS SEA LEVEL RISE

To model wetland restoration under the effect of the removal of tidal exclusion structures and sea level rise, we combined the layers from the previous scenario with the sea level rise scenario. In sites where inundation occurred from both removal of tidal exclusion structures and sea level rise, tidal exclusion structures were given priority.

PLANNING FOR SEA LEVEL RISE

We used the predicted storm tide inundation area including sea level rise impacts until 2100 (Department of Environment and Science, 2015) combined with the current and historic distribution of blue carbon ecosystems to model carbon sequestration due to sea level rise. For this scenario, our assumptions were:

- Pre-clearing ecosystem's extent would be inundated in 2040 by early stages of sea level rise followed by inundation outside of pre-clearing ecosystem extent by 2070.
- All restored blue carbon ecosystems would become saltmarshes.
- No new tidal exclusion structures to prevent sea level rise were created to restrict the tidal flow between 2020 and 2100.

EROSION

We have modelled carbon emissions due to erosion (Department of Environment and Heritage Protection, 2016) (Figure A2), considering that blue carbon ecosystems within these areas would be transformed in mudflats or open water. For this transition, we assumed that an ecosystem-specific percentage of carbon would be release to the atmosphere from blue carbon ecosystems during this transition:

- **Saltmarsh**: 40% and 70% of carbon loss when transitioning to mudflat or open water, respectively (Howe et al., 2009; Adams et al., 2012).
- **Mangrove**: 75% and 50% of carbon loss when transitioning to mudflat or open water, respectively (Kauffman et al., 2014; Kauffman et al., 2018; Cameron et al., 2019).
- **Seagrass**: 55% and 65% of carbon loss when transitioning to mudflat or open water, respectively (Rozaimi et al., 2016).

We evaluated this scenario under two conditions: 1) coastal erosion due to storm impact and long term trends of sediment loss and channel migration, and 2) coastal erosion and permanent inundation due to sea level rise of 0.8 m (Department of Environment and Heritage Protection, 2016). For this scenario, we assumed that no wetland restoration took place within eroded blue carbon ecosystems. It is important to highlight that erosion is less likely to influence projects focused on the mid to high intertidal zone.

Valuation of carbon sequestration

The Coastal Blue Carbon InVEST 3.7.0 model also estimates the economic value of carbon sequestration as a function of the amount of carbon sequestered, the value of sequestered carbon (price/ton), and a discount rate. For that, we estimated the valuation of carbon sequestration for each scenario using three pricing approaches:

1. **Bottom-range price** based on the Australian Carbon Credit Units Market Price: AU$14.17, 1.5% discount rate, which was the average price from the Emissions Reduction Fund Auction from October 2019 (Clean Energy Regulator, 2019).

2. **Mid-range price** based on the average carbon price for the Savannah Burning Carbon Method, which recognises the co-benefits associated with restoration projects: AU$22, 1.5% discount rate.
3. **Top-range price** based on the Social Cost of Carbon, which assumes that the price of carbon increases over time, 2.5% discount rate (US Environmental Protection Agency, 2016). Prices were converted from US$ to AU$ (US$ 1= AU$1.53, 28/02/2020).

For the purposes of this project, we focused our results in the bottom range price and showed the net value of carbon sequestration between 2020 and 2100. Results for the mid- and top-range prices will be discussed in a future scientific paper (in preparation). In addition, the carbon sequestration valuation presented in this project did not account for the crediting period of blue carbon credit time period (i.e. 25 years for sequestration projects and 7 years for emission avoidance projects) required by the Australian Government's Emission Reduction Fund.

Results

We found that current blue carbon ecosystems (no net change scenario) within the entire GBR catchments would sequester **251 million** Mg CO_2 equivalent by 2100 (Figure 6). If we restore tidal exchange at ~90,000 ha within land that is protected by throughout the GBR catchments we could increase total carbon sequestration by **2% (~5 million Mg CO_2 equivalent)** by 2100 compared to the no net change scenario (with a net value gain of **AU$24.7 million by 2100** in the 2019 Australian Carbon Credit Units Market Price, AU$14.17, Figure 7). When combining the reinstatement of tidal exchange with sea level rise predictions, we found that carbon sequestration could increase by **~12% (~30 million Mg CO_2 equivalent)** by 2100 when compared to the no net change scenario. In this case, net value could increase by **10%** (~**AU$210 million** by 2100 in the 2019 Australian Carbon Credit Units Market Price, AU$14.17, Figure 7).

If investments are made towards land use planning for sea level rise at the scale of the whole of the GBR catchments, there is the opportunity to increase total carbon sequestration by **12% (~30 million Mg CO_2 equivalent)** compared to the no net change scenario (Figure 6). This carbon sequestration could represent a **potential opportunity of ~AU$185 million** by 2100.

We found that erosion may pose a major risk to the increase of carbon emissions, having a negative impact in the coastal wetlands within the erosion prone areas mapped in the GBR catchments. Consequently, total net carbon sequestration would **decrease by 30-47%** with a potential net loss of ~AU$86-89 billion (2019 Australian Carbon Credit Units Market Price (AU$14.17, Figure 7) by 2100 when compared to the no net change scenario. Both total net carbon sequestration and economic value were negative (Figures 6 and 7) and represent carbon emissions from ecosystem loss due to erosion. Therefore, erosion management within the GRB catchments represents a great opportunity to avoid future loss of blue carbon ecosystems and, consequently, avoid increase in carbon emission.

Blue carbon opportunities within Natural Resource Management regions

We also evaluated the blue carbon opportunities in the six Natural Resource Management (NRM) regions located within the GBR region (Figure 8). Despite recognising that restoration and management at large scale might not be feasible, the results provided here aim to guide future on-ground investigations at local local scale. Cape York and Fitzroy NRM regions hold more than 60% of the soil carbon stocks (Figure 6), and could sequester **~130 million Mg CO_2 equivalent** by 2100 (Figure 8).

Fitzroy, Burdekin and Mackay Whitsunday NRM regions have large areas of land behind mapped tidal barriers, and consequently, if tidal exchange is restored, would have the greatest blue carbon opportunities. For example, carbon sequestration would increase by ~**6**%, **2.4**% and **2**%, respectively, by 2100 compared to the no net change scenario (Figure 8). For these three NRM regions combined, this increase in carbon sequestration could be valued at **AU$24.4 million by 2100** in the 2019 Australian Carbon Credit Units Market Price (Figure 9).

When combining the reinstatement of tidal exchange with sea level rise predictions, we found that carbon sequestration could increase by **~19%, 10% and 20%** (which corresponds to ~**18.8 million CO_2 equivalent**) in the Fitzroy, Burdekin and Mackay Whitsunday NRM regions, respectively, by 2100 when compared to the no net change scenario. In this case, net value by 2100 could increase by **~AU$124 million** in the 2019 Australian Carbon Credit Units Market Price (AU$14.17, Figure 9). Wet Tropics and Burnett Mary could also have great opportunities, with an increase in carbon sequestration by ~20% and 9%, respectively. This increase is due to their large area (~ 130,000 ha combined) of pre-clearing distribution of coastal wetlands that were assumed to be gradually inundated and restored with sea level rise.

Wet Tropics, Mackay Whitsundays and Fitzroy NRM regions would have the greatest opportunities if further investments are made towards land use planning for sea level rise. We estimated that these NRM regions would increase their carbon sequestrations by **19%, 17% and 11%**, respectively, by 2100 compared to the no net change scenario (Figure 8). Together, this carbon sequestration would represent and **increase in value of ~AU$117 million** by 2100 in the 2019 Australian Carbon Credit Units Market Price (AU$14.17, Figure 9).

In relation to erosion, Fitzroy would be one of NRM regions with greatest potential loss of blue carbon ecosystems within the erosion prone area related to long term trends of sediment loss (~ -13 million Mg CO_2 equivalent) with a potential net loss of AU$26 billion by 2100 (in the 2019 Australian Carbon Credit Units Market Price) when compared to the no net change scenario. When considering the erosion prone area related to permanent inundation and sea level rise, Wet Tropics NRM region could face a major loss of blue carbon ecosystems, and consequently, a decrease of carbon sequestration by up to 80% by 2100 (with a potential net loss of ~AU$18 billion by 2100 when compared to the net change scenario) (Figures 9 and 10).

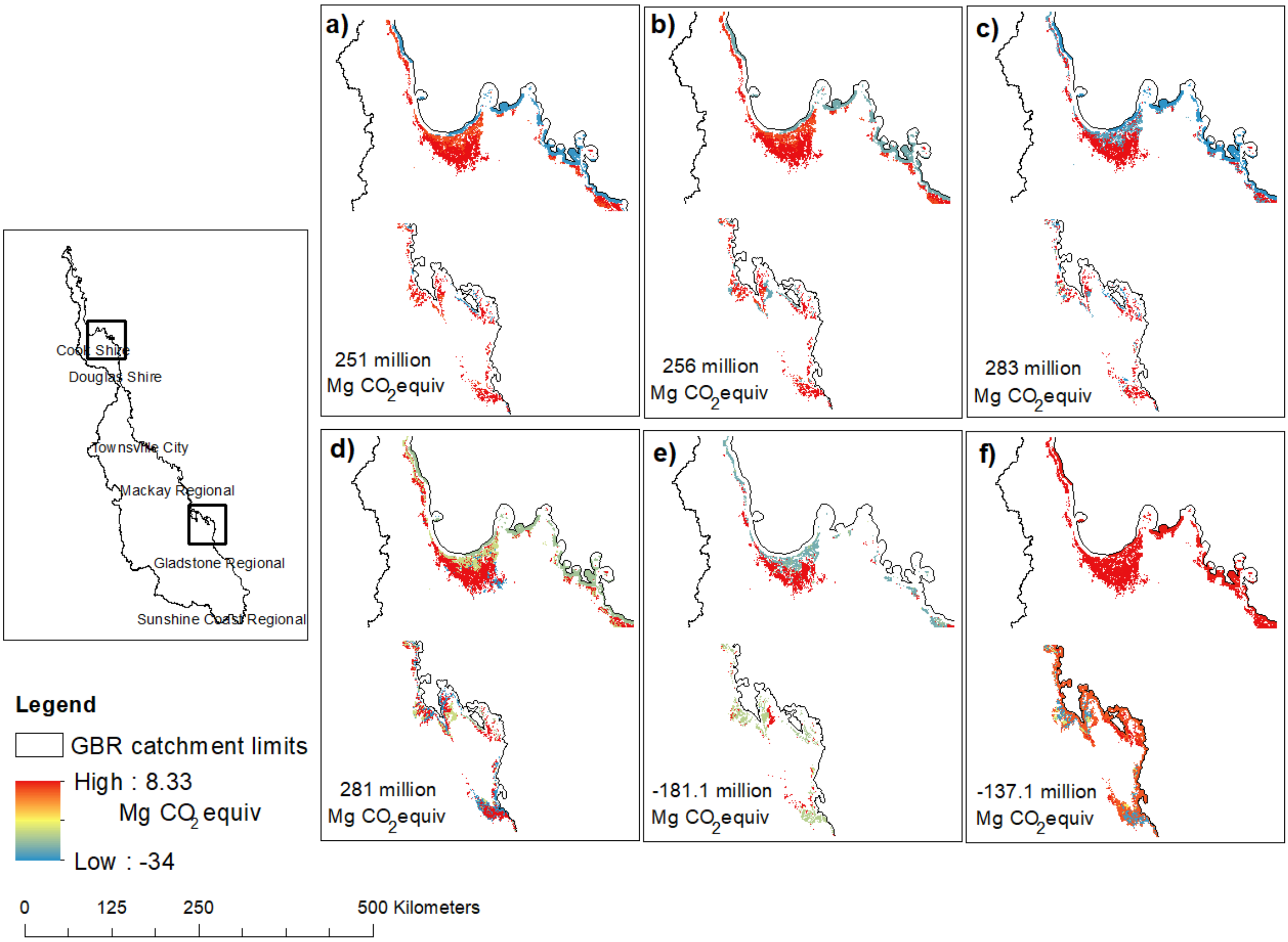

Figure 6: *Total net sequestration at 15 m resolution from 2020 to 2100 for each scenario modeled at two locations within the GBR catchments: a)* ***no net change****, b)* ***tidal restoration through the removal of tidal exclusion structures****, c)* ***removal of tidal exclusion structures and sea level rise****, d)* ***sea level rise****, e)* ***erosion (long term trends of sediment loss)*** *and f)* ***erosion (and permanent inundation due to sea level rise)****. Total sequestration values for the entire region is displayed at the bottom corner of each panel. Full maps are available here.*

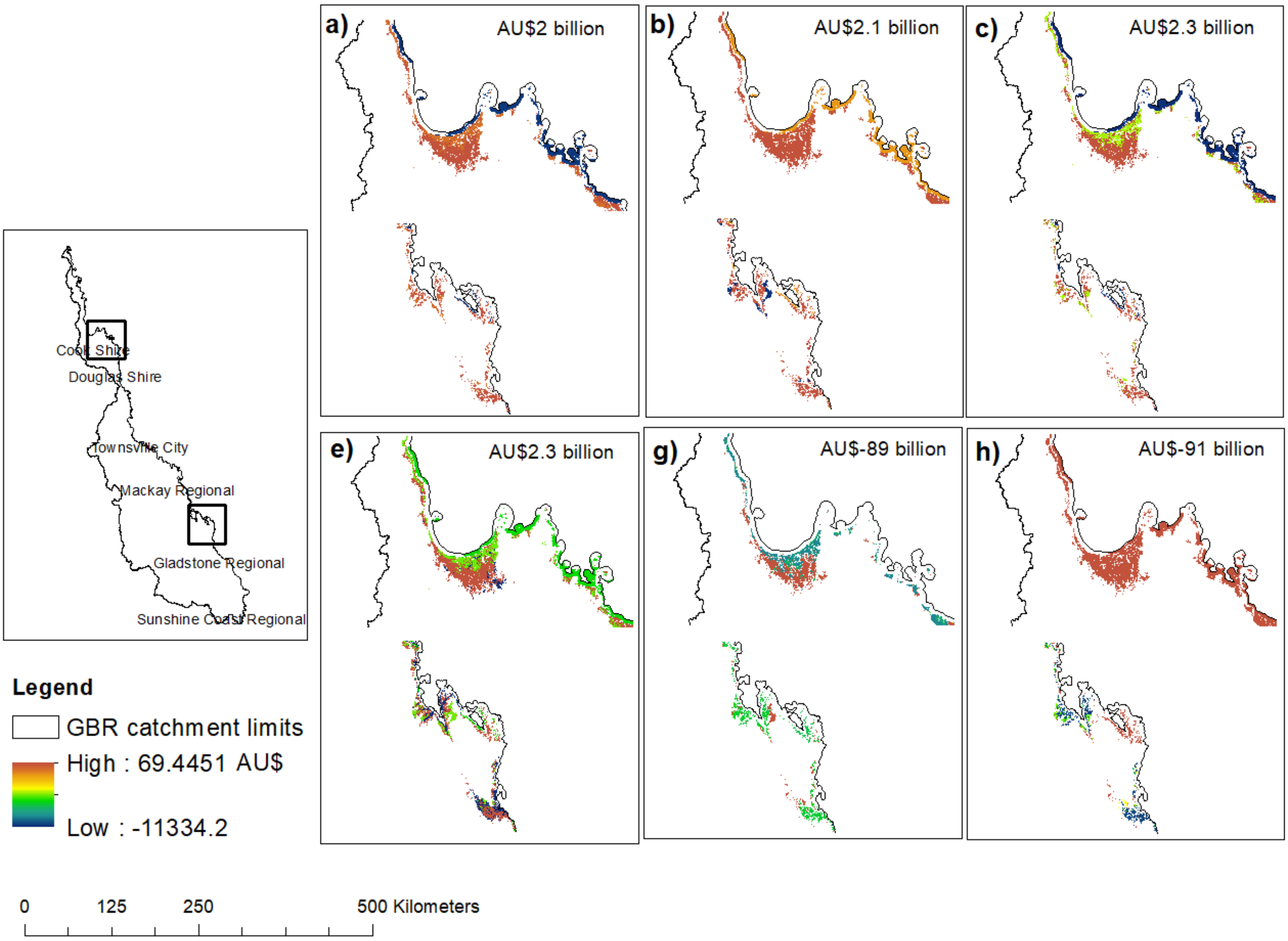

Figure 7: *Net present value of equivalent carbon at 15 m resolution by 2100 for each scenario modeled at two locations within the GBR catchments. Here we used the Australian Carbon Credit Units Market Price from October 2019 (AU$14.17) as a constant price for one metric ton of carbon dioxide equivalent sequestered with a discount rate of 1.5%. a)* ***no net change****, b)* ***tidal restoration through the removal of tidal exclusion structures****, c)* ***removal of tidal exclusion structures and sea level rise****, d)* ***sea level rise****, e)* ***erosion (long term trends of sediment loss)*** *and f)* ***erosion (and permanent inundation due to sea level rise)****. Net values for the entire region is displayed at the top corner of each panel.*

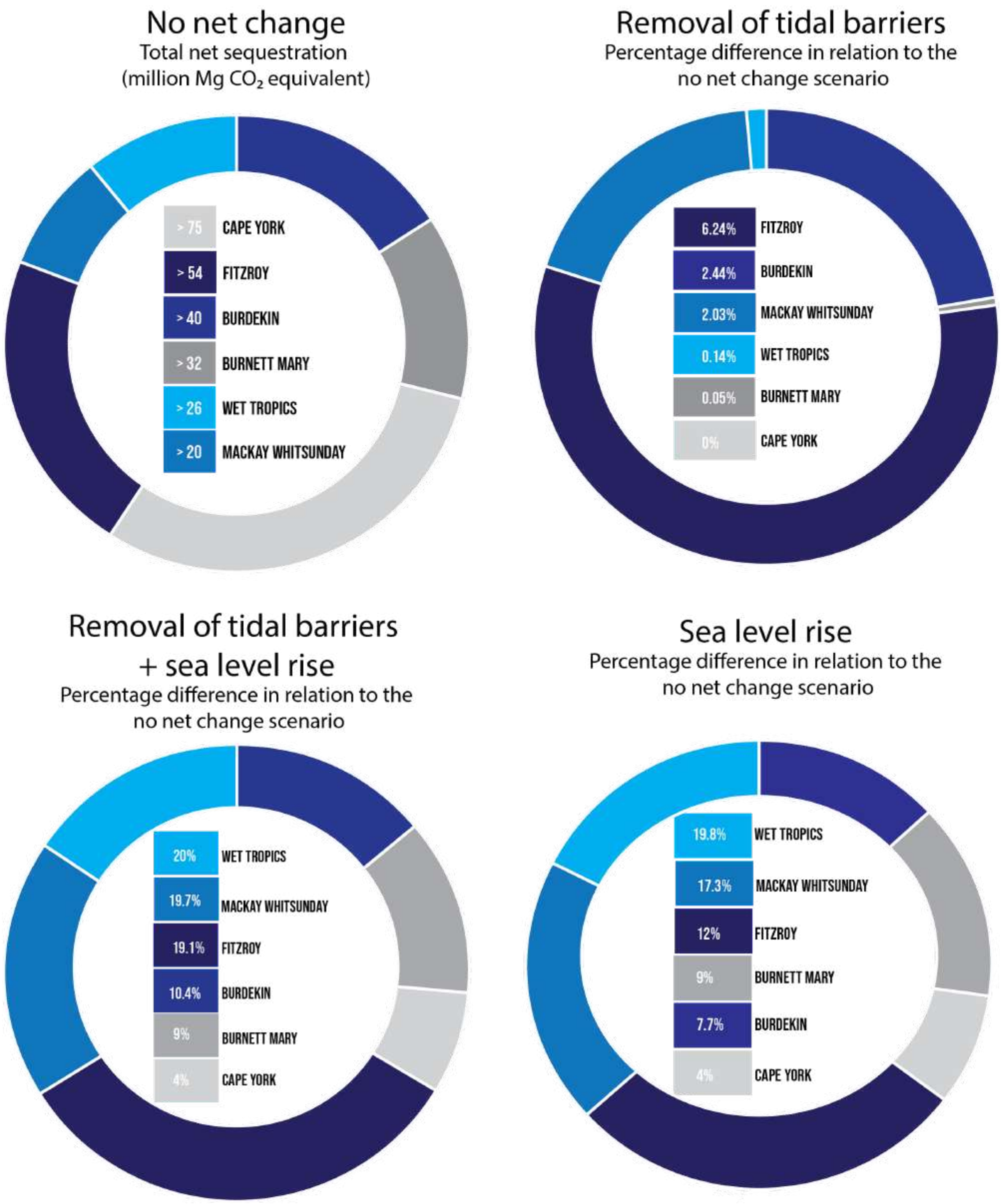

Figure 8: *Total net sequestration (Mg CO_2 equivalent) from 2020 to 2100 for the no net change= scenario and the carbon gains (Mg CO_2 equivalent) in relation to the no net change scenario.= The percentage difference is shown in the legend for each scenario within each Natural= Resources Management in the GBR catchments.*

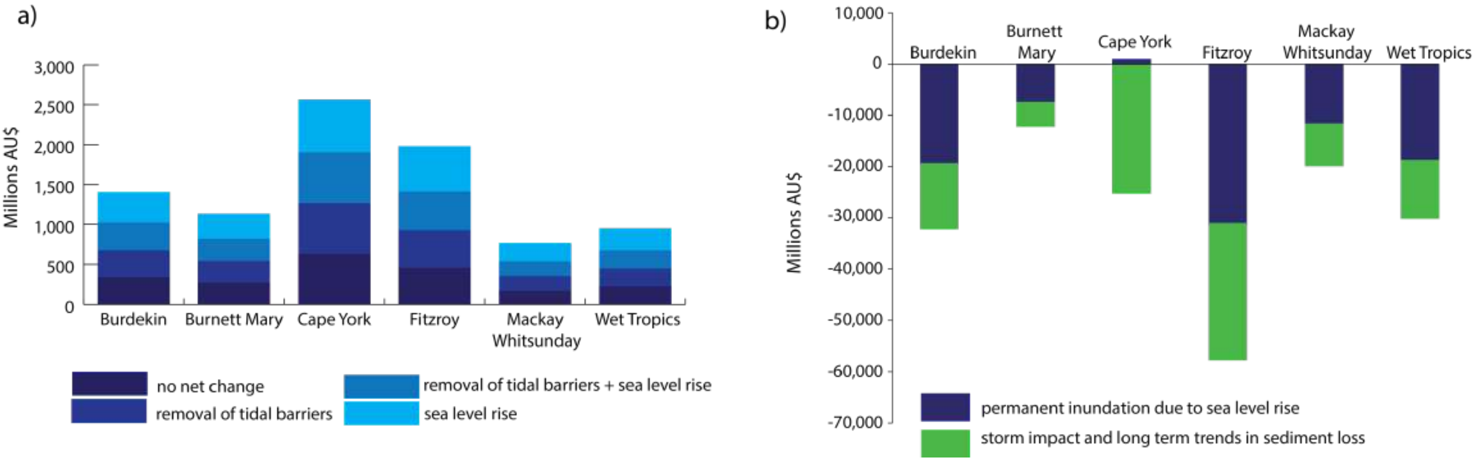

Figure 9: *Net present value of equivalent carbon by 2100 for each Natural Resource Management region within the GBR catchments. Here we used the Australian Carbon Credit Units Market Price from October 2019 (AU$14.17) as a constant price for one metric ton of carbon dioxide equivalent sequestered with a discount rate of 1.5%.*

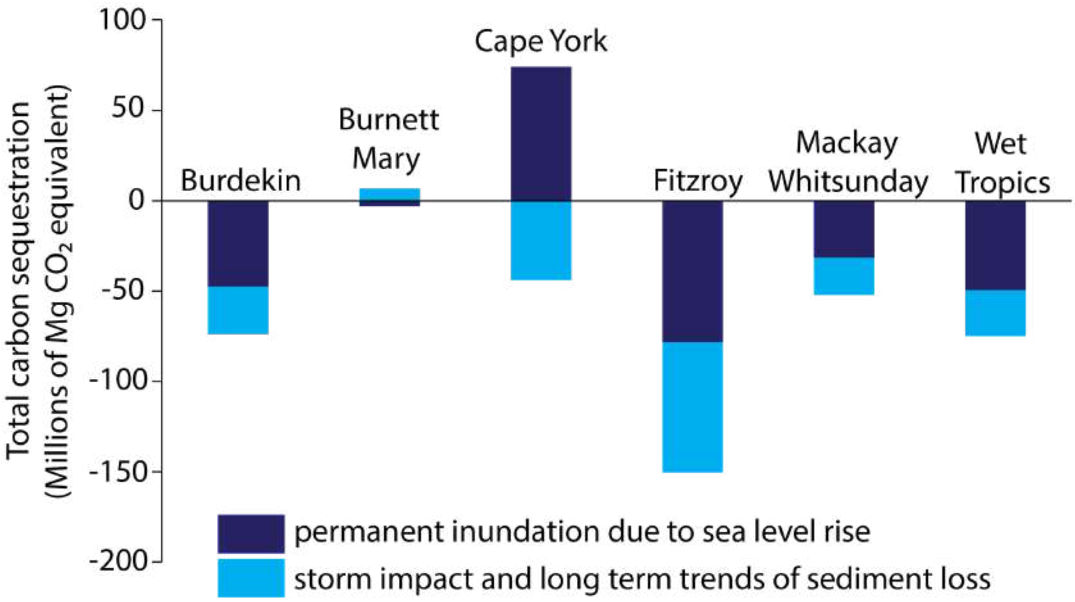

Figure 10: *Total net carbon sequestration (Mg CO_2 equivalent) from 2020 to 2100 for the erosion= scenarios in each Natural Resources Management within the GBR catchments.*

Discussion

Coastal wetlands within the Great Barrier Reef region play an important role in carbon storage and sequestration. Here, we predicted for the first time blue carbon stocks in coastal wetlands within the GBR catchments, and the opportunities for increasing carbon stocks through removal of tidal barriers. We found that reinstating tidal exchange and planning for future sea level rise may increase carbon sequestration, while, erosion have a negative impact in coastal wetlands through the modelled time period (2020-2100), posing a major risk to release carbon back to the atmosphere.

We found that mangrove forests and seagrass meadows within the GBR catchments hold blue carbon stocks of over 111 million tonnes, which is equivalent to the annual emissions of ~87 million cars. Our estimate is lower than the total estimated for Queensland's mangroves and seagrasses (~676 Tg) by Serrano et al. (2019). Such difference was expected since Serrano et al. (2019) used the ecosystem's extent to estimate its carbon stock rather than a spatially-explicit approach as the one used in this study. In addition, we focused only in the coastal wetlands within the GBR catchments limits and saltmarsh was not included in this study.

The substantial amount of carbon stored in the soils of mangrove forests and seagrass meadows within the GBR catchments is a major asset for Queensland, which can be increased by restoration projects (i.e. additionality) aiming to expand the total area of blue carbon ecosystems, and consequently, help Queensland to achieve multiple goals such as climate change mitigation and adaptation targets. Our spatially-explicit results at regional scale can help underpin future blue carbon projects by providing baseline information on soil carbon stocks. This information is critical for informing potential future investment in blue carbon through the Land Restoration Fund and support future developments of the blue carbon methodology for tidal restoration projects proposed by the Australian Government's Emission Reduction Fund.

All the scenarios modelled in this project considered that actions were taken at the scale of all of the GBR catchments. Our aim was to develop a first-pass assessment for increasing carbon sequestration at large-scale to guide future blue carbon projects. The reinstatement of tidal exchange has been considered as the main strategy for restoration of mangrove forests and saltmarshes in Australia (Kelleway et al., 2020), and we showed that such management activity can increase carbon sequestration mainly in Fitzroy, Burdekin and Mackay Whitsunday NRM regions, since these regions have large areas behind tidal exclusion barriers. However, future blue carbon projects must consider the current local conditions and ecosystem services provided by the freshwater wetlands created due these barrages. Currently, there is an effort to map sensitive freshwater wetlands along the GBR catchments, and future studies should overlap the results obtained in this project to identify sites that should be protected and those suitable to restoration (Waltham et al., 2019).

Recent hydrodynamic modeling of an earth wall removal project at Mungalla, Ingham, has revealed that the frequency and extent of tidal incursion upstream of structure was hindered by catchment freshwater flow, along with the presence of excessive vegetation accumulation on the upstream of the structure - effectively holding back tidal incursion (Abbott et al., 2020). Under a modeled simulation of sea level rise (2100), it is possible that more frequent and extensive tidal intrusion occurs, though catchment flow might still hinder some of the exchange potential (Waltham et al., 2020).

There are some major caveats for estimating net carbon abatement when upscaling restoration projects at the GBR catchments scale. For example, net sequestration and economic values presented here do not account for the crediting period (i.e. 25 years for sequestration projects and 7 years for emission avoidance projects) required by the Australian Government's Emission Reduction Fund or the natural loss of carbon and emissions (e.g. additional vehicle or electricity use) resulting from undertaking the restoration project. In addition, financial viability and the legal complexity due to the location of blue carbon ecosystems in the intertidal zone (e.g. law permits might be necessary in some cases or the discussion of land and carbon rights with the state government, Bell-James & Lovelock, 2019) were not considered in the scope of the project, but should be considered when designing a blue carbon project.

Caveats

- One of the major limitations in this project was the gap in blue carbon data within saltmarshes, which was identified early in the project. Despite the efforts to realise a coring campaign during this project, such initiative was put on hold due to the COVID-19 outbreak. Saltmarshes encompass an approximately equivalent area as mangrove forests within the GBR catchments (~207,000 ha), therefore, results presented in this report are likely conservative.
- Our restoration project scenarios did not consider assisted regeneration, and we suggest that future blue carbon projects should evaluate how some level of assisted regeneration could improve carbon gains where tidal exclusion structures are removed.
- We only investigated carbon gains in the soil, and we suggest that future blue carbon projects should evaluate how plant biomass could improve the estimates of net abatement amount.
- We assumed that land behind tidal barriers were converted to saltmarsh, however, future sea level rise may lead to colonisation by mangrove forests.
- Our models did not account for biogeochemical consequences of reintroducing tidal flow in freshwater ecosystems or other biodiversity changes that may occur.

In this sense, we suggest future work focuses on:

- Evaluating how future environmental conditions are likely to influence blue carbon stocks in the Great Barrier Reef catchments.
- Upscaling our predictions to the entire Queensland coastline.
- Exploring case studies for local changes in management strategies along the Great Barrier Reef catchments.
- Executing a field campaign to collect core samples along the Great Barrier Reef coastline.
- Evaluating the impact of erosion on CO_2 emissions (i.e. is the carbon redeposited in the marine environment or is it mineralized to CO_2?).

- Mapping tidal exclusion structures and the impacts of their removal at finer scale.
- Evaluating the role of the Queensland Government's Land Restoration Fund Co-Benefits Standards if applied in blue carbon projects.
- Evaluating the biogeochemical consequences of reintroducing tidal flow in freshwater ecosystems.

Queensland is in a strong position to be at the forefront of national and international efforts to capitilise on blue carbon opportunities, and consequently, help mitigate climate change.

Meetings and Outreach

As part of this project, we held several individual meetings with our partners and attended relevant events that maximised the outreach of our project. Meetings were originally proposed as a 1-2 day workshop with all partners, however, we decided to run it in the format of individual meetings based on feedback from the main partners. This format allowed for a more engaging interaction with industry partners and potentially increased the impact of our results. Table 1 shows the details for all meetings that occurred during the project. Table 2 shows details for the relevant events that have been attended as part of this project. Two upcoming events (7th Australiasian Emissions Reduction Summit and Australian Marine Science Association & New Zealand Marine Science Society Conference 2020) that were scheduled for this year were cancelled due to the COVID-19 outbreak.

Table 1: *Detailed information for each individual meeting held since May 2019. (BCL: Blue Carbon Lab, Deakin University; UQ: The University of Queensland; JCU: James Cook University; LRF: Land Restoration Fund; DES: Department of Environment and Science, Queensland Government; ESP: Ecosciences Precint Dutton Park).*

Meeting with	Attended the meeting	Date & Location	Objective & Outcome
Prof Catherine Lovelock	Prof Cath Lovelock (UQ) and Dr Micheli Costa (BCL)	Monthly meetings at UQ	These meetings aimed to discuss scientific feedback from modelling and results obtained during the project, including the management scenarios evaluated by Objective 3.
Dr Nathan Waltham	Dr Nathan Waltham (JCU) and Dr Micheli Costa (BCL)	Meetings held on 3 Sept 2019 by Skype and on Nov 19 2019 at UQ	In these meetings, we discussed the modelling approach and results, including the management scenarios included in Objective 3. They were also an insight into the NESP TWQ projects related to wetland restoration (specifically project 3.3.2, funded by the Australian Government.
Wetlands Team, DES	Dr Don Butler (LRF), Wetlands Team (DES) and Dr Micheli Costa (BCL)	Meeting held on 17 Sept 2019 at DES	Dr Micheli Costa presented a general update of the project and got feedback for the modelling approach.
LRF, BCL, Wetland Team DES, JCU	Dr Don Butler, Megan Surawski, A/Prof Peter Macreadie (BCL), Dr Micheli Costa (BCL), Dr Pawel Waryszak (BCL), Dr Maria Palacios (BCL), Dr Melissa Wartman (BCL), Dr Fernanda Adame (Griffith Uni), Dr Nathan Waltham (JCU)	Meeting held on 10 Oct 2019 at DES	In this meeting, we discussed the project updates and highlighted the need of additional sampling for saltmarshes within the GBR catchments. The main purpose of this meeting was to discuss potential funds and strategy for a systematic coring campaign for this ecosystem.
Dr Evan Thomas	Dr Evan Thomas (DES) and Dr Micheli Costa (BCL)	Meetings held on 3 Dec 2019 and 29 Jan 2020 at ESP	These meetings were to discuss data availability for the East Trinity site and the potential inclusion of this site as a case study for the project.
Alpa Bhattacharjee	Alpa Bhattacharjee (HSBC) and Dr Maria Palacios (BCL)	Meeting held on 10 Feb 2020 at the HSBC Bank Australia Limited (Sydney)	In this meeting, Dr Palacios (Science Communicator responsible for this project) discussed with Alpa our preliminary results and next steps that will be pursued with HSBC's additional funding and media strategies.
Dr Jeff Baldock	Dr Jeff Baldcok (CSIRO), A/Prof Peter Macreadie (BCL) and BCL's postdocs and PhD students	Meeting held on 19 Feb 2020 at Deakin University (Melbourne)	During this meeting, we discussed ways to improve the measurements of blue carbon additionality.

***Table 2:** Detailed information for each event attended since May 2019. (GBRF: Great Barrier Reef Foundation; BCL: Blue Carbon Lab, Deakin University; LRF: Land Restoration Fund; UQ: The University of Queensland; DoEE: Department of the Environment and Energy, Australian Government; ERF: Emissions Reduction Fund).*

Outreach	Date & Location	Objective & Outcome
Lunch & Learn at the GBRF	13 Nov 2019 at the GBRF office (Brisbane)	In this session, Dr Costa presented ongoing projects led by BCL, including preliminary results derived from the LRF project.
3rd Carbon Farming Industry Forum	29-30 Aug 2019 at the Novotel, Sunshine Coast	A/Prof Peter Macreadie and Dr Costa participated in the event, which focused on blue carbon opportunities and exploration of avenues for Queensland to develop the industry and capture a global leadership position in blue carbon and carbon farming. The event included people from the Queensland, LRF, Australian Government along major stakeholders from across the land-sector carbon credit supply chain. A/Prof Macreadie was a keynote in the Blue Carbon session.
#SWSTwitterSymp 2019	16 Oct 2019, Twitter Symposium	BCL was a keynote for the Society of Wetland Scientists Twitter Symposium 2019, where we presented about several ongoing projects, including our LRF Pilot project.
Blue carbon Method Working Group	12-13 Nov 2019 at UQ	DoEE established the Blue Carbon Method Working Group to progress blue carbon opportunities under the ERF. The working group is bringing together researchers, carbon project developers, industry, natural resource managers and federal, state and local government. Dr Costa attended the meeting at UQ and A/Prof Macreadie continue to contribute to the working group.
LRF Co-benefits Standard Workshop	27-28 Nov 2019 at the Stamford Plaza Hotel (Brisbane)	Dr Costa and Dr Melissa Wartman attended this workshop, which aimed at helping project proponents to the LRF to understand and build the skills to implement the Accounting for Nature Framework in order to measure and gain assurance for environmental co-benefits generated by carbon offset and other projects. During the workshop, Dr Costa presented some of the preliminary results derived from this project.

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Appendices

Methods - Objective 2

Boosted Regression Trees

We used Boosted Regression Trees (BRTs) (Elith et al., 2008) to examine the blue carbon soil stocks in relation to biophysical and anthropogenic predictors (Table A1). This method is a machine learning approach and ensemble method for modelling the relationship between response (i.e. blue carbon soil stocks) and explanatory variables (i.e. blue carbon drivers, Table A1). This method is a powerful algorithm that is efficient when dealing with large datasets or a large number of variables, is very robust to missing values and outliers, and improves predictive performance due to its ability to fit non-linear relationships (Elith et al., 2008). The blue carbon soil stock (Mg C ha^{-1}) was rounded to the nearest integer to meet the assumptions of a Poisson distribution and a log-link function was used following the *gbm.step* function (Elith et al., 2008) in the dismo package v. 1.1-4 (Hijmans et al., 2017) within R version 3.6.1 statistical software (R Core Team, 2019). To fit our BRT models, we used a tree complexity of 5, learning rate at 0.001 and bag fraction of 0.5 (Table A2). Model performance was evaluated by 10-fold cross-validation, which allows for testing the model against withheld parts of the data which are not used in the model fitting (Elith et al., 2008). We looked at the cross-validated per cent deviance explained, calculated as (1-(cross-validated deviance/mean total deviance)), using the function *ggPerformance* in the ggBRT package (Jouffray et al., 2019), as a measure of model performance. After identifying the predictors with greatest importance to the distribution of blue carbon soil stocks in mangrove forests and seagrass meadows, we determined the optimal number of trees to use in each final model. Once the final model was identified for each blue carbon ecosystem, we used the BRT to predict blue carbon soil stocks across the GBR catchments. To evaluate uncertainty of the predictive performance of our models, we ran 100 bootstrapped BRTs with 70% of our original data with random sampling with replacement each time. This allowed us to calculate the standard deviation of our predictions (Figure A1).

Table A1: *Description of the parameters used in the final BRT models.*

BRT Model Parameters	Mangrove Forests	Seagrass meadows
Error distribution	Poisson	
Learning rate	0.001	
Interaction depth	5	
Number of trees	15,950	3,850
Number of explanatory variables	8	12
Mean residual variance	23.607	10.134
Training data correlation	0.89	0.71
Performance explained	78%	51%

Table A1: *Biophysical and anthropogenic predictors of blue carbon soil stock used to model and predict its distribution, which considered three categories: 1) ecological, 2) geomorphological, and 3) climatic conditions.*

Predictor	Relationship with BC stocks	Data Source
Elevation	Usually, lower elevations are associated with higher BC soil stocks.	Digital Elevation Model of Australia derived from LiDAR 5 Metre Grid
Slope (%)	Shallower slope is also associated with higher BC soil stocks, since steeper slopes are more vulnerable to erosion.	Derived from the elevation layer using the ArcGIS slope tool.
Distance to the closest estuary	Distance to the estuary is negatively associated with BC soil stocks.	
Distance to the coast	Distance to the estuary coast is also negatively associated with BC soil stocks.	
Terrestrial soil type from nearest land	BC soil stocks varies in relation to the terrestrial soil type from nearest land	ASRIS Australian Soil Classification
Tidal range	Tidal ranges influence wetland stability and resilience of blue carbon ecosystems.	CAMRIS Tidal Range Dataset for the Australian Coast
Acid Sulphate Soil (sediments containing iron sulphides)	Soils that have formed naturally in sediments where long-term water-logged conditions occur.	Atlas of Australian Acid Sulphate Soils
Terrestrial soil carbon	Terrestrial soil carbon stock from terrestrial ecosystems in top 30 cm layer.	Baseline map of Australian soil organic carbon stocks
Temperature	Temperature is positively associated with BC soil carbon, with higher temperatures increasing the productivity and growth of vegetation.	Australian Bureau of Meteorology
Rainfall	High rainfall rates are associated with an increase in BC soil stocks due to its influence in the freshwater runoff.	Australian Bureau of Meteorology
Solar Radiation	Solar radiation affects plant productivity, and consequently, BC soil stocks.	Australian Bureau of Meteorology
Population	BC soil stocks can vary according to urbanisation levels.	Population at Local Government Area from the Australian Bureau of Statistics
Wave energy	High wave energy can increase erosion rates in blue carbon ecosystems (mainly mangroves and salt marshes).	Geological and Oceanographic Model of Australia's Continental Shelf on a 0.1-degree grid
Current speed	High current speed may contribute to the erosion and loss of wetlands.	eReefs CSIRO Hydrodynamic model
Wave height	Flow attenuation reduce wave height and maximum inundation extent but increases ponding time, which then affects vegetation establishment and survival.	Mean Significant Wave Height – Australian Region GEOSAT Wave Dataset

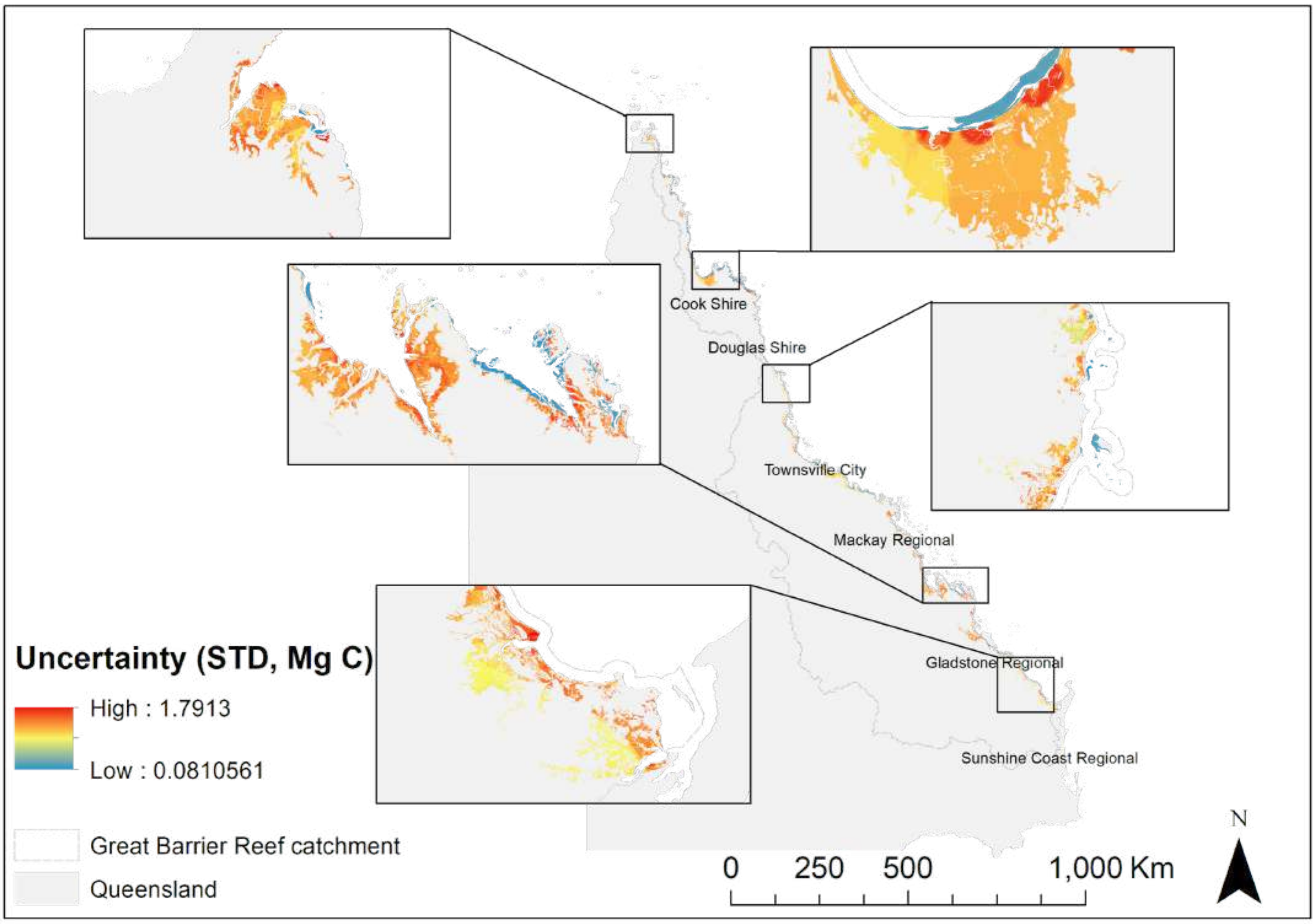

Figure A1: *Uncertainty (standard deviation) map of the predictive performance of our mangrove and seagrass models. We ran 100 bootstrapped BRTs with 70% of our original data with random sampling with replacement each time to calculate the standard deviation of our predictions.*

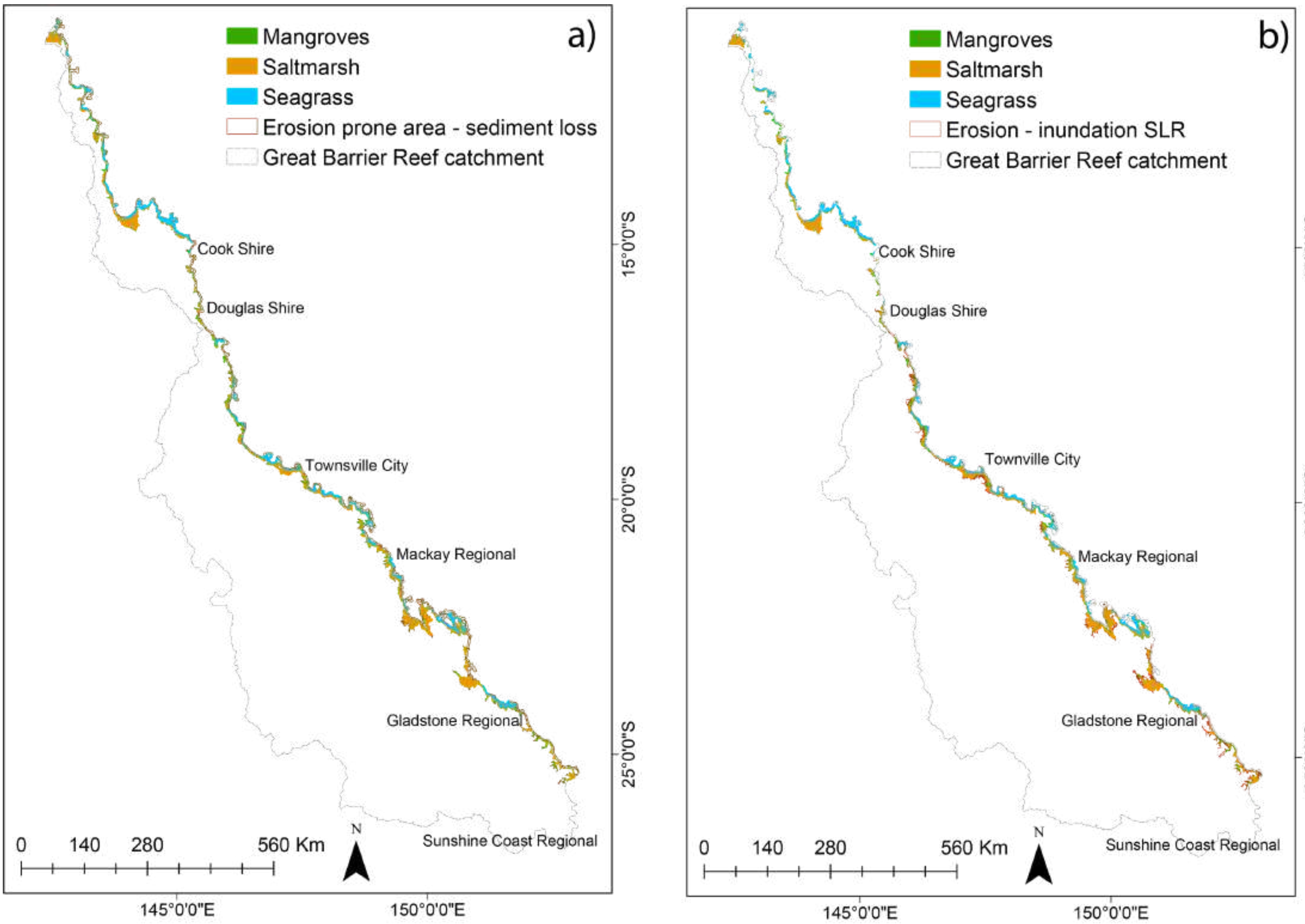

Figure A2: *Erosion prone areas overlapping blue carbon ecosystems within the GBR catchments: a) coastal erosion due to storm impact and long term trends of sediment loss and channel migration, and b) coastal erosion and permanent inundation due to sea level rise of 0.8 m, Department of Environment and Heritage Protection, 2016).*

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