



The effect of catchment land management on seagrass habitat in the Great Barrier Reef

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Summary

The ecological health of the Great Barrier Reef (GBR) is affected by water quality, which is impacted by catchment land use. The Reef Water Quality Improvement Plan 2017-2022 aims to improve GBR water quality, and ecologically-relevant targets can be used to prioritise investments and optimise cost-effectiveness of activities under the plan. The Queensland Government and CSIRO have modelled the effects of improvements to land management practices in GBR catchments on river sediment and nutrient loads, that will potentially improve marine water quality. We combined the outputs of these models together with seagrass distribution models to assess how the extent of five seagrass species could potentially change. The models indicate that improving land management practices will increase the area of suitable seagrass habitat and improve the quality of existing habitat for both shallow-water and deep-water specialists. The potential improvement is largest for the species *Halophila decipiens* and *Halophila spinulosa*, which can grow throughout deep waters of the lagoon. There are also regional differences, with the largest potential improvements in the Mackay-Whitsunday and Fitzroy NRM regions and the smallest improvement in Cape York, which receives relatively small river loads under current conditions. These findings build upon complementary assessments of current and predicted future risk to seagrass habitat. This can assist with prioritising land management interventions, spatial planning within the GBR, and to communicate the benefits of future investment in catchment management.



The Issue

Seagrass habitats form over vast areas of the Great Barrier Reef (GBR) potentially covering more than 88,000 km² (Carter et al., 2021a). At least 12 species of seagrass grow in estuaries, along coasts, on reef tops and in deep-water lagoonal areas to 76 m depth (Carruthers et al., 2002; Carter et al., 2021a; Coles et al., 2015). All species can be found in the coastal zone of the GBR, where the habitat requirements for each of the species can overlap (Carter et al., 2021a).

Seagrasses are important ecological assets in their own right and as habitats in the GBR. They support fisheries and culturally important fauna such as dugongs through provision of habitat and food (Coles et al., 2015; Scott et al., 2020). They also stabilise sediments, take up and store nutrients such as nitrogen, phosphorus and carbon, including as 'blue carbon' (Kelleway et al., 2020; Salinas et al., 2020), and reduce pathogen loads (Lamb et al., 2017). These all contribute to human well-being (Cullen-Unsworth et al., 2014), and can be economically valued as ecosystem services, which provide a way to assess the value of investing in conservation and restoration, including land-based activities to reduce sediment loads (Costanza et al., 1997).

The ecological health of the GBR is affected by the health of its seagrass habitats. Poor water quality, mostly due to run-off from adjacent catchments, is one of the main threats to the condition of inshore GBR ecosystems that can be influenced by local management actions (Bainbridge et al., 2018; Fabricius et al., 2013; Fabricius et al., 2014; Waterhouse et al., 2017). Suspended particulate matter (including fine sediments and particulate nutrients) from land runoff attenuates light and reduces both the amount and quality of light reaching benthic habitats (Bainbridge et al., 2018; Robson et al., 2020). Repeated resuspension of particulate matter means that newly delivered sediments continue to influence turbidity and benthic light for six to eight months (Fabricius et al., 2014; Fabricius et al., 2016; Lewis & Bainbridge, 2021; Lewis et al., 2020).

The Reef 2050 Water Quality Improvement Plan 2017 – 2022 (State of Queensland, 2018) and associated land management regulations aim to reduce the loss of sediments and nutrients from catchments to improve water quality in the GBR. Action to reduce sediment loads is costly and controversial, so it is important to develop ecologically relevant targets (ERTs) with which to measure the cost-effectiveness of the delivery of sustainable ecosystem outcomes (Brodie et al., 2017a; Brodie et al., 2017b; Kroon et al., 2016; Lambert et al., 2019; Lambert et al., 2020). The costs and benefits of land management strategies to improve water quality also need be weighed up against seagrass conservation strategies in the marine zone (Grech et al., 2012; Saunders et al., 2017; Tulloch et al., 2020) using precise information on seagrass community composition, distribution and desired state (Carter et al., 2021a; McKenzie et al., 2020b) and an understanding of the risks of failing to act in time to avoid recalcitrant degradation (Adams et al., 2016; O'Brien et al., 2018).

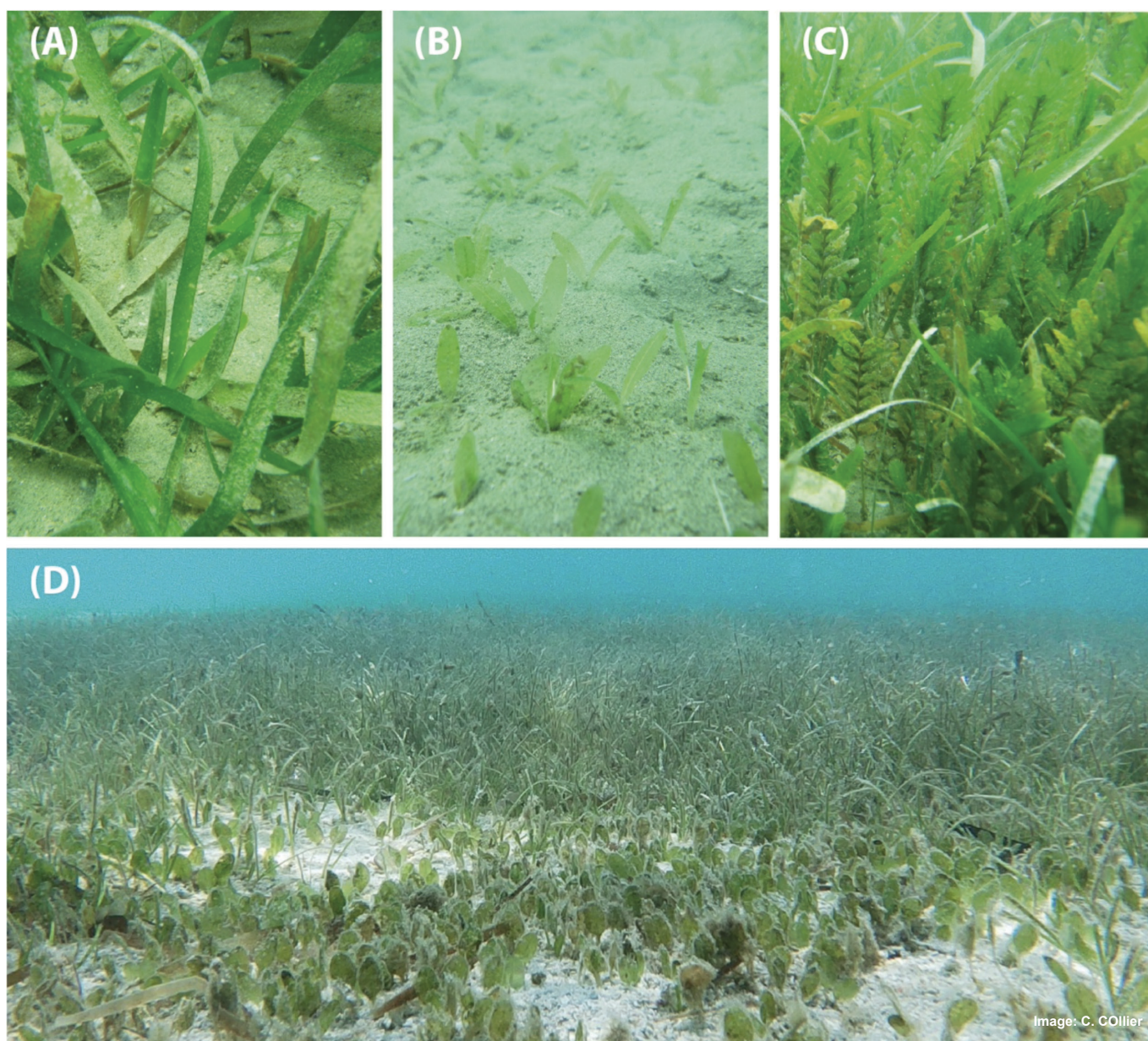


Figure 1: Common seagrass species in the GBR, including: (A) *Cymodocea serrulata*, (B) *Halophila decipiens*, (C) *Halophila spinulosa*, and (D) *Halophila ovalis* (front of image), and *Halodule uninervis* (rear of image).

The Solution

Under the Reef 2050 Water Quality Improvement Plan, the Australian and Queensland Governments are working to improve water quality through advances in agricultural land management practices (State of Queensland, 2018). The effects of potential changes in land management practices on sediment and nutrient loads in rivers that discharge to the GBR, and on marine water quality have been modelled through the Paddock to Reef program and the eReefs project (Baird et al., 2021; McCloskey et al., 2021).

In this case study, we have used the outputs of these models together with seagrass species distribution models developed through [NESP TWQ project 5.4](#) to assess how different land management scenarios affect seagrass habitat suitability. We considered five seagrass species that occur in the GBR, because the light requirements of species vary considerably (Collier et al., 2016; Waycott et al., 2004), and changes in marine water quality are also likely to affect them in different ways.

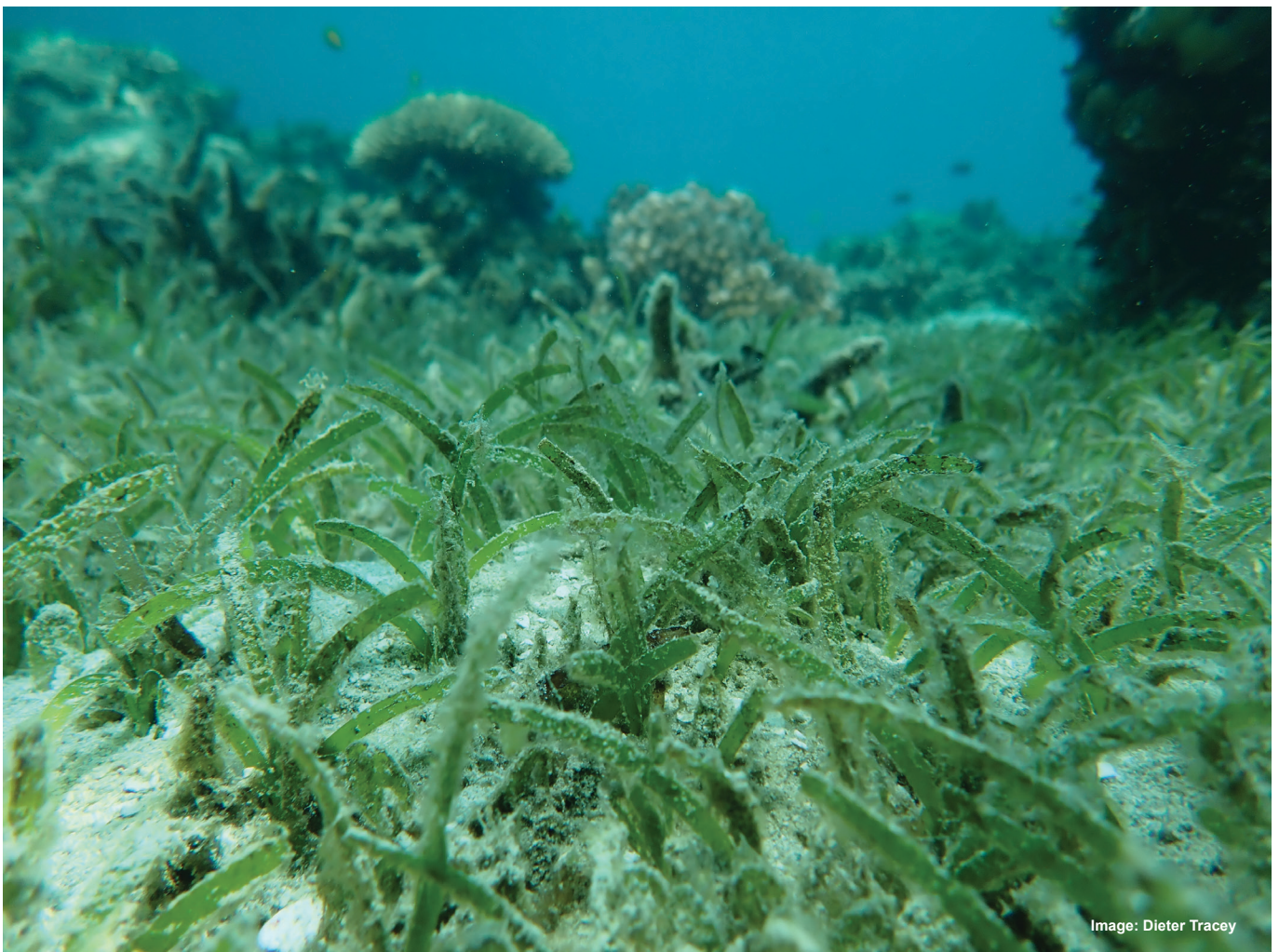


Image: Dieter Tracey

Modelling the impact of catchment land use on benthic light

Several management scenarios have been simulated in the eReefs modelling system, ranging from the complete removal of all natural and anthropogenically-derived river sediment and nutrient loads through to continuation of current land management practices with no reduction in loads (Baird et al., 2021; McCloskey et al., 2021). Here, we consider four of these water quality scenarios in terms of their potential impacts on seagrass habitats.

In order from worst case to best case, these scenarios are:

1. q3base: Current land management practices continue (baseline)
2. q3C: Full adoption of minimal standard land management practices
3. q3B: Full adoption of best-practice land management practices
4. q3A: Full adoption of innovative land management practices (i.e., better than current “best practice”).

Scenarios q3C, q3B and q3A all represent an improvement over current land management practices and result in a reduction in sediment and nutrient loads reaching the GBR compared with q3base. River loads for each scenario are derived from Queensland Government “Paddock to Reef” program catchment modelling and the assumptions associated with each scenario are described in detail by McCloskey et al. (2021).

We synthesised daily outputs from the eReefs marine models from the wet season months (November – May) between 2011 and 2019 (inclusive) to produce maps of the average (mean) photosynthetically active radiation (PAR). This represents benthic light that would be expected to reach the bottom of the water column at midday and hence be available to any seagrasses present over the entire GBR in each scenario. These maps are based on the eReefs model output variable, ‘EpiPAR_sg’ (epibenthic PAR directly above the seagrass), which is available for each scenario on a nominal 4km grid. EpiPAR_sg is equivalent to the bPAR (benthic PAR) data product available from remote sensing ocean colour observations (Magno-Canto et al., 2019; Robson et al., 2020) used in previous seagrass habitat modelling (Carter et al., 2021a). The calculation of EpiPAR_sg in the eReefs models has been described in detail by Baird et al. (2020). From here-on, EpiPAR_sg is referred to as ‘benthic light’.

Because our seagrass models required higher-resolution maps, we downscaled the eReefs outputs to a 1 km grid by comparing the outputs of the 4km baseline scenario with the existing 1 km-resolution eReefs model outputs. The available 1 km eReefs model run also assumes current land management practices and it produced similar results to the 4 km-resolution baseline model, although it was run using an earlier version of the eReefs biogeochemical model. For each location in the 1 km grid model, we compared the mean annual benthic light with the mean annual benthic light in the matching grid cell in the 4 km model over the period for which the two versions of the model overlapped (i.e. 2014 to 2019 inclusive) and calculated a linear scaling factor which was then applied to scenario outputs to produce 1 km resolution maps for each scenario. While this downscaling approach introduces some error, this is likely to be small relative to other sources of uncertainty in the combined modelling approach.

We then developed a seagrass habitat model relating mean benthic light in the baseline scenario (q3base) to observed seagrass distributions in the GBR. This model provides the ability to predict seagrass distributions as a function of eReefs benthic light. Finally, we applied the model using the predicted benthic light distribution from each eReefs land management improvement scenario to assess the likely change in seagrass habitat under that scenario.

The seagrass habitat model

The seagrass composite summarises 35 years of seagrass spatial data collection (1984 –2018) within the GBR into one GIS shapefile containing seagrass survey data as seagrass presence and absence for each species at 81,387 sites (Carter et al., 2021a). The data set is publicly available on e-atlas: <https://eatlas.org.au/data/uuid/5011393e-0db7-46ce-a8ee-f331fcf83a88>. The methods used to collect the data, and the strengths and limitations of composite data are described in Carter et al. (2021b).

This analysis uses data on seagrass presence of five seagrass species from the whole data set which overlapped with the environmental data set:

- *Cymodocea serrulata*
- *Halophila decipiens*
- *Halophila ovalis*
- *Halophila spinulosa*
- *Halodule uninervis*

GENERAL MODEL ANALYSIS

We used Maximum Entropy (MaxEnt) software (version 3.4.1) to generate seagrass species distributions and potential distribution based on the complementary log-log (cloglog) link (Phillips et al., 2006; Phillips & Dudik, 2008) as described in Carter et al (In prep). This assumes that the species' presence or absence at nearby sites (pixels) are independent and is suitable for freely dispersed species such as seagrasses. MaxEnt models were generated using 10 replicate runs each with 10,000 background points and a maximum of 1000 iterations each. The convergence threshold was set to 10^{-5} with a regularization multiplier of 1. Occurrence records were thinned to 1km resolution so only one point was present in each of the environmental layer cells. The seagrass species distribution models are summarised in Carter et al (In prep). The baseline was re-run for each scenario. It is important to note that this model was developed using benthic light and seagrass presence data only. Other factors also influence the distribution of seagrass species (Carter et al., In prep; Robson et al., 2020), and seagrass communities (Carter et al., 2021a) and these could either limit or improve habitat suitability based on benthic light alone, but they were not included in this analysis in order to highlight responses to benthic light.

SPECIES AREA CHANGES

The potential habitat area of each species in each scenario were assessed. MaxEnt rasters of habitat suitability for each species and scenario were processed in ARC GIS (WGS84 projection). Each file was reclassified into classes based on suitability from zero to one. The number of 1-kilometer pixels in each of the classes was counted, and then expressed as area (km²). Probability >0.6 was considered as 'suitable habitat' and area calculated by summing all 1km² pixels for probabilities ranging from 0.6 – 1.0 for each species and each scenario.

Change in the area of suitable habitat for scenario q3A was calculated as:

$$Ch_{q3A} = Aq3A_{61} - Aq3A_{b61} \quad \text{Equation 1}$$

Where $Aq3A_{61}$ is the area of suitable habitat in the band 0.6 to 1.0 for the baseline run for scenario q3A and $Aq3A_{b61}$ is the area of suitable habitat in the band 0.6 to 1.0 under scenario q3A. This identifies where suitable habitat (>0.6) occurred in the management scenario, which was not in the baseline scenario (i.e. <0.6). This was calculated for each species.

Improvement in habitat suitability was calculated for each pixel within the range 0.6 – 1.0 according to the following:

$$Imp_{px} = HSq3A_{px} - HSq3A_{bpx} \quad \text{Equation 2}$$

Where $HSq3A_{px}$ is the value for pixel x (px) within the range 0.6 – 1.0 in scenario q3A, and $HSq3A_{bpx}$ is the value for the same pixel in the baseline.

The Outcome

The area of suitable habitat (>0.6) based on benthic light varied among species (Figures 2 to 6). *H. decipiens* has the largest area of suitable habitat (36,376 km²). It is tolerant of low light levels and occupies the deep-water lagoonal habitats between reefs, but typically occurs as sparse, low biomass habitat throughout much of this range (Chartrand et al., 2018; York et al., 2015). The area of *H. decipiens* was followed closely by *H. spinulosa* (30,795 km²). This species can also occur in deep water and form meadows in places (Coles et al., 2009). Compared to other *Halophila* spp., it can reach larger biomasses with a greater proportion of fibrous stem and rhizomes (Waycott et al., 2004) and because of that, compared to *H. decipiens*, it has higher respiratory rates (Chartrand et al., 2018) and grows in slightly shallower water on average (Coles et al., 2009). *H. ovalis* (20,812 km²), *H. uninervis* (15,453 km²) and *C. serrulata* (17,455 km²) had smaller areas of suitable habitat, with the latter two generally being constrained to the coastal and shallow reef areas where they tend to form 'meadows'.

Habitat suitability based on the benthic light model identified suitable habitat for a number of species on reef tops on the mid- and outer shelf. Many of these reefs, such as the Swains Reefs in the southern GBR, are not occupied by long-bladed species like *C. serrulata* and *H. uninervis* (Figure 2c) because other conditions such as currents, water temperature and the availability of benthic substrate and nutrients limit their growth. The area of suitable habitat is therefore likely to be an over-estimate for the shallow water species, which tend to occur in protected areas, and an under-estimate for the sparse deep-water species, in particular *H. decipiens* because of the habitat suitability cut-off applied (>0.6). The changes in habitat suitability based on catchment scenarios identified in this analysis should be viewed as relative for making comparisons amongst scenarios, species and regions.

Habitat suitability increased with increasing benthic light, reaching an optimal range (for habitat suitability >0.6) of $\sim 12 - 48$ mol m⁻² d⁻¹ for *C. serrulata*, *H. ovalis* and *H. uninervis* (Figure 7a,c,e), and $\sim 8 - 48$ mol m⁻² d⁻¹ for *H. decipiens* and *H. spinulosa* (Figure 7b,d). The suitability of habitat is predicted to decline when benthic light is high. This is not because they can't tolerate higher light levels, rather that the species are not usually found in locations where higher light levels occur (e.g. on a number of reef tops such as the Swains) and so the model predicts they won't occur there. For this reason and following the habitat suitability-benthic light response curves (Figure 7), there are a small number of places where light increases in the catchment scenarios but the suitability of habitat declines. In reality, if habitat is suitable for seagrass under current conditions, then increases in benthic light are highly unlikely to reduce suitability, as seagrass growth and biomass increase as light levels approach full sunlight (Abal et al., 1994). The habitat suitability estimates are probably less reliable at these higher light levels, owing largely to inadequate seagrass data (low survey effort) in very high light regions of the GBR.

The benthic light values in this model are not equivalent to in situ light monitoring, and therefore cannot be compared to other published light thresholds (e.g. Collier et al., 2016). The primary reason for this is that the pixel size (1 km²) used here is an 'average' for the pixel, but benthic light will vary according to depth within the pixel.

Habitat suitability under different catchment scenarios

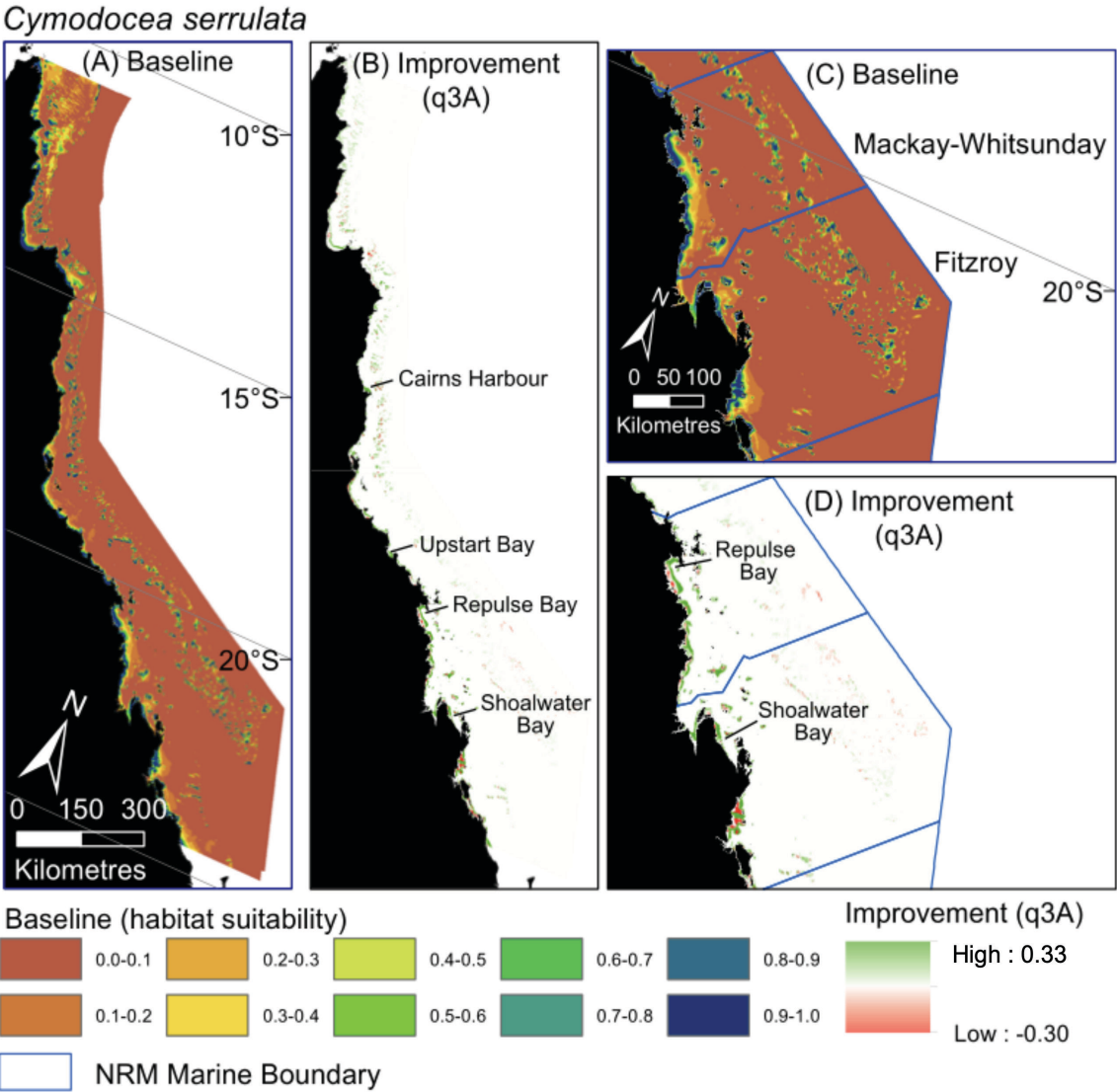
There was an increase in suitable habitat with increasing investment into catchment management because of the predicted increases in benthic light, which is essential for seagrass growth. The greatest increase in suitable habitat for all species was under scenario q3A (full adoption of innovative land management practices). Increases in suitable habitat also varied regionally: the smallest increases occurred in Cape York for all species, and the largest increases in the Fitzroy or Mackay-Whitsunday regions depending on species.

Cymodocea serrulata

The range of *C. serrulata* is constrained to shallow and intertidal coastal and reef habitat (Figure 2a, c) and suitable habitat (0.6 – 1.0) covered 17,455 km². Completely unsuitable habitat for *C. serrulata* (0 – 0.2) occurs throughout most of the GBR lagoon.

There was an increase in the area of suitable habitat in all water quality scenarios across the GBR, with the maximum increase (569 km², ~3.3%) under the q3A scenario (full adoption of innovative land management practices; Figure 2e). The largest regional increase in area of suitable habitat occurred in the Fitzroy, but as a relative change, the greatest increase was in the Mackay-Whitsundays (5.0%).

There was also an improvement in the suitability of habitat (i.e., suitability increased within the range 0.6 – 1.0), particularly in the shallow subtidal coastal areas and reefs (Figure 2b, d). The area over which habitat suitability improved was 11,779 km². Areas with the greatest magnitude of improvement (represented by the darker green shades in the improvement panels; Figure 2 b and d) included Cairns Harbour, Upstart Bay and from Repulse Bay to Shoalwater Bay.



	Relative increase in suitable habitat (%Ch)			Area increase of suitable habitat (km ²)		
	q3A	q3B	q3C	q3A	q3B	q3C
GBR	3.3	1.3	0.4	569	227	64
Cape York	1.3	0.8	0.4	82	50	23
Wet Tropics	2.7	1.6	0.0	58	35	0
Burdekin	2.1	1.1	0.5	41	21	9
Mackay-Whitsunday	5.0	1.7	0.8	157	52	24
Fitzroy	4.3	1.8	0.2	171	70	8

Figure 2: Habitat suitability for the seagrass species *C. serrulata* and changes under the catchment scenarios for (A) baseline habitat suitability, (B) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3), (C) zoom-in of baseline habitat suitability in the Mackay-Whitsunday and Fitzroy regions, (D) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3) in the Mackay-Whitsunday and Fitzroy regions, and (E) increase in the area of suitable habitat (%Ch) i.e. where there is an increase from <0.6 in the baseline scenario to suitable habitat (>0.6) in the catchment scenario. The GBR values include changes in the portion of the Burnett Mary NRM that occurs within the GBR World Heritage Area. Bold type indicates the NRM with the largest increase within each scenario.

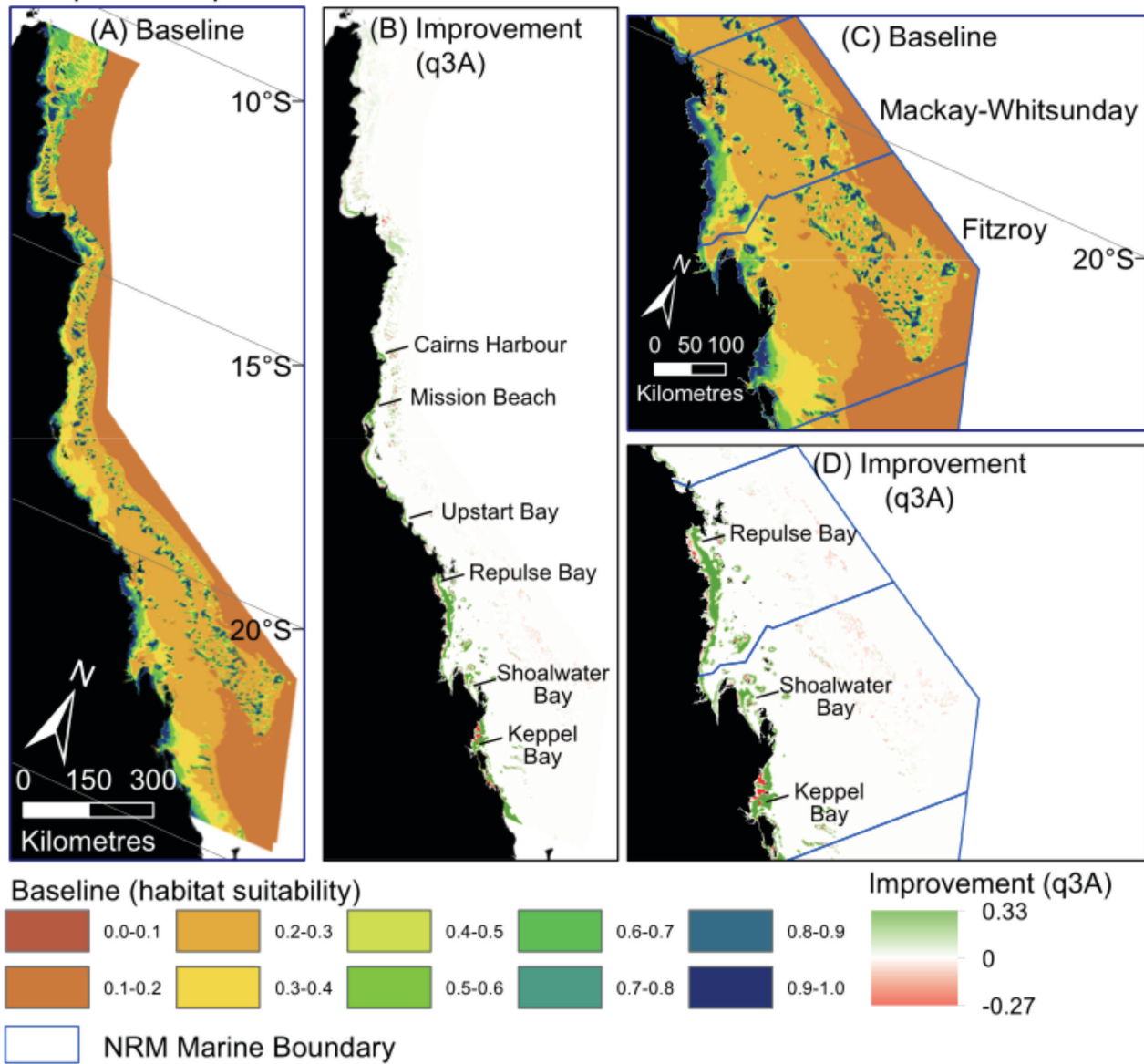
Halophila decipiens

H. decipiens had the largest area of suitable habitat of 36,376 km² over the GBR in the baseline scenario (Figure 3a, c). Like other species, this included inshore coastal and reef areas, but also extended further into deeper water than for other species. *H. decipiens* can also be commonly found in lagoonal areas where suitability in this model is 0.2 – 0.6 (Carter et al., 2021a; Coles et al., 2015), but at very low density and also varying seasonally. Our definition of suitable habitat therefore likely underestimates the area suitable for this species. Completely unsuitable habitat (0 – 0.2) occurs only in the GBRWHA beyond the continental shelf where water depths are >100 m.

H. decipiens had the largest increase in suitable habitat area in the catchment management scenarios across the GBR; there was a 3.8% increase (1384 km²) in the q3A scenario (full adoption of innovative land management practices) relative to the baseline (Figure 3e). The largest regional increase was in the Fitzroy (7.3%, ~548 km²) and the lowest was in Cape York (0.8%, ~121 km²).

There were vast areas (total area: 26,628km²) where habitat suitability improved within the suitable habitat area. Improvement occurred throughout the GBR including in Cairns Harbour and Mission Beach to Upstart Bay, but the greatest magnitude of improvement occurred in the Mackay-Whitsunday and Fitzroy regions, especially Repulse Bay to Shoalwater Bay and around Keppel Bay (Figure 3b,d).

Halophila decipiens



	Relative increase in suitable habitat (%Ch)			Area increase of suitable habitat (km ²)		
	q3A	q3B	q3C	q3A	q3B	q3C
GBR	3.8	1.6	0.4	1384	589	148
Cape York	0.8	0.6	0.3	121	83	44
Wet Tropics	2.9	1.9	0.4	105	68	14
Burdekin	1.8	0.8	0.2	62	27	6
Mackay-Whitsunday	5.5	2.5	1.3	331	153	75
Fitzroy	7.3	2.5	0.6	548	187	44

Figure 3: Habitat suitability for the seagrass species *H. decipiens* and changes under the catchment scenarios for (A) baseline habitat suitability, (B) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3), (C) zoom-in of baseline habitat suitability in the Mackay-Whitsunday and Fitzroy regions, (D) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3) in the Mackay-Whitsunday and Fitzroy regions, and (E) increase in the area of suitable habitat (%Ch) i.e. where there is an increase from <0.6 in the baseline scenario to suitable habitat (>0.6) in the catchment scenario. The GBR values include changes in the portion of the Burnett Mary NRM that occurs within the GBR World Heritage Area. Bold type indicates the NRM with the largest increase within each scenario.

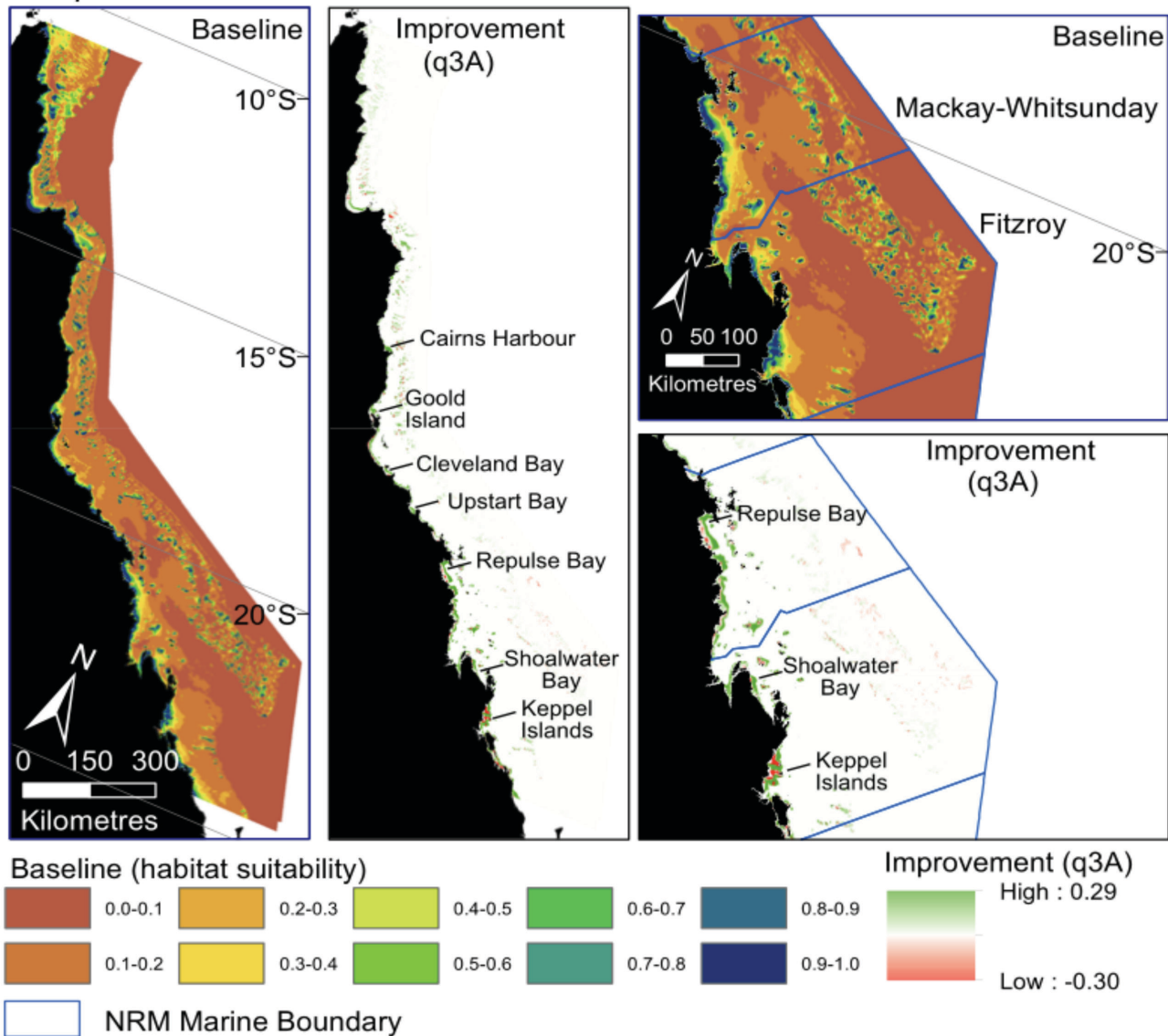
Halophila ovalis

H. ovalis is a species occurring in a wide range of environmental conditions (Waycott et al., 2004). *H. ovalis* had the third largest suitable habitat area and distribution (20,812 km²). Lower levels of suitability (0.2 – 0.6) extend into the deep water inshore and mid-shelf where it can be found at times. Therefore the suitable habitat range used in this analysis is likely to be an underestimate for this species.

There was an increase in the area of suitable habitat in all scenarios across the GBR, with the maximum improvement (749 km², ~3.6%) in the q3A (full adoption of innovative land management practices) scenario (Figure 4e). The largest regional increase in area of suitable habitat occurred in the Fitzroy region (5.6%).

There was also an improvement in the suitability of habitat, particularly in the shallow subtidal coastal areas and reefs (Figure 4 b, d). The area over which habitat suitability improved was 14,274 km². Areas with the greatest magnitude of improvement were around Cairns, Goold Island, Cleveland Bay, Upstart Bay, Repulse Bay to Shoalwater Bay and in inshore waters of the Keppel Islands.

Halophila ovalis



	Relative increase in suitable habitat (%Ch)			Area increase of suitable habitat (km ²)		
	q3A	q3B	q3C	q3A	q3B	q3C
GBR	3.6	1.5	0.4	749	309	79
Cape York	1.2	0.7	0.3	85	52	24
Wet Tropics	2.8	1.9	0.3	68	45	7
Burdekin	2.3	0.8	0.2	51	18	4
Mackay-Whitsunday	4.7	1.7	0.6	172	63	22
Fitzroy	5.6	2.2	0.0	257	103	0

Figure 4: Habitat suitability for the seagrass species *H. ovalis* and changes under the catchment scenarios for (A) baseline habitat suitability, (B) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3), (C) zoom-in of baseline habitat suitability in the Mackay-Whitsunday and Fitzroy regions, (D) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3) in the Mackay-Whitsunday and Fitzroy regions, and (E) increase in the area of suitable habitat (%Ch) i.e. where there is an increase from <0.6 in the baseline scenario to suitable habitat (>0.6) in the catchment scenario. The GBR values include changes in the portion of the Burnett Mary NRM that occurs within the GBR World Heritage Area. Bold type indicates the NRM with the largest increase within each scenario

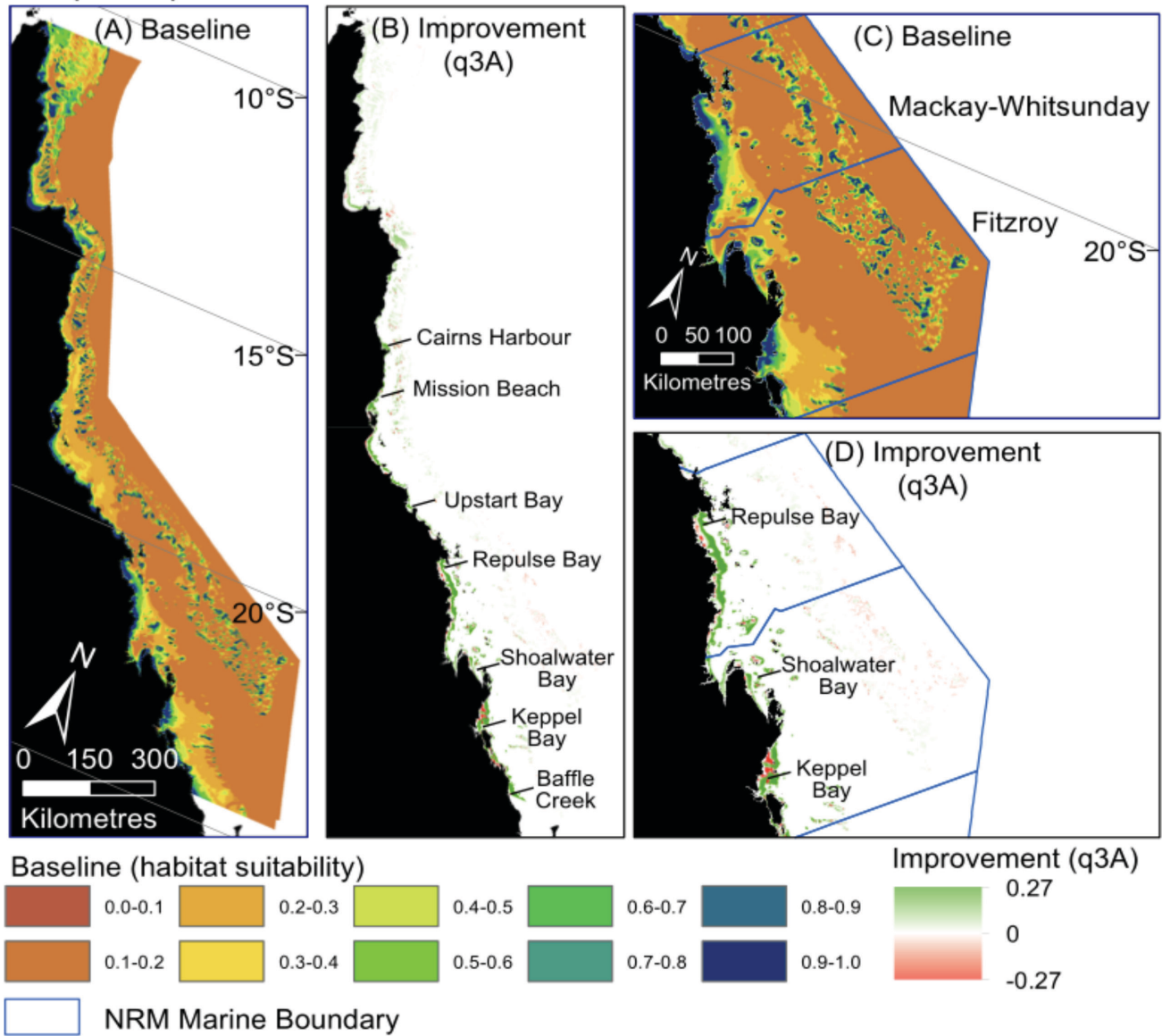
Halophila spinulosa

H. spinulosa had the second largest area of suitable habitat (>0.6) (Figure 5a, c). Like other species, this included inshore coastal and reef areas, but also extended into deeper water though not as far as *H. decipiens*.

The response of this species to the catchment management scenarios is similar to *H. decipiens*. *H. spinulosa* had the largest increase in suitable habitat area in the q3A (full adoption of innovative land management practices) catchment management scenario, with an approximately 3.7% increase in area across the GBR ($\sim 1133 \text{ km}^2$) (Figure 5e). The Fitzroy region had the largest increase in area ($\sim 336 \text{ km}^2$), but the Mackay-Whitsundays had the largest relative change (5.5%, $\sim 286 \text{ km}^2$) and Cape York the lowest (1.0%, $\sim 118 \text{ km}^2$).

As for *H. decipiens*, there were vast areas ($22,125 \text{ km}^2$) where the suitability of the habitat improved within the suitable habitat area. Improvement occurred throughout the GBR, including Cairns Harbour, Mission Beach to Upstart Bay and Bustard Bay to Baffle Creek, but the greatest magnitude of improvement occurred in the Mackay-Whitsunday and Fitzroy regions, especially between Repulse Bay and Shoalwater Bay and areas inshore from the Keppel Islands (Figure 5 b,d).

Halophila spinulosa



	Relative increase in suitable habitat (%Ch)			Area increase of suitable habitat (km ²)		
	q3A	q3B	q3C	q3A	q3B	q3C
GBR	3.7	1.5	0.4	1133	454	137
Cape York	1.0	0.6	0.2	118	66	24
Wet Tropics	3.1	1.8	0.4	102	59	13
Burdekin	2.3	1.0	0.4	73	31	13
Mackay-Whitsunday	5.5	2.1	0.8	286	112	43
Fitzroy	5.2	1.7	0.4	336	114	27

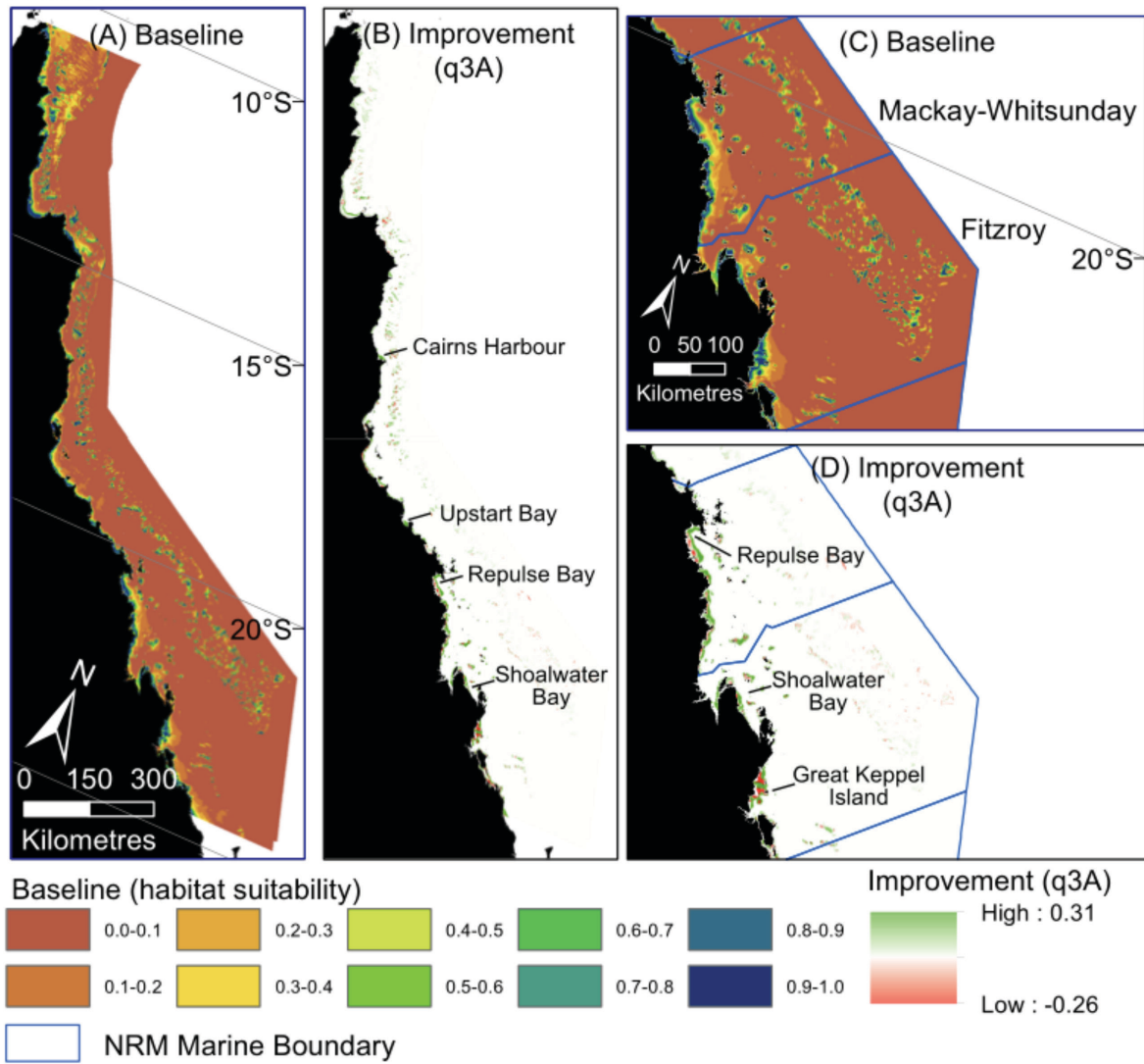
Figure 5: Habitat suitability for the seagrass species *H. spinulosa* and changes under the catchment scenarios for (A) baseline habitat suitability, (B) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3), (C) zoom-in of baseline habitat suitability in the Mackay-Whitsunday and Fitzroy regions, (D) change in suitability within the suitable habitat range 0.6-1.0 (Imp_{px} , Equation 3) in the Mackay-Whitsunday and Fitzroy regions, and (E) increase in the area of suitable habitat (%Ch) i.e. where there is an increase from <0.6 in the baseline scenario to suitable habitat (>0.6) in the catchment scenario. The GBR values include changes in the portion of the Burnett Mary NRM that occurs within the GBR World Heritage Area. Bold type indicates the NRM with the largest increase within each scenario.

Halophila uninervis

The range of suitable habitat for *H. uninervis* is constrained to shallow and intertidal coastal and reef habitat, similar to the predicted range for *C. serrulata* (Figure 6a, c). However, its distribution is generally not as patchy because it can tolerate higher levels of exposure and is morphologically plastic, being able to adapt to a range of conditions. The completely unsuitable range (0 – 0.2) covers most of the GBR lagoon.

There was an increase in the area of suitable habitat in all scenarios across the GBR reaching ~3.0% (462 km²) in the q3A (full adoption of innovative land management practices) scenario (Figure 6e). The largest regional increase in area of suitable habitat occurred in the Mackay-Whitsundays (4.8%, 130 km²), followed closely by the Fitzroy region (3.6%, 123 km²) (Figure 6d). The largest regional area increase under scenario q3C (full adoption of minimal standard land management practices) was in Cape York (20 km²), and the largest relative increase in q3C was in the Wet Tropics (0.5%).

The improvement in the suitability of habitat was very similar to *C. serrulata* (Figure 6b, d). The area over which habitat suitability improved was 10,314 km². The greatest magnitudes of improvement were around Cairns, Upstart Bay, from Repulse Bay to Shoalwater Bay and around the Keppel Islands.

Halodule uninervis

	Relative increase in suitable habitat (%Ch)			Area increase of suitable habitat (km ²)		
	q3A	q3B	q3C	q3A	q3B	q3C
GBR	3.0	1.2	0.4	462	183	60
Cape York	1.1	30.0	0.4	59	30	20
Wet Tropics	3.0	40.0	0.5	56	40	9
Burdekin	2.6	17.0	0.4	44	17	7
Mackay-Whitsunday	4.8	43.0	0.4	130	43	11
Fitzroy	3.6	39.0	0.3	123	39	10

Figure 6: Habitat suitability for the seagrass species *H. uninervis* and changes under the catchment scenarios for (A) baseline habitat suitability, (B) change in suitability within the suitable habitat range 0.6-1.0 (Imp^{px} , Equation 3), (C) zoom-in of baseline habitat suitability in the Mackay-Whitsunday and Fitzroy regions, (D) change in suitability within the suitable habitat range 0.6-1.0 (Imp^{px} , Equation 3) in the Mackay-Whitsunday and Fitzroy regions, and (E) increase in the area of suitable habitat (%Ch) i.e. where there is an increase from <0.6 in the baseline scenario to suitable habitat (>0.6) in the catchment scenario. Bold type indicates the NRM with the largest increase within each scenario.

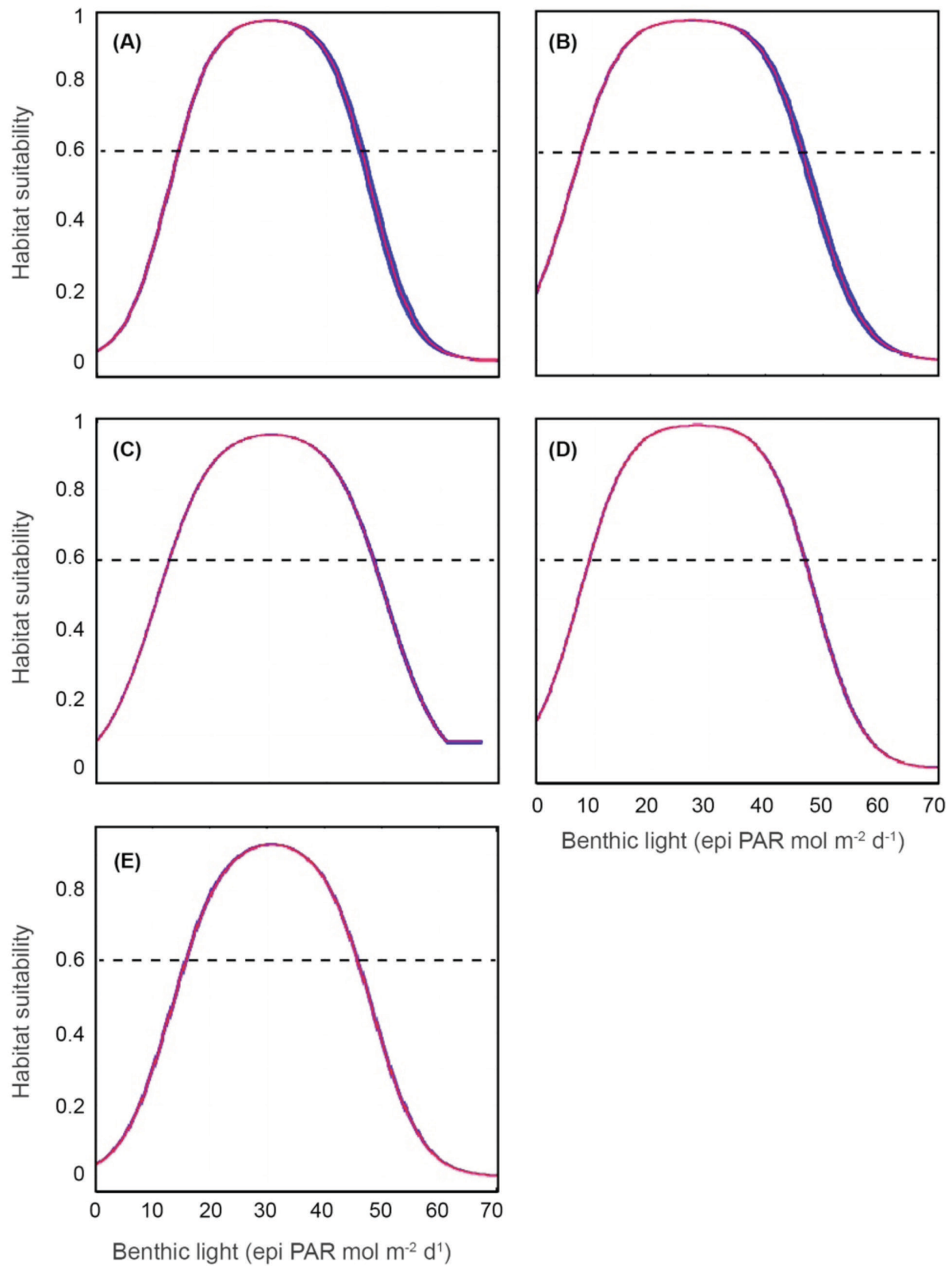
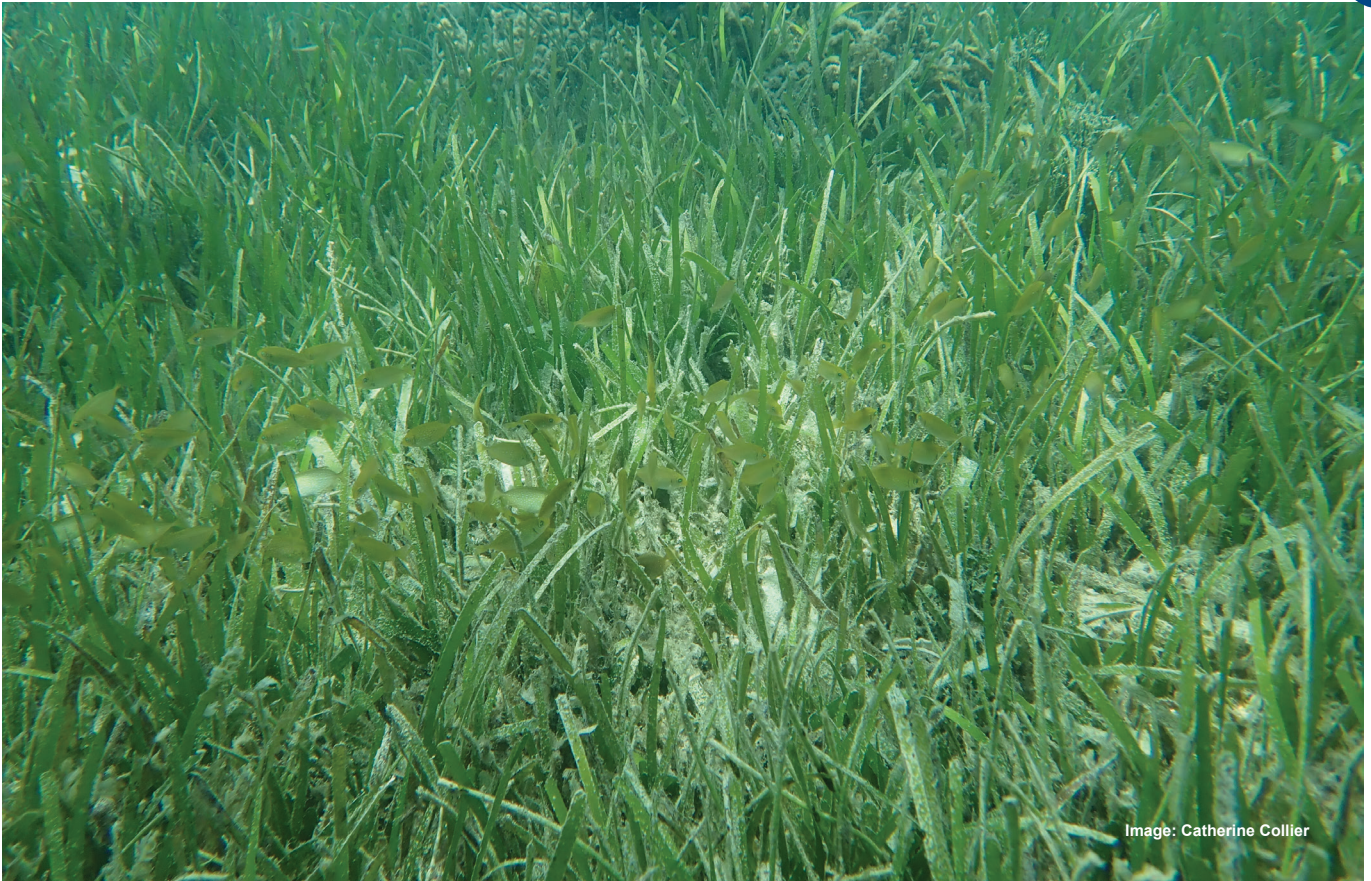


Figure 7: Habitat suitability in relation to benthic light (epiPAR_sg) for (A) *C. serrulata*, (B) *H. decipiens*, (C) *H. ovalis*, (D) *H. spinulosa* and, (E) *H. uninervis*.



Key Messages

Enhancing land management practices that improve water quality could substantially increase and improve the area of seagrass habitat due to improvements in the benthic light environment. This could increase the extent and density of seagrasses in the GBR, with flow-on effects for biodiversity and cultural values.

The relative increase in suitable habitat areas for the most ambitious land management change scenario (i.e., q3A - full adoption of innovative land management practices) was similar for all species (3 – 3.8%), but the largest increases in total area were for *H. decipiens* and *H. spinulosa*. These species occur over wide areas of the GBR already, including lagoonal deep waters where they are the two most common species (Carter et al., 2021a; Coles et al., 2009). There were also large areas over which benthic light improved leading to 1,384 km² and 1,133 km² increases in total area of suitable habitat for *H. decipiens* and *H. spinulosa*, respectively. The distributions of these species are in fact much wider than the suitable habitat threshold used in this analysis, especially for *H. decipiens* (Carter et al., 2021a; Coles et al., 2009). It is only sometimes present at sites that are suitable for it to grow because of its dynamic, low density and patchy growth. Furthermore, the lagoon inter-reefal areas have lower sampling effort primarily because of the challenges of sampling there. The probability of this species being present in the site data is therefore low across its actual range. A conservative approach was taken here by restricting the analysis to habitat suitability >0.6, but this is likely an underestimate of the range of these species.

The ecological role of *Halophila* species in inter-reefal deep water areas is not well understood, but they are generally perceived to have relatively lower value in inter-reefal areas than in shallow water because they are sparse and lack a canopy for animal refuge (Mtwana Nordlund et al., 2016). However with such large increases in area, even if the *Halophila* has low density, the resultant increases in seagrass productivity will also increase nutrient uptake rates and the subsequent flow of nutrients through food webs as the additional seagrass or seagrass detritus is grazed (Coles et al., 2009).

Most seagrass communities in the GBR contain multiple species, and the changes identified here are not additive; i.e., the total potential increase in suitable seagrass habitat is less than the sum of the increased area for individual species. Most notably, the geographical locations of suitable habitat in both baseline and land management improvement scenarios mostly overlapped for *C. serrulata* and *H. uninervis*. *C. serrulata* is rarely dominant and usually co-occurs with *H. uninervis* or other species (Carter et al., 2021a; McKenzie et al., 2020a). *H. uninervis* is tolerant of a wider range of environmental conditions but is none-the-less constrained to shallow coastal habitats. Changes identified for these species are representative of increases in shallow inshore seagrass habitats in general. The species *H. ovalis* is a generalist and as such it overlaps in distribution with all of the other four species to some extent. It is more common in shallow and intertidal areas and becomes less common with increasing depth and does not grow as deep, on average, as the other *Halophila* species (Carter et al., 2021a; Coles et al., 2009).

There was also an improvement in the suitability of habitat across 67 to 73% of the suitable habitat range of all species. Higher light levels and increasing habitat suitability are likely to correspond to denser meadows (Chartrand et al., 2016; Chartrand et al., 2018; Collier et al., 2007; Collier et al., 2012a). Taller, denser meadows have higher value to some ecosystem services such as fisheries (McCloskey & Unsworth, 2015). This will be especially significant for the canopy-forming species that grow in meadows in the inshore zone.

Based on these models, seagrass habitat in the Mackay-Whitsundays and Fitzroy regions stand to benefit the most from (improved) catchment management, and had the highest increases in habitat suitability in scenario q3A (full adoption of innovative land management practices). By contrast, in a risk assessment undertaken for the Scientific Consensus Statement, the greatest risk to seagrasses was in the Burdekin region followed by the Burnett Mary (Bainbridge et al., 2018; Waterhouse et al., 2017). The difference may be due to the risk assessment being based on risk to seagrass from sediments, and high sediment loads occur in discharges from those regions. By contrast, the scenarios used in this analysis represent broader changes to water quality. When the same scenarios used here were applied to the eReefs biogeochemical model to predict seagrass biomass mechanistically (eReefs) there was overlap in the hotspot areas we identified including Cairns, Townsville, Repulse Bay, and around the Keppel Islands (See appendix and Baird et al., 2021). The increases were more wide-spread in the eReefs scenarios, which considered the change in extent in late 2011, thus reflecting the impact of a single large event (TC Yasi, and the very high river flows that preceded it) (see appendix).

Habitat suitability models were based on seagrass observations (presence data) in any of the data records over the past 35 years of the composite data set. Most of the lagoonal inter-reef seagrass data records are from surveys occurring prior to 2008 (Carter et al., 2021b), while the catchment scenarios are modelled based on conditions from 2011 – 2019. GBRMPA's Marine Monitoring Program data shows that there has been a long-term decline in nearshore water quality over the period from 2006 to 2019 (Gruber et al., 2020), and nearshore seagrass health also declined and did not fully recover in some communities and/or habitats (Carter et al., 2021a; Kroon et al., 2016; McKenzie et al., 2020a). The accuracy of the models for predicting changes in suitability in the lagoonal waters (the *Halophila* spp.), in particular, will be limited by this mis-match in the data sets.



Image: J. Jones

The models presented here can be used to assess relative changes in suitability, for comparing among species, scenarios and regions. The coastal species, including *C. serrulata*, *H. uninervis*, and *H. ovalis* have rich data records from localised inshore ports monitoring extending back to the early 2000's (e.g. McKenna et al., 2015), but are most widespread and consistent from 2009 onwards, and therefore more closely coincide with the catchment modelling scenarios (Carter et al., 2021b).

Changes in river loads are likely to have the most significant effect during the wet season (Fabricius et al., 2016; Lewis et al., 2020). Therefore, this exercise was based on average changes in benthic light (chronic light reduction) during the wet season. Seagrass meadows are exposed to low light levels at times throughout the year due to river discharge and resuspension of sediments and organic matter. However, it is the wet season and river discharge that typically causes the largest and most prolonged periods of light stress for seagrasses (Collier et al., 2012b; McKenzie et al., 2020a; Rasheed et al., 2014; York et al., 2015). Impacts from very low light levels could occur within days to weeks for the small *Halophila* species (Chartrand et al., 2018; York et al., 2015) and therefore, future investigations should examine the effects of catchment management on discrete events (sensu. Baird et al., 2021)

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Appendix

In this appendix, we compare the results of the mechanistic modelling of seagrass biomass in the eReefs biogeochemical models (Baird et al., 2021) with the results from our habitat suitability modelling (described in the main body of this report). We have taken the same approach in visualising the eReefs model outputs in this Appendix as those in the main report. The two models take very different approaches, so where there is substantial agreement, we can be more confident of the predictions.

For several reasons, the results cannot be compared directly:

- Our models report distribution of potentially suitable habitat, while the eReefs biogeochemical model reports predicted seagrass nitrogen content (mg N m^{-2});
- Our models report changes in habitat suitability for specific species, while the eReefs models report changes in seagrass nitrogen content for each of three general seagrass groups ('*Halophila*', 'deep *Halophila*' and '*Zostera*').
- Our models consider long-term mean change in wet-season habitat suitability, while Baird et al. (in press) report changes in seagrasses during a representative high catchment discharge year (2011).

For this reason, we present qualitative visual comparisons rather than quantitative comparisons of the results of the two models.

This comparison is provided as an addendum to our report in order to facilitate discussion. It is not a comprehensive analysis.

'*Halophila*'

The '*Halophila*' seagrass group in the eReefs biogeochemical model represents *Halophila ovalis* and functionally similar species. A visual comparison of Figure 8 (eReefs results for the *Halophila* groups) and Figure 4 (habitat suitability model results for *Halophila ovalis*) is possible, noting that the units for the two models are different and hence the colour scales cannot be directly compared. Nonetheless, it is clear that although both approaches predict a significant improvement in habitat suitability, the eReefs biogeochemical model predicts a much larger area of change in this seagrass group than does our habitat suitability model, particular in the northern GBR. The reasons for this difference are not immediately clear and would require detailed analysis in order to be understood.

It is possible that some of the difference is an artefact of considering only the 2011 year in the visualisation of the eReefs results, versus considering long-term average conditions in the habitat suitability model, as 2011 was a year with much higher-than-average catchment sediment and nutrient loads. Analysis of the entire eReefs seagrass time-series would allow this point to be checked, but was beyond the scope of this study.

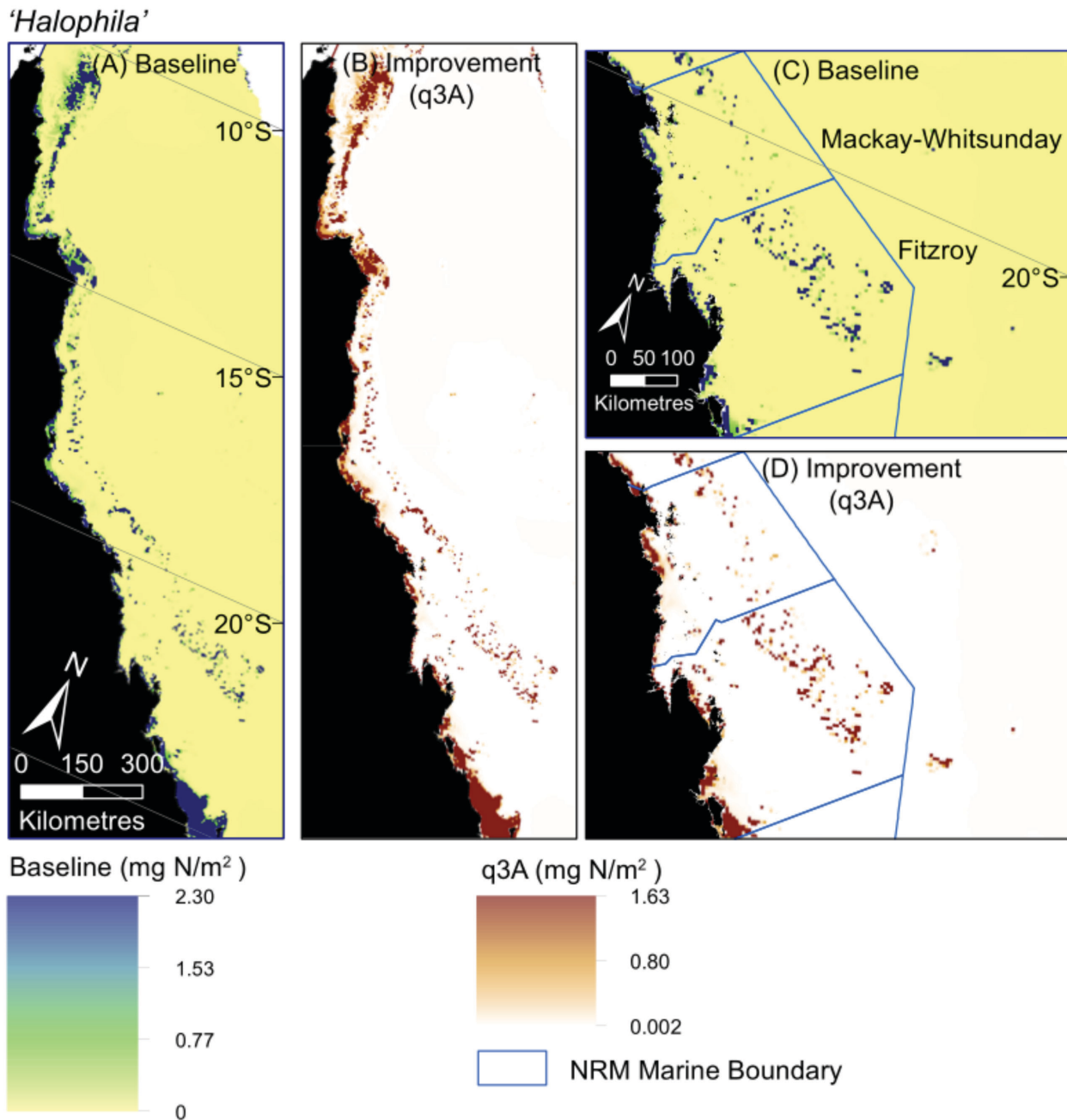


Figure 8: The impact of river load reductions (q3A) on the biomass of the 'Halophila' seagrass group simulated by the eReefs biogeochemical model (adapted from Baird et al., 2021). Under the catchment scenarios for (A) baseline scenario (current land management practices), (B) predicted change in biomass under innovative land management practices, (C) zoom-in of baseline biomass in the Mackay-Whitsunday and Fitzroy regions, (D) change in biomass in the Mackay-Whitsunday and Fitzroy regions.

'Deep Halophilas'

The 'deep *Halophilas*' group included in the eReefs biogeochemical model represents *Halophila decipiens* and similar species. As for the '*Halophilas*' group, the eReefs model predicts a more extensive improvement in seagrass habitat, particularly in the northern GBR (Figure 9).

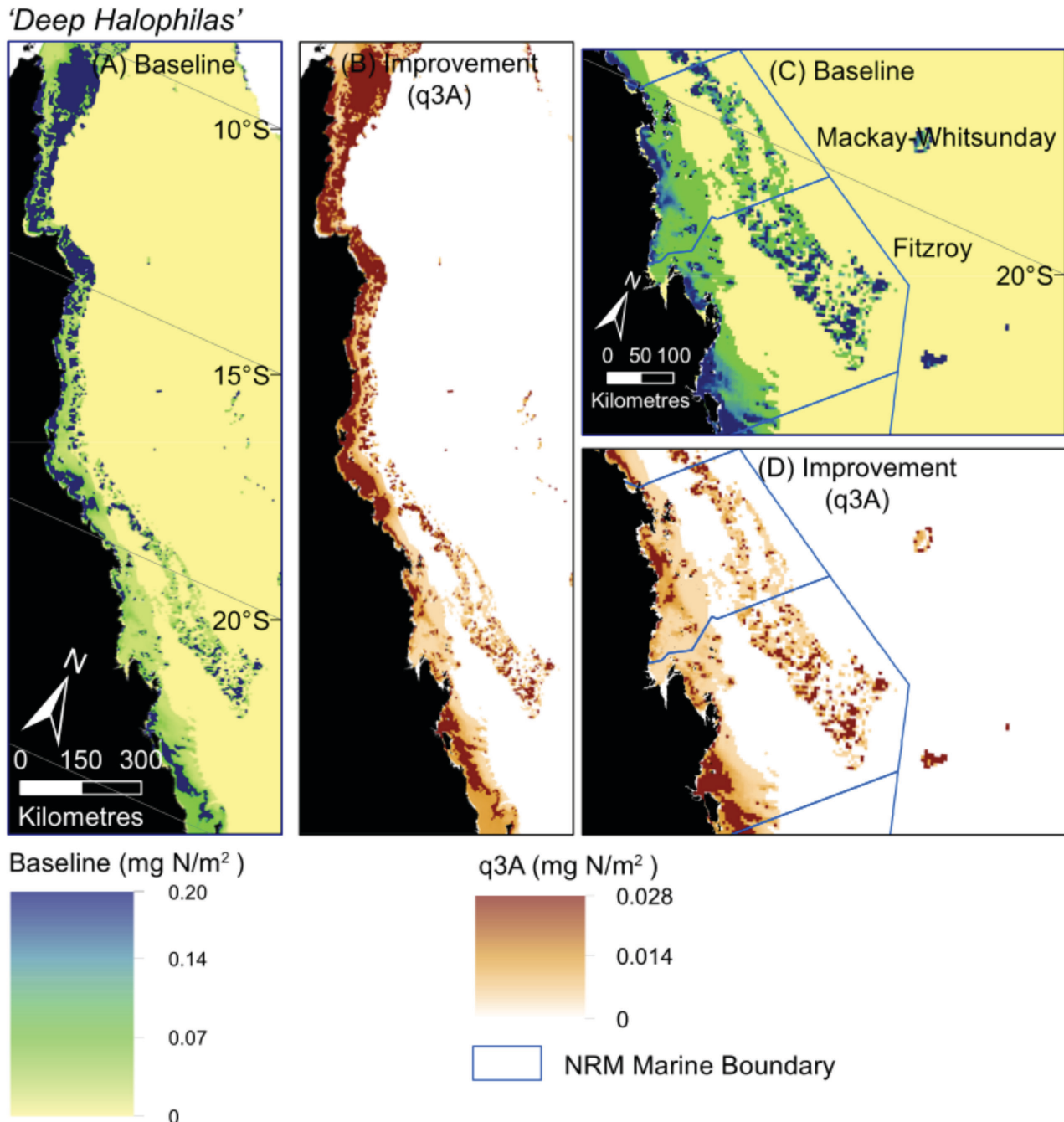


Figure 9: The impact of river load reductions (q3A) on the biomass of 'deep Halophila' simulated by the eReefs biogeochemical model (adapted from Baird et al., 2021) under the catchment scenarios for (A) baseline scenario (current land management practices), (B) predicted change in biomass under innovative land management practices, (C) zoom-in of baseline biomass in the Mackay-Whitsunday and Fitzroy regions, (D) change in biomass in the Mackay-Whitsunday and Fitzroy regions.

‘Zostera’

The ‘Zostera’ seagrass group in the eReefs biogeochemical model can be taken to represent seagrasses that prefer sheltered, muddy habitats. It is therefore most directly comparable with *C. serrulata* and *H. uninervis* in our habitat suitability model. Both models predict relatively small changes in the coverage of these seagrasses under the land management improvement scenarios (Figure 10), though the habitat suitability model shows greater potential for improvement in the Mackay-Whitsunday and Fitzroy regions. It is possible that factors other than benthic light (not considered in the habitat suitability model but included in the eReefs simulations) reduce the potential for improvement in this seagrass group.

‘Zostera’

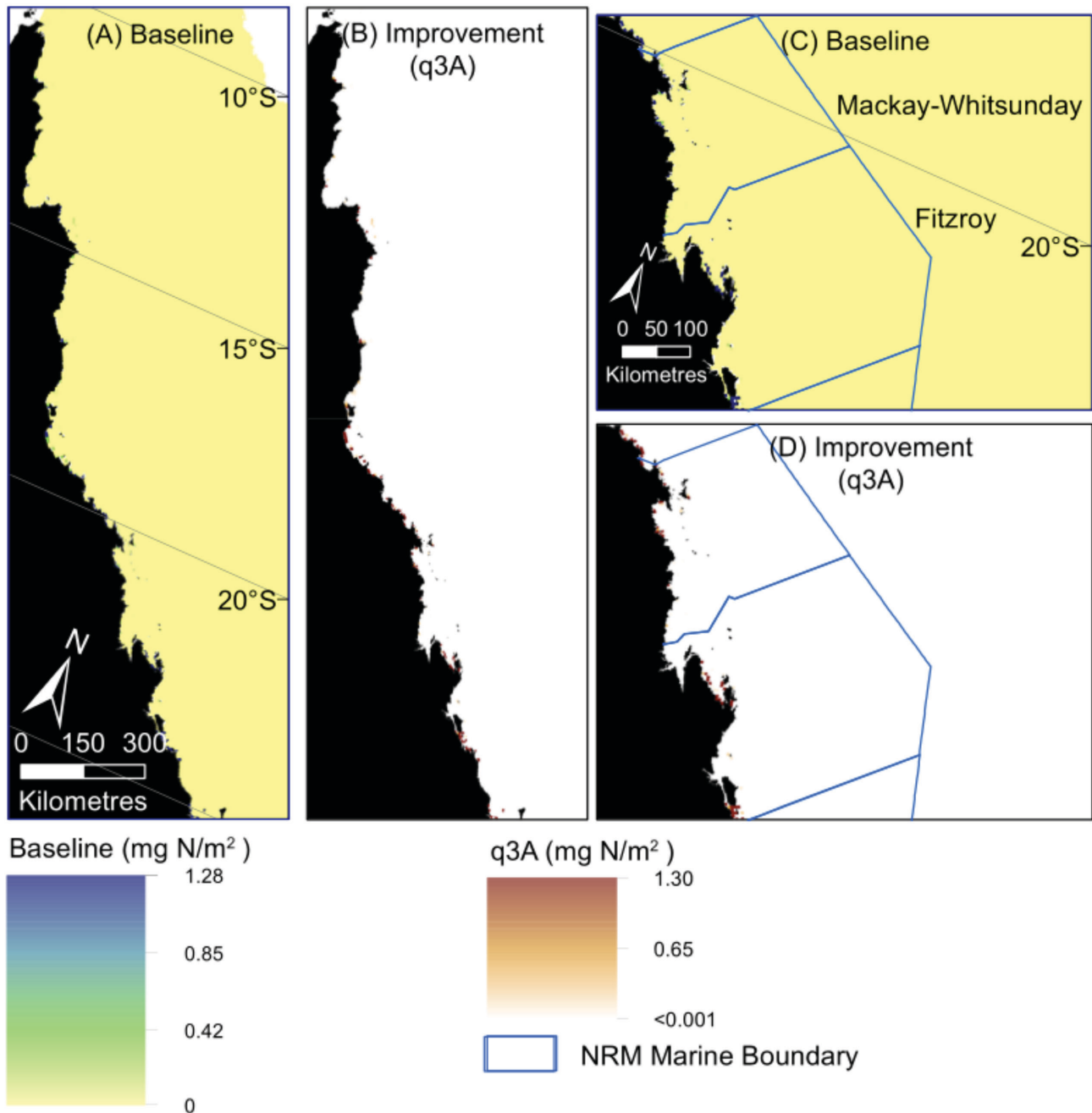


Figure 10: The impact of river load reductions (q3A) on the biomass of the ‘Zostera’ seagrass group simulated by the eReefs biogeochemical model (adapted from Baird et al., 2021) under the catchment scenarios for (A) baseline scenario (current land management practices), (B) predicted change in biomass under innovative land management practices), (C) zoom-in of baseline biomass in the Mackay-Whitsunday and Fitzroy regions, (D) change in biomass in the Mackay-Whitsunday and Fitzroy regions.



Image: D. Perrine



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