Australian Government

Queensland Government

Methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

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Citation

Australian and Queensland governments, 2024, Methods, Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

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Ground cover monitoring methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

Citation

Australian and Queensland governments, 2024, Ground cover monitoring methods, Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

CONTENTS

Ground cover monitoring methods

This report summarises the data and methods used for reporting progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) (Australian and Queensland governments 2018) 2025 land and catchment management target for ground cover.

The target for ground cover is:

- 90% of grazing lands will have greater than 70% ground cover in the late dry season.

"The ground cover target focusses on late dry season ground cover levels across grazing lands, recognising that water quality risk is generally highest at the onset of the wet season. The target incorporates an area-based component (i.e. 90% of grazing lands will have achieved the ground cover target), while providing for natural variability in ground cover levels. Research supports a ground cover target of 70% to minimise erosion."(Reef 2050 WQIP)

Background

Why measure ground cover?

Ground cover is defined as the vegetation (living and dead) and biological crusts and rocks that are in contact with the soil surface and is a key indicator of catchment condition. Ground cover is a key component of many soil processes including infiltration, run-off and surface erosion. In the Great Barrier Reef catchments, low ground cover can lead to soil erosion which contributes to increased sediment loads reaching the Great Barrier Reef lagoon and loss of productivity for grazing enterprises.

It is particularly important to maintain ground cover during dry periods, or periods of unreliable rainfall, to minimise loss of water, soil and nutrients when rainfall eventually occurs. This practice will also maximise the pasture growth response to rainfall. Implementing appropriate and sustainable land management practices, particularly careful management of grazing pressure, can help to maintain or improve ground cover, reducing erosion and improving the stability and resilience of the grazing system.

Factors that influence ground cover

Ground cover levels are the result of complex interactions between landscape function (soil type, topography and vegetation dynamics), climate and land management. Some areas maintain naturally higher levels of ground cover due to factors such as high soil fertility and consistently high annual rainfall. The impacts of grazing land management practices on ground cover levels in these areas can be minimal due to the resilience of the land in responding to pressures. In areas where rainfall is less reliable and soils are less fertile, ground cover levels can vary greatly and the influence of grazing land management practices on ground cover levels, and on the species composition of the ground cover, can be more pronounced.

A number of initiatives aimed at improving grazing land management in Great Barrier Reef regions are in place or are planned. They include programs which are improving management of ground cover levels appropriate to the regional conditions such as:

- the Grazing Resilience and Sustainable Solutions (GRASS) program provides one-on-one support to help graziers improve poor and degraded land
- infrastructure projects such as fencing key areas and better distribution of watering points for stock
- trials of different grazing strategies
- a range of extension and education activities including development of online, interactive and reporting tools for accessing and viewing ground cover information.

Reporting ground cover levels for the Reef 2050 Water Quality Improvement Plan

Progress towards the 2025 land and catchment management ground cover target is assessed by the Queensland Ground Cover Monitoring Program. It is based on the measurement of late dry season ground cover using Landsat satellite imagery for historical measurements and Sentinel-2 satellite imagery in more recent years (post-2015). All imagery has been processed to produce fractional ground cover estimates, using field data for calibration. While a range of factors influence ground cover levels at local scales, reporting is focused only on information that describes regional ground cover levels in the current and historical context. Rainfall data is provided for context only, as it is the primary driver of ground cover levels at a regional scale.

A range of products have been developed by the Queensland Ground Cover Monitoring Program that account for the influence of climate, land management and soil type. These products are more appropriate for monitoring local-scale variability and differences in ground cover levels and are of limited use for regional-scale reporting. Access to some of these products is via the interactive online tool VegMachine and the online reporting tool, FORAGE. A decision support tool, the p2r projector has now been released and includes components to inform managements practices on grazing lands.The p2r projector assists land managers and investors to assess the most cost-effective land management strategies for the greatest reduction in sediment loss. Further, there are a number of commercial platforms now providing access to the same ground cover information with additional functionality like property infrastructure mapping and estimation of Total Standing Dry Matter. New data products that prove useful for describing ground cover levels at the regional scale will help to revise future ecologically-relevant and regionally-focused targets, and will be incorporated into future reporting, where appropriate.

Methods

Ground cover data

Satellite imagery and fractional ground cover

Measurement of ground cover for reporting is based on fractional ground cover data derived following methods described in Scarth et al. (2010), Guerschman et al. (2015) and Trevithick et al. (2014). The fractional ground cover method measures the proportion of green cover, non-green cover and bare ground using reflectance information from late dry season from several sources of satellite imagery. This includes the longer-term dataset of Landsat imagery (1987 to present): Landsat 5 Thematic Mapper, Landsat 7 Enhanced Thematic Mapper and Landsat 8 Operational Land Imager satellites with a spatial resolution of approximately 30m and an acquisition frequency of 16 days. In more recent years (mid-2015 to present), the European Space Agency's Sentinel-2A and Sentinel-2B satellites have augmented the Landsat record. These satellite sensors have a spatial resolution of 10m and an acquisition frequency of five days. Analyses undertaken by Flood (2017) has shown that fractional cover data produced from the two imagery sources is statistically comparable as the surface reflectance values of the Sentinel-2 products have been adjusted to closely match those from the Landsat satellites. The inclusion of the Sentinel-2 data is expected to improve ground cover estimates, particularly in areas that are cloud affected, due to the more frequent acquisition strategy. For all reporting, the Sentinel-2 data are downscaled (i.e. degraded) to 30m to match the spatial resolution of the Landsat data.

It is important to note that the fractional cover data measures all cover as viewed from above by the satellite, including the trees and shrubs as well as the ground cover and bare ground. To derive a ground cover estimate, a further step is applied following Trevithick et al. (2014) which uses another remote sensing product, called the 'persistent green', to effectively remove the influence of trees and shrubs on the fractional cover data. The persistent green product is based on a time-series of imagery and an analysis of the behaviour of the green cover fraction over that time-series. The assumption with this product is that the minimum of the time-series represents the less seasonally-variable woody vegetation, effectively providing an estimate of the level of woody cover at any given (pixel) location.

This estimate is then converted to a measure of the gap fraction of the woody vegetation, which is basically a measure of the amount of gaps or spaces in the tree and shrub layer(s) when viewed vertically from above (or below). A relationship is then defined, based on quantitative field data estimates of overstorey and ground cover data and gap fractions, which estimates the amount of ground cover and bare ground that is expected given a particular overstorey gap fraction estimate. An adjustment is then made to the fractional cover to provide individual (i.e. pixel-level) estimates of the level of green ground cover, non-green ground cover and bare ground at ground level, thus producing a fractional *ground* cover estimate (Figure 1). As a final step, the green and the non-green ground cover fractions are summed to produce a total ground cover estimate, as erosion and run-off are influenced by all ground cover. This estimate of total ground cover is used for reporting and is hereafter referred to simply as 'ground cover'.

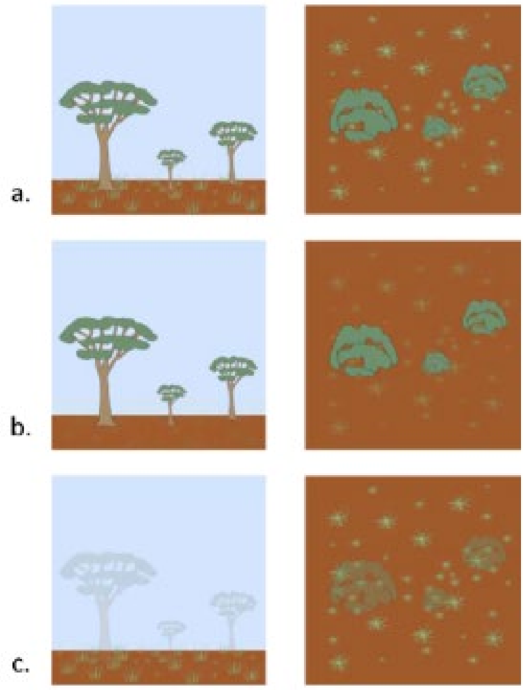

Figure 1: Schematic representation of the correction of the fractional cover data to estimate the fractional ground cover used for reporting (Trevithick et al., 2014). (a) Fractional cover measures all vegetation cover including trees, shrubs and ground cover, as well as bare ground. The ground cover and bare ground are partially obscured by the trees and shrubs. (b) Next, a time-series approach is used to estimate the percentage of 'persistent green' cover in the tree and shrub layers. (c) Finally, a correction factor is applied, based on field data, to effectively remove the 'persistent green' cover in the tree and shrub layers, thus providing an estimate of the green cover, non-green cover and bare ground, all at the ground level – the fractional ground cover or simply 'ground cover'.

The method for deriving ground cover can be applied in areas of woody vegetation cover up to approximately 60% persistent green cover, at which point the canopy becomes too dense to reliably achieve an estimate of the ground cover. Given the lower levels of woody vegetation cover in the Great Barrier Reef catchment areas, this means that generally, ground cover can be reported for the majority (i.e. >90%) of the grazing lands.

The use of the persistent green product to derive ground cover does have some limitations. Given it is an estimate of green cover behaviour over time, some non-woody areas which are persistently green (e.g. in high rainfall areas), can have very high persistent green cover values (i.e. >60%), resulting in them not being included in the areas for analysis and reporting. Further, due to the way the persistent green product is derived using time-series approaches, it can only be calculated up to a date which is two years prior to the current (reporting) season. As a result of these limitations, ground cover reporting statistics calculated in one reporting period may vary slightly when re-calculated and updated in the next reporting period, as will the area of the grazing lands actually analysed and reported. In general, the reporting of mean cover helps to account for these differences. Future work will consider ways to further limit the impact these issues have on the ongoing consistency of the ground cover reporting.

The version of the fractional ground cover product used for this reporting was developed using around 2000 field observations across a range of ground cover, tree cover and shrub cover levels within a range of environments (Scarth et al., 2010; Guerschman et al., 2015). It has been assessed using linear regression to have an accuracy of 17% Root Mean Square Error (Figure 2). Due to a collaborative national effort, there are now over 4000 field observations collected using the same field protocols across Australia, and a re-calibrated and revised fractional cover model has been developed. This updated version helps address some known limitations in the previous version (e.g. in bright soil areas) and will be incorporated into reporting in the future. Re-processing of previous years will be undertaken to produce reporting statistics which are based on a single, consistent product.

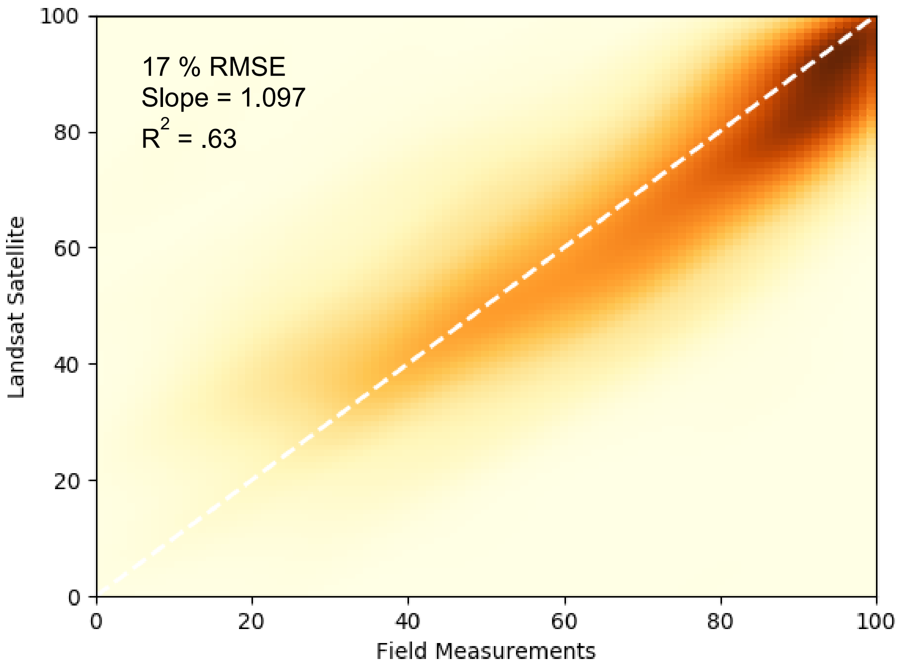

Figure 2: Comparison of field measurements of fractional cover with Landsat derived fractional ground cover for 2047 sites across Australia. The linear regression shows an overall RMSE of 17%.

Late dry season ground cover

Late dry season ground cover is defined using seasonal composites of images for spring (September–November) (for the period 1987 to present). It is estimated using a seasonal composite of fractional ground cover data images (Landsat prior to 2015 and Sentinel-2 post-2015) acquired throughout the season following Flood (2013). This approach has the advantage of removing errors and outliers in the data (e.g. due to cloud or cloud shadow artefacts) and produces a composite image for the season which is based on the selection, per pixel, of the most representative value for that season. Each pixel is a real estimate selected from the set of images available for that season; it is not a modelled or synthesised value. The method requires at least three valid observations in any given season before a pixel is selected for inclusion in the composite image. It provides the most spatially comprehensive coverage as there is generally very little missing data due to cloud, cloud shadow or satellite sensor issues. For areas where there is still missing data, further infilling can be undertaken using what are referred to as seasonal ground cover ‘patches’. These are pixel values generated in areas where less than three valid observations were made in a season. This process is only undertaken for the Landsat imagery, as the more frequent acquisition strategy of the Sentinel-2 satellites typically results in very little missing data once composited.

Reporting regions and grazing lands

Reporting is based on the six natural resource management regions of the Great Barrier Reef region:

- Cape York
- Wet Tropics
- Burdekin
- Mackay Whitsunday
- Fitzroy
- Burnett Mary.

Grazing lands in the reporting regions are spatially-defined based on land use data provided by the Queensland Land Use Mapping Program (DSITIA, 2012). The version of the mapping used for this reporting has the Burdekin and Wet Tropics mapped to 2016, the Fitzroy and Burnett Mary to 2017, and Cape York and the Wet Tropics mapped to 2013 and 2015, respectively. Updated land use data for all GBR catchments is now available for 2022 and this will be used to define grazing lands in future reporting.

A *reporting region* is defined as that part of a region which is grazing land and has less than approximately 60% persistent green cover. Any reporting region with less than 10% area reported as grazing lands, or less than 10% ground cover data within the grazing lands, is excluded from the results.

Reporting ground cover

This report provides a regional overview of late dry season ground cover levels in the Great Barrier Reef catchments based on analysis of seasonal (i.e. spring) ground cover data. The statistics are calculated for each pixel (i.e. 30m x 30m area) and then summarised (i.e. averaged) for each of the 35 catchments.

Statistics reported include mean late dry season ground cover from 1987 to the current reporting period, and the percentage of the region's reported grazing area with late dry season ground cover greater than 70% in the current reporting year. Graphs show the mean ground cover levels over time, with rainfall included to provide context. Maps of ground cover percentages are also provided for the entire Great Barrier Reef region, and for each reporting region, to show where in each region the ground cover levels were higher or lower.

It is important to note that averaging ground cover across whole regions can mask localised areas of lower or higher cover, particularly in large catchments with a strong rainfall gradient (e.g. the Burdekin and Fitzroy). The mean ground cover reported is, therefore, indicative of general levels of ground cover within the reporting region. Reporting is further divided into catchments (and sub-catchments for larger catchments). For more detailed or localised ground cover information and to visualise ground cover data products, refer to VegMachine or FORAGE.

Rainfall data

Rainfall data is provided for current and historical context as rainfall is the primary driver of ground cover levels at the regional scale. In general, high rainfall in the preceding seasons results in higher ground cover levels and low rainfall results in lower ground cover levels. Rainfall data is obtained from SILO as a 5km grid. The mean annual rainfall is then calculated for each reporting region from September to August for each year from 1986, to align the mean annual rainfall with the late dry season reporting period. It should be noted that rainfall statistics are constantly updated by the Bureau of Meteorology as more data becomes available, thus reported mean annual rainfall may change slightly between reporting periods.

Scoring system

A standardised scoring system is used for each of the key indicators in the reef report card. The scoring system is used to assess and communicate the status of the indicator against the Reef 2050 WQIP 2025 targets.

Ground cover target

- 90% of grazing lands will have greater than 70 per cent ground cover in the late dry season.

Table 1: The colour-coded ground cover scoring system

Status	Criteria	Grade and colour code
Very poor ground cover	Less than 60% of grazing lands meet the adequate ground cover level	E - Red
Poor ground cover	Between 60-69% of grazing lands meet the adequate ground cover level	D - Orange
Moderate ground cover	Between 70-79% of grazing lands meet the adequate ground cover level	C - Yellow
Good ground cover	Between 80-89% of grazing lands meet the adequate ground cover level	B - Light Green
Very good ground cover – Target met	More than 90% of grazing lands meet the adequate ground cover level	A - Dark Green

Adequate ground cover for 2019 is defined as >70% late dry season ground cover.

Semiquantitative confidence ranking

Data confidence ●●●●○

A multi-criteria analysis is used to score the confidence in each indicator used in the report card from low to high. The approach combined the use of expert opinion and direct measures of error for program components where available. Ground cover has received a four-bar confidence ranking.

Groundcover

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Remote sensed data with no or limited ground truthing	1:1,000,000	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	Remote sensed data with regular ground truthing (not comprehensive)	1:100,000	Measurement of data that have a quantifiable relationship to reported indicators	10-25% error
Established methodology in published paper	Remote sensed data with comprehensive validation program supporting (statistical error measured)	1:10,000	Direct measurement of reported indicator with error	Less than 10% error
3 x0.5 = 1.5	3	3	2	2

Bolded cells indicate assessment ranking

Total score = 11.5, equates to **four dots**.

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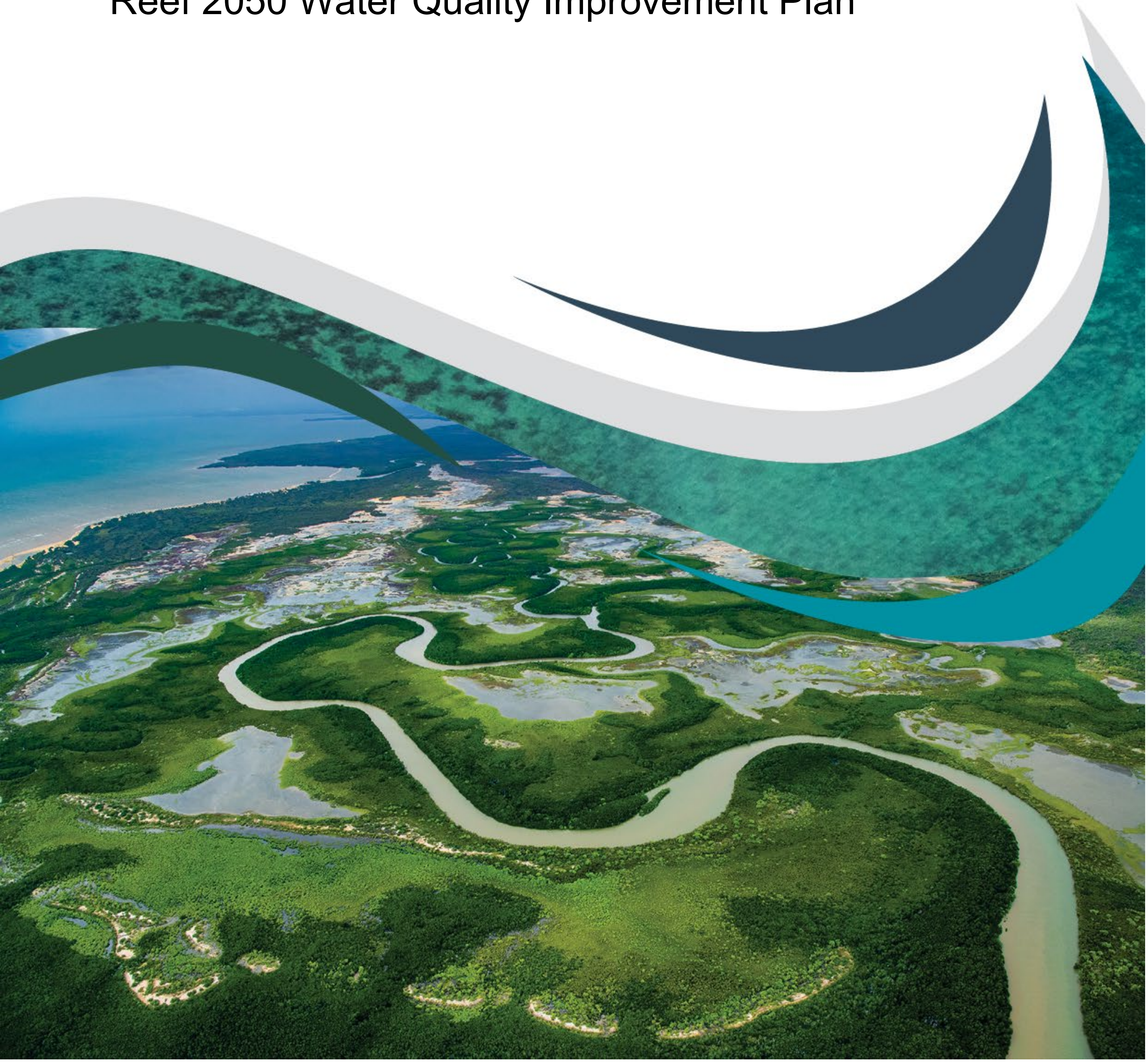
Catchment Condition

Riparian Vegetation Extent Monitoring Methods

Reef 2050 Water Quality Improvement Plan



Citation

Australian and Queensland governments, 2024, Riparian Vegetation Extent Monitoring Methods, Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

CONTENTS

CATCHMENT CONDITION – RIPARIAN VEGETATION EXTENT MONITORING

This report summarises the data and methods used for reporting progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2025 catchment management target for riparian vegetation extent. The target is as follows (Australian and Queensland governments, 2017):

- The extent of riparian vegetation is increased.

Riparian woody vegetation and ground cover are the vegetation adjacent to waterways which can help reduce pollutant flow to the waterways and stabilise the streambank (Lyons et al., 2000). For the current era, *riparian woody vegetation* areas include those areas within the riparian zone that meet the following structural criteria, after Specht (1970): forest (trees > 5m height with dense foliage cover); woodlands (trees >5m in height with sparse foliage cover); and, shrublands (shrubs < 8m in height). Riparian areas that are non-woody and have very low ground cover levels may be areas of concern for soil and nutrient loss to the stream (Lyons et al., 2000). Maintaining and enhancing riparian woody vegetation and ground cover in riparian areas is, therefore, important to minimise impacts on water quality in Great Barrier Reef catchments.

Monitoring of riparian vegetation extent is based on analysis of satellite imagery to map woody vegetation and ground cover in riparian areas. The program leverages monitoring of woody vegetation from the Statewide Landcover and Trees Study (SLATS) (Queensland Department of Environment and Science, 2022), and monitoring of ground cover as part of Queensland Ground Cover Monitoring Program.

Methods

Monitoring and reporting of riparian vegetation extent (and cover) is made up of three key components:

1. Defining and mapping riparian areas
2. Mapping riparian woody vegetation extent and measuring changes to this extent over time
3. Estimating riparian ground cover and analysing how it changes over time within riparian areas.

Defining and mapping riparian areas

Riparian areas range from small headwater creeks to major rivers. Many studies have shown the benefits of using geographic information systems (GIS) and remote sensing to analyse vegetation within a range of specified distances to a stream (Goetz, 2006; Yang, 2007, Apan et al., 2002). For the purposes of meeting the range of objectives for this component of the Paddock to Reef Integrated Monitoring, Modelling and Reporting program (Paddock to Reef program), riparian areas were defined by a 50m buffer zone applied to a combination of topographic drainage line data and riverine wetlands, as mapped by the Queensland Wetlands Program. Estuarine areas were excluded from the analysis. The same drainage data that is used for defining Category R areas for the *Vegetation Management Act 1999* is used here to ensure consistency. This is the same riparian area dataset used in the 2017 era mapping (reported in 2019), converted to a 10m resolution raster dataset, aligned to the underlying Sentinel-2 datasets. The raster conversion will lead to slight differences in area measurements, but has greatly increased processing speed, as well as more appropriately reflecting the scale of the source datasets.

Previous reporting included mapping of the original (pre-clearing) and current (2001, 2005, 2009, 2013) extent of riparian vegetation based on Landsat satellite imagery, which has a spatial resolution of approximately 30m. The spatial resolution of Landsat has some limitations and uncertainty for reporting on riparian vegetation, and riparian woody vegetation in particular, as these areas are often very narrow (i.e. < 30m) and fragmented as a result of historical clearing.

Mapping riparian woody vegetation extent

In previous reporting, riparian woody vegetation was mapped using Landsat (prior to 2017) and Sentinel-2 (2017 reporting) satellite imagery. An index of woody vegetation density or cover, known as Foliage Projective Cover (FPC) was applied to the satellite imagery to predict areas of woody vegetation cover within the riparian area. Riparian woody vegetation or forest were defined as those areas in the riparian area with an FPC greater than or equal to 11%. These FPC datasets generally provided a good indication of woody vegetation but required selection of an appropriate threshold and were also affected by missed cloud or other data issues. Predictions were also sensitive to annual variability in greenness. This can affect reliable change estimates and monitoring when FPC is compared between years, regardless of the thresholds used.

For this report, the extent of riparian woody vegetation was mapped using the Statewide Landcover and Trees Study (SLATS) Sentinel-2 - 2021 woody vegetation extent layer for 2021 (Queensland Department of Environment and Science, 2023). The 2021 layer is an update of the SLATS 2018 baseline woody extent layer.

The 2018 baseline layer was based on a U-net convolutional neural network classification, fitted on very high spatial resolution (i.e. ~1m) Earth-i satellite imagery to produce an initial binary woody presence/absence classification, as described in Flood et al (2019). The classification was subsequently down-sampled to 10m to approximate the spatial resolution of Sentinel-2, given it will be used for ongoing monitoring. The initial predictions were then manually edited, and quality checked by a team of remote sensing scientists through an extensive editing and quality assurance process. Features were categorised as either woody or non-woody, where woody vegetation is defined as stands of woody vegetation greater than 0.5ha with a crown cover greater than 10% (Queensland Department of Environment and Science, 2022). A minimum width of 20m was applied to linear features. Both woody and nonwoody features smaller than these sizes have been filtered out of the data set. No distinction is made between native and non-native vegetation; woody vegetation such as woody weeds and horticultural crops are included as woody in the final classification.

To produce the 2021 woody extent dataset, the 2018 baseline extent was updated using SLATS clearing data for the 2018-2019, 2019-2020 and 2020-2021, and SLATS regrowth data for 2019-20 and 2020-21 reporting to produce a 2021 woody extent. SLATS did not include regrowth data in the 2018-19 report as it was considered the existing regrowth had been captured in the 2018 baseline extent and insufficient time has elapsed for new regrowth to be reliably detected and mapped for the 2018-19 report. The recent losses relate only to anthropogenic clearing, and do not include vegetation loss from natural events such as cyclones and drought stress, which typically have a faster recovery time than regrowth after clearing. This distinction is determined through the SLATS classification process. Ancillary data on dams and waterbodies were also used to further refine the woody classification for the riparian analysis. These waterbodies were classified as 'no data'.

It is important to note that this reporting focusses solely on presence or absence of riparian vegetation, given its overall significance for streambank stability, slowing overland flows, and maintaining and improving water quality. The analysis does not examine vegetation type, structure, cover, age or the policy settings that protect vegetation in the landscape. No distinction is made between remnant and non-remnant woody vegetation, and no analysis is made regarding potential non-compliance of riparian vegetation losses (i.e. clearing) under Queensland’s Vegetation Management framework. Future methods could include analysis of the age and structure of woody vegetation, as well as the remnant and non-remnant status. Compliance status of vegetation clearing is assessed separately by the Department of Resources.

It is important to note direct comparisons with previous reporting cannot be made, due to the change from FPC to woody extent datasets, and the change in SLATS methodology.

Measuring changes to riparian extent over time

Riparian woody vegetation loss in extent is reported for two time periods for the Great Barrier Reef catchments:

1. From 2018 to 2021, based on losses from the 2018 woody extent baseline. Regrowth is not included in this analysis
2. From 2005 to 2009, 2009 to 2013 and 2013 to 2017 for context on relatively recent woody vegetation clearing trends. These results **cannot be directly compared** due to the change in SLATS methodology.

Estimating riparian ground cover

For non-woody riparian areas, ground cover is estimated and reported for the current reporting year. Ground cover monitoring is included to recognise the importance of having some level of vegetation cover in riparian areas to help minimise erosion, particularly where woody vegetation is not present to stabilise the soil. Ground cover reporting in riparian areas is based on Sentinel-2 seasonal fractional cover data derived using the method described by Flood. (2017). The Sentinel-2 fractional cover product is not specifically a ground cover product and does contain woody vegetation. However, as its use is restricted to non-forested areas it is suitable for the purposes of assessing ground cover. Ground cover levels will be assessed in the late dry season (i.e. the Spring seasonal image) for the reporting year of interest.

Assessing progress towards the target

The Reef 2050 WQIP 2025 target that '*the extent of riparian vegetation is increased*', will be reported in 2023 for data from 2018-2021. Specifically, the extent of riparian woody vegetation in 2021 will be compared to the extent in 2018 with progress measured by the net change between those two dates. A positive change in extent will indicate progress. A negative change would indicate that no progress has been made. As this reporting period is only three years compared to previous 4-year periods, the grade cut-offs have been adjusted as follows:

Assessment against the target as per the below criteria:

Status/progress	Criteria	Grade/Colour
Very poor progress towards target	Greater than 0.75% loss of riparian vegetation	E - Red
Poor progress towards target 0.51	Greater than 0.37% and less than or equal to 0.75% loss of riparian vegetation	D - Orange
Moderate progress towards target	Greater than 0.07% and less than or equal to 0.37% loss of riparian vegetation	C - Yellow
Good progress towards target	Greater than 0 and less than or equal to 0.07% loss of riparian vegetation	B - Light green
Target met	Increase of riparian vegetation	A - Dark green

Additional reporting on progress towards the target will be derived from analysis of the ground cover levels in riparian areas. Reporting the ground cover levels will help to report on the maintenance of ground cover in the riparian areas over time, providing some indication of the management of those areas in terms of grazing or other pressures such as cropping.

Semiquantitative confidence ranking

Data confidence ●●●○○

A multi-criteria analysis was used to score the confidence in each indicator used in the report card from low to high. The approach combined the use of expert opinion and direct measures of error for program components where available. Riparian vegetation extent received a three dot confidence ranking.

Riparian extent

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Remote sensed data with no or limited ground truthing	1:1,000,000	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	**Remote sensed data with regular ground truthing (not comprehensive)**	**1:100,000**	**Measurement of data that have a quantifiable relationship to reported indicators**	**10-25% error**
Established methodology in published paper	Remote sensed data with comprehensive validation program supporting (statistical error measured)	1:10,000	Direct measurement of reported indicator with error	Less than 10% error
2 x 0.5 = **1**	**2**	**2**	**2**	**2**

Bolded cells indicate assessment ranking

Total score = 9, equates to **Three dots**.

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Australian Government

Queensland Government

Catchment Condition

Wetland Extent Monitoring Methods

Paddock to Reef integrated Monitoring, Modelling and Reporting program

Citation

Australian and Queensland governments, 2024, Wetland Extent Monitoring Methods, Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

CONTENTS

CATCHMENT CONDITION – WETLAND EXTENT MONITORING

This report summarises the data and methods used for reporting progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) 2025 land and catchment management targets. Land and catchment management targets aim to deliver reduction in end-of-catchment loads. The target for wetland extent is as follows (Australian and Queensland Governments 2018):

- No loss of the extent of natural wetlands

Natural wetlands include lakes, swamps and estuarine wetlands. Catchment management targets aim to increase ground cover and riparian vegetation and to prevent further loss of wetland extent. Healthy wetlands can assist with filtering pollutants from the water in some situations. The condition of Reef wetlands is captured as an objective of improved water quality and is included under the ecosystem health theme in the Reef 2050 WQIP.

Wetlands are mapped every four years until 2017 (2001, 2005, 2009, 2013, 2017) and every two years after 2017 (2019, 2021, etc.). Changes in wetland extent are reported for each period (2001-2005, 2005-2009, 2009-2013, 2013-2017, 2017-2019, 2019-2021, etc.). Reporting on changes in wetland extent include comparisons of current wetland extent with pre-clearing extent.

Wetland mapping

Wetland mapping is derived primarily from two main source data sets: Biodiversity of Pre-Clearing and Remnant Regional Ecosystem (regional ecosystem mapping) and Wetland Waterbodies.

Regional ecosystem mapping

Regional ecosystem mapping consists of: 1) “pre-clearing mapping derived primarily from 1960s aerial photographs in conjunction with a range of other imagery and information” including geology and soils mapping, historical survey records and field survey; and 2) remnant cover mapping “derived primarily from Landsat Thematic Mapper (TM) imagery in conjunction with larger scale SPOT imagery and aerial photography” (Neldner et al. 2020). The Landsat TM satellite imagery used is supplied and rectified by the State Land and Tree Study (SLATS) (Neldner et al. 2020). “Remnant mapping shows the extent of vegetation at the time of the imagery and is updated about every two years” (Neldner et al. 2020). All regional ecosystems are classified in the accompanying Regional Ecosystem Description Database including their wetland system.

Generally, the mapping is validated to a scale of 1:100,000 which includes over 8,000 wetland ground-truthing sites, however coastal areas may be compiled at 1:50,000 scale and specific targeted areas may be compiled at 1:25,000 scale (e.g. some urban areas, property level assessments including Property Map of Assessable Vegetation under the *Vegetation Management Act 1999*).

Regional ecosystem mapping is updated every two years. This process requires:

1. processed and supplied satellite imagery from SLATS and
2. change detection based on an analysis of differences in satellite imagery used to generate the current mapping and more recent satellite imagery processed and supplied by SLATS.

There is usually a one-year turnaround time from the date of satellite image capture and the supply of processed imagery and change detection to the Queensland Herbarium for use in the regional ecosystems mapping update. Improvements in regional ecosystem mapping are backcast over all time periods.

Wetland mapping

Wetland mapping is a multi-step process that can be broadly grouped into four phases (Department of Environment and Science 2022a). Wetland mapping represents the maximum extent of a wetland with wetland dynamism (e.g. changes in wetland inundation included as additional attributes on the mapping).

Wetland waterbodies are derived every two to four years based on an analysis of open water as detected from Landsat TM supplied, rectified and transformed by the Remote Sensing Centre. Wetland waterbodies are classified with wetland system and wetland habitat hydrological modification. Wetland habitat hydrological modification distinguishes natural wetlands (those where no activities are observed at the habitat level that alter wetland hydrology) from modified wetlands (e.g. those where bunding, cultivation, cropping, controlled surface hydrology, channel construction, partial draining, excavation or partial infilling activities are observed at the habitat level).

Wetland waterbodies are compiled with wetland regional ecosystem mapping (derived from remnant cover mapping and supplemented with woody vegetation extent data from the Remote Sensing Centre) to map wetland extent. Improvements in wetland mapping are backcast over all time periods.

Change in wetland extent reporting

The Queensland Wetland System and Type Extent Statistics Method: A Method to Provide Baseline Wetland System and Type Extent Trend Statistics for Wetlands in Queensland (Department of Environment and Science 2022b) is applied to report on changes in wetland extent in the Reef by reporting area and wetland system.

Broadly, wetlands are allocated based on spatial location to a reporting area and their extent is summarised by reporting area, wetland system, and wetland habitat hydrological modification. Wetland extent and changes in wetland extent are reported on for the following wetland systems in the Reef:

1. Palustrine wetland system (e.g. swamps)
2. Lacustrine wetland system (e.g. lakes)
3. Intertidal wetland system that is dominated by mangrove or salt flat.

Riverine wetland systems, subtidal wetland systems, and intertidal wetland systems not dominated by mangrove or salt flat are not included in the analysis.

The extent of natural and slightly modified wetlands and change in extent is reported on for each wetland system by reporting area and region. Improvements in wetland mapping are backcast over all time periods and wetland extent reporting provides revised figures for all time periods. This avoids conflating trends in on-ground change in wetland extent with trends in the comprehensiveness and accuracy of source data capture processes.

Assessing progress towards the target

Wetland mapping will be used to report on the current extent of wetlands and the change in wetland extent. The change in extent is reported as a percentage of the current extent to enable comparison between catchments of different sizes. The change in extent is also reported for some reporting periods as an average change in extent over two years to enable comparison between reporting periods of different lengths. Results are reported at the Great Barrier Reef-wide, regional, catchment and major sub-catchment scales.

Scoring

	Very good	No loss (0 %) of wetlands
	Good	< 0.05 % loss of wetlands
	Moderate	>= 0.05 and < 0.25 % loss of wetlands
	Poor	>= 0.25 and < 1.5 % loss of wetlands
	Very poor	> 1.5 % loss of wetlands
	No data	

Semiquantitative confidence ranking

Data confidence ●●●●○

A multi-criteria analysis was used to score the confidence in each indicator used in the report card from low to high. The approach combined the use of expert opinion and direct measures of error for program components where available. Wetland extent received a four-dot confidence ranking.

Glossary

Natural wetlands: Wetlands where activities that modify wetland hydrology and/or structures associated with these activities cannot be observed from aerial or satellite imagery and are not known from field survey data.

Modified wetlands: Former natural wetlands where activities that modify wetland hydrology and/or structures associated with these activities have been observed from aerial or satellite imagery or from field survey data.

Slightly modified wetlands: Modified wetlands where the nature of these activities and/or structures are considered to enable the wetland to retain many of their functional and ecological characteristics.

Highly modified wetlands: Modified wetlands where the nature of these activities and/or structures are considered to significantly degrade the wetland's functional and ecological characteristics.

Artificial wetlands: Artificial wetlands refer to anthropogenically constructed wetlands where no natural or modified wetlands existed prior to the commencement of construction.

Wetland extent: Wetland extent refers to the maximum areal extent of the wetland.

Baseline wetland extent: Baseline wetland extent is a relative term referring to the maximum areal extent of the wetland at the start of a given reporting period.

Pre-clearing wetland extent: Pre-clearing wetland extent refers to the maximum areal extent of the wetland prior to clearing (Nelder et al. 2020).

Historical loss: Estimated difference between pre-clearing wetland extent and 2001 wetland extent. As wetland mapping does not have a pre-clearing baseline, historical loss is estimated from an analysis of Regional Ecosystem mapping.

Reporting period: Reporting period refers to the time over which changes in wetland extent are calculated. Generally, reporting periods parallel the temporal resolution of available wetland extent time-series data. Wetland mapping reporting periods will be four years in length from 2001-2017 and every two years thereafter.

Palustrine wetland system: Palustrine wetland system "includes all nontidal wetlands dominated by trees, shrubs, persistent emergent, emergent mosses or lichens, and all such wetlands that occur in tidal areas where salinity due to ocean-derived salts is below 0.5‰. It also includes wetlands lacking such vegetation, but with all the following three characteristics: (1) where active waves are formed or bedrock features are lacking; (2) where the water depth in the deepest part of basin less than 2 m at low water; and (3) the salinity due to ocean-derived salts is still less than 0.5‰." (Department of Environment and Science 2022b).

Lacustrine wetland system: Lacustrine wetland system "includes wetlands and deepwater habitats with all of the following characteristics: (1) situated in a topographic depression or a dammed river channel; (2) lacking trees, shrubs, persistent emergents, emergent mosses or lichens with greater than 30% areal coverage; and (3) total area exceeds 8 ha…Similar wetland and deepwater habitats totalling less than 8 ha are also included in the Lacustrine System if an active wave-formed or bedrock shoreline feature makes up all or part of the boundary, or if the water depth in the deepest part of the basin exceeds 2 m…at low water. Lacustrine waters may be tidal or nontidal, but ocean-derived salinity is always less than 0.5‰." (Department of Environment and Science 2022b).

Intertidal wetland system: "Intertidal wetlands consist of estuarine and/or marine systems located "between the level of high tide and low tide" (Department of Environment and Science 2022b).

SLATS: Statewide Landcover and Trees Study.

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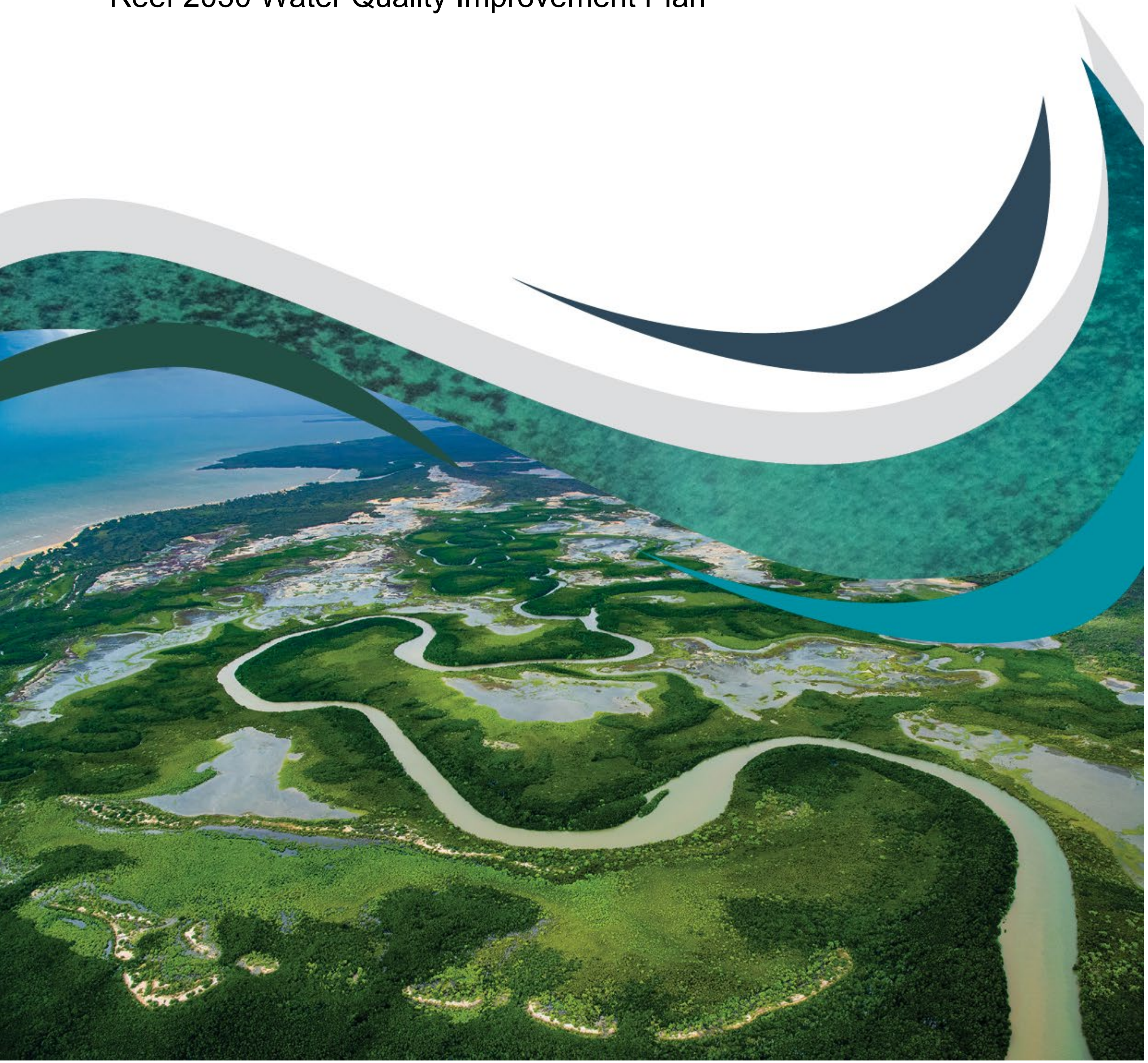
Australian Government

Queensland Government

Wetland Condition Methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan



Citation

Australian and Queensland governments, 2024, Wetland Conditioning Monitoring Methods, Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

CONTENTS

Catchment Condition: Wetland condition monitoring methods

This report describes methods used to produce the Reef Water Quality Report Card 2021 and 2022 wetland condition results. Within the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program, the Wetland Condition Monitoring Program (the Program) tracks progress towards the improved wetland condition objective of the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP*)*.

The Program's initial design is described in Tilden et al. (2015) and the Program's analysis methods up to 2020 inclusive are outlined in Tilden and Vandergragt (2017).

Baseline data for pressure on wetland values and the state of wetland values were reported in 2016. Wetland condition (anthropogenic pressure on wetlands and state of environmental values) was reported for 2018, along with an analysis of change between 2016 and 2018, including power to detect change between the two years. Change in wetland condition between 2018 and 2020 and between the 2016 baseline study and 2020 were reported in 2020 along with differences between panel 1 and panel 4 data gathered in 2020. Panels are groups of wetlands with the same schedule of repeat assessments across years.

Since 2020, sampling effort has intensified to enable reporting by Natural Resource Management (NRM) region, done for the first time in 2022, replacing the previous reporting by land use type (conservation area vs non-conservation area). To date, 'sampling-effort intensification' (i.e. increasing the number of wetlands sampled) has commenced in the Wet Tropics, Burdekin, Fitzroy and Burnett Mary NRM regions.

The Program's data analysis methods have also been updated since the last report, to state of the art methods that can deal with nonresponse (see below) and enable reporting on change over time (trend) in wetland condition. Trend is reported on for the first time in the 2022 report card, replacing tests of change between reporting years. The methods used in 2022 are described in more detail below.

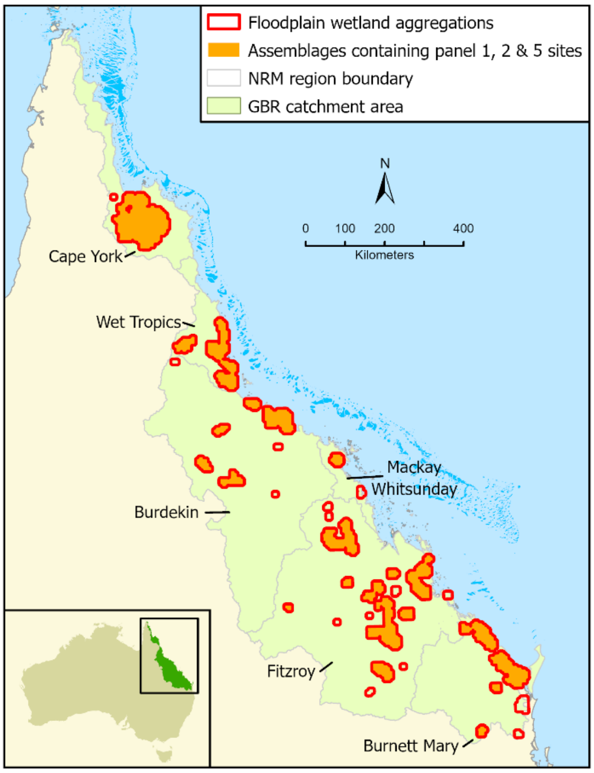


Figure 1. High density wetland aggregations and the wetlands assessed since last reported.

Program design and data analysis

Progress with the monitoring design

The Program focuses on the subpopulation of natural, freshwater floodplain wetlands in high density aggregations in the Great Barrier Reef catchment area (GBRCA) (Figure 1). A spatially balanced random sample of wetlands from the subpopulation, selected using the Generalised Randomised Tessellation Stratified (GRTS) method, is surveyed according to an augmented serially alternating panel design that repeats every four years (Table 1).

Initially, one panel of 20 wetlands was assessed every year and four panels of 20 were assessed in alternate years. In 2020, the number of wetlands sampled in each NRM region started to increase (as part of the 'sampling-effort intensification') to enable reporting at the NRM region scale, in addition to GBRCA-wide reporting. By the end of 2025, when sampling-effort intensification for the Wet Tropics, Burdekin, Fitzroy and Burnett Mary NRM regions is complete, the total sample size for the Program will be ~240 wetlands.

Table 1. Panel design for the Great Barrier Reef catchments wetland monitoring program.*

Panel	Year									
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
1	20	20	20	20	28	36	50	50	50	50
2	20		20				44			
3		20		20				49		
4					27				49	
5						32				46
Year total	40	40	40	40	55	68	94	99	99	96
Total sample	**40**	**60**	**60**	**60**	**96**	**136**	**174**	**203**	**225**	**239**

*Some wetland sample sizes per panel differ slightly from the planned size due to factors such as attrition and replacement. For example, panel 1 originally comprised 21 wetlands, but only 19 of these have been assessed repeatedly; two have dropped out and been replaced. Since 2020, more wetlands have been added to panels as part of the NRM-region sampling-effort intensification process.

Data collection

Wetland assessment data are collected in two ways:

- Desk top analysis based on imagery and spatial data using a range of data sets for 15 indicators primarily related to pressure
- Field-based data collection methods for nine indicators primarily related to state.

Data gathered from wetlands in all six NRM regions (Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy, Burnett Mary) contribute to reporting on the status of and trend in wetland condition at the GBRCA-wide scale. The 2022 GBRCA-wide assessment of status focuses on 2022 data from wetlands across all six NRM regions (Table 1). The 2022 GBRCA-wide assessment of change over time (trend) is based on data gathered annually since 2016 from all six NRM regions.

The 2022 assessments of status in NRM-regions focus on 2022 data from wetlands in individual NRM regions. Status at the NRM region scale is only reported for the four NRM regions in which sampling-effort intensification has commenced: the Wet Tropics, Burdekin, Fitzroy and Burnett Mary. Sampling-effort intensification has not occurred in Mackay Whitsunday or Cape York NRM regions, hence why they do not have NRM region-scale status assessments yet. The Mackay Whitsunday region is small, and this has constrained the ability to increase the number of wetlands sampled there. Cape York is logistically challenging to sample, which constrains the ability to increase the number of wetlands sampled there[1].

Trend is not reported at the NRM region scale, because there are three or fewer years only of sampling-effort intensification data available to date, which is insufficient for trend detection (Starcevich et al. 2018a; White 2019).

Wetland Tracker indices

For each wetland, the condition assessment tool, Wetland Tracker (WT), produces overall scores for anthropogenic **pressure** on wetlands and the **state** of wetland environmental values, plus scores for

[1] Note also that in 2020 and 2021, field assessments could not be conducted in the Cape York NRM region due to COVID19 restrictions. Scores for Cape York field indicators in 2020 and 2021 were imputed based on data from previous years.

four 'pressure class' (PC) subindices of pressure, and four 'wetland environmental value' (WEV) subindices of state:

- PC1: pest introductions (e.g. plant pests and animals changing a wetland)
- PC2: habitat modification (e.g. loss of natural vegetation around a wetland)
- PC3: change to water regime (e.g. natural wetland water levels being altered by a dam or levee)
- PC4: pollutant inputs (e.g. land use associated with the likelihood of sediment and nutrients going into a wetland)
- WEV1: biotic integrity (the biological health and diversity of a wetland)
- WEV2: local physical integrity (a wetland's natural physical state and integrity)
- WEV3: local hydrology (a wetland's natural hydrological cycle)
- WEV4: connectivity (the natural interaction of a wetland with other ecosystems, including other wetlands).

Each subindex comprises two or more individual indicators.

Scoring scales for individual wetland and GBRCA-wide assessments

Generating the wetland condition scores for sampled wetlands, for each of the **pressure** and **state** subindices and overall indices, is a four step process, as follows:

Step 1. Scores per indicator: Individual indicators of pressure and state are assessed on ordinal scales with integer scores ranging from one to five**:**

Condition	**Very low pressure/Very good state**	**Low pressure/ Good state**	**Moderate pressure/ Moderate state**	**High pressure/ Poor state**	**Very high pressure/ Very poor state**
Indicator scores (individual wetlands)	1	2	3	4	5

Step 2. Aggregation of indicator scores into subindex scores: The indicator scores are aggregated into numeric subindex scores between one to five, inclusive, for each of the eight subindices per wetland.

Independently, the indicator scores are aggregated to generate an overall numeric pressure and overall numeric state score per wetland, which can take on values between one to five, inclusive.

Step 3. GBRCA wide and NRM region scores: Generating scores at the GBRCA-wide and NRM region scales follows a new process that uses model-assisted methods to account for non-response bias and frame error (see below) and assess change over time (trend) in wetland condtion. GBRCA-wide scale scores are no longer generated by averageing the values from individual wetlands, because this does not adequately account for nonresponse bias (see below).

The resulting GBRCA-wide and NRM-region scale numeric scores for the eight subindices and overall state and pressure indices range in value from one to five, inclusive.

Step 4. Report card grades: All subindex and index scores are reported as decimal values ranging from one to five. Breakpoints (cutoffs) for report card grades are as follows:

Index and subindex cutoffs	<1.50	≥1.50 to <2.50	≥2.50 to <3.50	≥3.50 to <4.50	≥4.50
Report Card grade	A	B	C	D	E

Non-response bias

The 2016 Reef wetland condition report established that there was non-response bias in the Program's wetland assessment data.

Most wetlands that are approached for inclusion in the Program can be sampled and these are known as ‘responding’ wetlands. ‘Nonresponse’ occurs when a wetland cannot be sampled for some reason. Reasons for nonresponse are recorded annually and include: site inaccessibility (e.g., due to geography); absence of landholder contact information; landholder declining to grant access for sampling; landholder postponement of access for sampling; no reply from landholder. When this occurs, the nonresponding wetland is replaced from the randomly generated sample list by the next wetland in the list from the same NRM region that *can* be sampled (making the replacement wetland a responding wetland). As a result, the sample of wetlands on which data are collected represents the subpopulation of responding wetlands rather than wetlands from the entire target subpopulation. This represents a potential source of what is known as nonresponse bias.

To account for the non-response bias, a state-of-the-art multiple imputation method (Little and Rubin 2019) is used to impute subindex and overall index scores for non-responding wetlands, NRM region by NRM region. This is because analysis performed on data gathered to date indicates that NRM region is the best predictor of whether a wetland will be nonresponding or responding (logistic regression analysis using the corrected Akaike Information Criterion of Burnham and Anderson 2002 and with statistical significance, alpha, set at 0.05).

Nonresponding wetlands that are inaccessible due to geography or have no contact information are treated as missing at random (MAR) and those for which landowners decline or postpone participation or do not reply, are treated as missing not at random (MNAR). Wetland condition is assumed to be related to MNAR but not MAR nonresponse, so MNAR and MAR scores are imputed differently. For each index within each NRM region, score means and variances for MAR wetlands are considered similar to those of responding wetlands, under the quasi-randomisation assumption (Oh and Scheuren 1983). So, for each NRM region, forty imputations are drawn for each MAR wetland and index from the truncated normal distribution, within the bounds of the 95% confidence interval for the responding wetland mean (Rodwell et al. 2014). For MNAR cases, scores for each index within each NRM region are assumed to be no lower than the average score observed for responding wetlands. So, for each NRM region, forty imputations are drawn for each MNAR wetland and index from the truncated half-normal distribution (Rodwell et al. 2014), within the bounds of the responding wetland mean up to the maximum score of 5.

The imputed scores for nonresponding wetlands are analysed together with scores from responding wetlands to produce estimates of status and trend in wetland condition. Analyses are conducted in R, a language and environment for statistical computing (R Core Team 2022), using the Program’s GBRCATrend package (Starcevich 2022).

Frame error

Another source of bias in the data is frame error, which results when some wetlands in the list of those approached for inclusion do not actually belong to the target subpopulation of natural, freshwater floodplain wetlands in major aggregations (e.g. they might have been converted from estuarine to fresh water). Results of analysis performed on data gathered to date indicate that frame error, i.e. whether or not a wetland is a member of the target subpopulation, is best predicted by NRM region (logistic regression analysis using the corrected Akaike Information Criterion and with statistical significance, alpha, set at 0.05).

So, to account for frame error, design weights are applied within NRM regions that sum to the total number of target-subpopulation wetlands in each relevant NRM region. This ensures that the sample of wetlands in an NRM region will represent the target subpopulation of wetlands in that NRM region. Specifically, the weight for a wetland in any one NRM region and year is the inverse of the probability of its inclusion in the sample for that NRM region and year, as per the Horvitz-Thompson estimator (Horvitz and Thompson 1952; Cordy 1993).

Status of wetland condition

GBRCA-wide and NRM-region scale reporting

Annual design-based estimates of status in wetland condition for the GBRCA-wide, Wet Tropics, Burdekin, Fitzroy and Burnett Mary NRM regions were computed for each subindex and the overall pressure and state indices (Table 2).

Table 2. Pressure and state score estimates for 2022, with 95% confidence intervals in parentheses, at the GBRCA-wide and NRM-region scales. Note, all six NRM regions contribute to the GBRCA-wide results, but only four regions are reported on at the NRM-region scale.

Measure	**GBRCA-wide**	**Wet Tropics**	**Burdekin**	**Fitzroy**	**Burnett Mary**
State of wetlands	2.46 (2.41 – 2.52)	3.18 (3.13 – 3.23)	3.09 (3.02 – 3.15)	3.11 (3.01 – 3.22)	2.61 (2.54 – 2.68)
Biotic integrity	2.45 (2.36 – 2.53)	3.18 (3.09 – 3.27)	3.35 (3.27 – 3.43)	3.38 3.26 – 3.49)	2.50 (2.36 – 2.64)
Local physical integrity	2.91 (2.76 – 3.06)	2.79 (2.69 – 2.88)	2.98 (2.86 – 3.09)	2.96 (2.78 – 3.14)	2.07 (1.96 – 2.17)
Local hydrology	2.14 (2.07 – 2.21)	3.29 (3.21 – 3.37)	3.11 (2.97 – 3.25)	2.55 (2.35 – 2.76)	2.84 (2.71 – 2.96)
Connectivity	2.62 (2.57 – 2.66)	3.69 (3.59 – 3.80)	3.17 (3.05 – 3.29)	4.00 (3.86 – 4.13)	3.13 (3.00 – 3.25)
Pressure on wetlands	2.86 (2.81 – 2.91)	3.70 (3.66 – 3.75)	3.49 (3.43 – 3.56)	3.60 (3.53 – 3.68)	2.98 (2.89 – 3.06)
Pest introductions	3.49 (3.43 – 3.54)	4.00 (3.94 – 4.06)	4.18 (4.13 – 4.23)	4.10 (4.02 – 4.19)	3.60 (3.51 – 3.69)
Habitat modification	2.87 (2.77 – 2.98)	4.04 (3.95 – 4.12)	3.19 (3.09 – 3.28)	4.07 (3.95 – 4.20)	3.35 (3.24 – 3.45)
Water regime change	2.96 (2.92 – 3.01)	3.35 (3.30 – 3.40)	3.51 (3.44 – 3.57)	3.49 (3.35 – 3.63)	2.84 (2.71 – 2.97)
Pollutant inputs	2.34 (2.26 – 2.42)	3.63 (3.58 – 3.69)	3.29 (3.21 – 3.37)	3.09 (3.02 – 3.16)	2.37 (2.24 – 2.50)

To produce the estimates, datasets containing both the imputed-nonresponding and the observed-responding wetland scores were analysed using weighted linear regression for design-based estimates (WLRDB; Starcevich et al. 2018b), the 'cont_analysis' function in the spsurvey package (Dumelle et al. 2022) and the neighbourhood variance estimator (Stevens and Olsen 2003, 2004). The online Reef Water Quality Report Card 2021 and 2022 reports the status estimates only; the 95% confidence intervals for those estimates are reported in this Methods report card (Table 2).

Backcasting data to maintain comparability across seven years of monitoring

Any comparisons made in the Reef Water Quality Report Card 2021 and 2022 between scores from 2022 and previous years, and all assessments of trend, are based on scores calculated using the new methods. As such, scores provided in the online Reef Water Quality Report Card 2021 and 2022 (for 2022 and previous years) are calculated using the new analysis methods. This is made possible by backcasting scores for previous years using the new methods.

In most cases, there has been no change in previous years' grades as a result of backcasting. The few cases where a change has occurred involve scores lying very close to the breakpoint between B and C grades. The greatest difference in score for these grade changes was 0.34, which is much smaller than 0.99, the range between the lowest and highest score possible within either a B or C grade.

The backcast scores also indicate there has been minimal change between 2020 and 2022 in the grades for pressure and state indices. Although the Pest introductions pressure subindex received a backcast 2020 grade of D, and a 2022 grade of C, the 2022 score is only 0.01 points below the D-C breakpoint. Likewise, the overall state index received a backcast 2020 grade of C, and a 2022 grade of B, but 2022 score is only 0.04 points below the C-B breakpoint.

Change over time (trend)

GBRCA-wide scale reporting

Change over time, as the annual improvement, decline or no change, in wetland condition since 2016, along with 95% confidence intervals, is estimated using a trend modelling approach. For each overall index and each subindex, trend estimates and variances are combined across imputations so that the additional variation from multiple imputation is reflected in the variance of the trend estimate.

The linear mixed effects trend model of Piepho and Ogutu (PO; Piepho and Ogutu 2002), which can include random intercept and slope effects (e.g. for NRM regions and/or wetlands), is used to provide inference and perform diagnostic checks on residuals. PO models are fitted using the 'glmmTMB' package (Brooks et al. 2017). The 'lmerTest' package (Kuznetsova et al. 2017) is used to construct 95% confidence intervals and perform Wald t-tests for trend testing.

The probability-weighted iterative generalized least squares (PWIGLS) model of Starcevich et al. (2018b), which can incorporate design weights to account for frame error, is then used to provide inference on annual trend. Using both the PO and PWGLS methods enables the effect of weighting and random effects on trend inference to be evaluated.

Statistical significance of trends is set at alpha = 0.05.

Power to detect trends using the new methods is being investigated and will increase over time as more years of data become available.

The online Reef Water Quality Report Card 2021 and 2022 reports the results of PWIGLS models only and does not report 95% confidence intervals (CI), which are reported here instead.

Since 2016, there has been no annual trend in the overall pressure on or state of freshwater floodplain wetlands in the GBRCA overall. However, an annual score increase of 0.06 (CI: 0.02 – 0.09) has been detected in the pressures associated with water regime change (PWIGLS model). There has also been an overall decline in the biotic integrity of wetlands, represented by an annual score increase of 0.08 (CI: 0.04 – 0.12) since 2016 (PWIGLS model). There has been an improvement in the local physical integrity of wetlands, represented by an annual score decrease of 0.10 (CI: 0.04 – 0.16; PWIGLS model).

Note that no trends were detected using PO models that included random effects. However, when random effects were removed, an increase in pressures associated with water regime change and a decline in the biotic integrity of wetlands was detected. These findings align with results of the PWIGLS models (that do not include random effects but do include design weights to account for frame error) for these two subindices. The trends detected using the PWIGLS and PO models should be re-evaluated as more data become available in coming years.

Data confidence

A multi-criteria analysis is used to qualitatively score the confidence in each index used in the Reef Water Quality Report Card 2021 and 2022, from low to high (Australian and Queensland Governments 2017). The approach combines expert opinion and direct measures of error for program components where available.

Wetland condition received a two-bar confidence ranking, out of 5 bars, in previous Reef Report Card wetland condition results reports. This year data confidence can be raised to three bars.

Maturity of methods (weighting = 0.5)

Score 3 out of 3

The Wetland Tracker assessment tool (current Version 2.0, used since 2019) has been independently reviewed and published. We are now also using peer-reviewed, state of the art, model-assisted analytical methods (see above) to account for frame error and nonresponse bias and to estimate status of and trend in wetland condition.

Validation (weighting = 1)

Score 2 out of 3

The assessment uses a combination of remotely sensed, ground-validated (score 2) and directly measured field survey data (score 3).

Representativeness (weighting = 1)

Score 3 out of 3

The annual sample of ≈40 wetlands has been bolstered to ≈100 wetlands since the last report, as a result of an intensification process that has increased sample sizes in the NRM reporting regions. This is an 150% increase in the annual GBRCA-wide representative sample of wetlands contributing to GBRCA-wide analysis and reporting. The increase has also enabled reporting on wetland condition at the NRM-region scale as well at the GBRCA-wide scale. Power to detect trend in condition will continue to increase over time.

Directness (weighting = 1)

Score 2 out of 3

The Wetland Tracker assessment tool (Version 2.0) uses updated indicators and simplified scoring scales that have improved the directness of reporting.

Measurement error (weighting = 1)

Score 2 out of 3

The issue described in 2018, regarding loss of data precision due to overly complex scoring scales has since been addressed through the simplification of report card scoring and grading scales in the wetland assessment tool (Version 2.0).

While it is still not possible to quantify the variance attributable to different sources of error in the data, a repeatability study was conducted in 2017 to identify sources of inter-operator variance, and versions of the assessment tool used from 2018 onward have focused on minimising this source of error variance.

Data confidence score

The average of the above scores, taking into account their individual weightings, is 2.1 out of 3. This equates to 3.5 bars on a 5-bar scale of data confidence.

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Glossary

Aggregated wetland assessment scores of state of and pressures on wetland condition: The wetland assessment method uses scores at three levels – **state** *indicators* are aggregated into four **state** *subindices* based on wetland environmental values (WEVs), and **pressure** indicators are aggregated into four **pressure class** subindices. State and pressure indicators are each aggregated into an **overall state** and an **overall pressure** index, respectively.

Augmented serially alternating design: A monitoring design consisting of a number of panels of sites (wetlands), where one panel is assessed every year (the augmented component of the design) and the remaining panels are assessed in different years on a regular and repeating schedule.

Baseline: A baseline is the initial collection of data used for comparison with data acquired subsequently. In the case of the wetland condition monitoring component of the Reef Report, baseline data were collected in 2015 and 2016 and reported in the Reef Water Quality Report Card 2016.

DPSIR framework: A causal framework for describing the interaction between society and the environment. Driver, Pressure, State, Impact, Response.

Floodplain: Land adjacent to a waterway that is naturally subject to occasional or periodic flooding. Floodplains can be narrow, or wide and flat with steeper sides at the edges.

Lacustrine: Lake-like; referring to large, open, water-dominated systems.

Natural, freshwater wetlands: Natural freshwater wetlands covered by the Great Barrier Reef Wetland Condition Monitoring Program comprise both lacustrine (lake) and palustrine (vegetated) wetlands. 'Natural' freshwater wetlands are those areas that existed as freshwater wetlands before European occupation in Australia and that still meet the definition of wetlands (whether modified or not) in Queensland-wide wetland mapping (Queensland Environmental Protection Agency 2005). Freshwater wetlands created by bunding natural estuarine wetlands to keep out salt water are not included.

Nonresponse bias: A nonresponse bias occurs when randomly selected experimental units (wetlands) cannot be involved in a study (wetland assessment), not at random, but in ways that are meaningful to the phenomenon under study (wetland condition).

Palustrine: Swamp-like; primarily vegetated, non-channel environments.

Panel: A panel is a group of wetlands with the same schedule of repeat assessments across years.

Power (to detect a change): In statistical testing, Power = $(1 - \beta)$, where β is the probability of making a Type II error, that is, failing to detect an effect when it is present.

Pressure: Under the DPSIR framework, pressure refers to human activities directly affecting the environment.

Spatially balanced random sample: A random sample whose sample sites are more or less evenly dispersed over the extent of the population being studied.

State: Under the DPSIR framework, characteristics, at a particular time, of ecosystem processes and the organisms and habitats that define, support and/or adversely affect ecosystem environmental values.

Index/indices/subindex/subindices: The Great Barrier Reef Wetland Condition Monitoring Program assesses two indices of wetland condition, overall anthropogenic **pressure** on and overall **state** of wetland condition. Subindices of pressure are classes of pressure on wetlands (PCs), defined as: pest introductions, habitat modification, changes to water regime and pollutant input pressures. State subindices are wetland environmental values (WEVs), defined as: biotic integrity, local physical integrity, local hydrology and connectivity.

Wetland condition: Under the Great Barrier reef Wetland Condition Monitoring Program, wetland condition refers to the pressure on the natural environmental values of wetlands and the state of those values under a DPSIR conceptual framework.

Australian Government

Queensland Government

Catchment monitoring methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

Citation

Australian and Queensland governments, 2024, *Catchment monitoring methods, Reef Water Quality Report Card 2021 and 2022,* State of Queensland, Brisbane.

Contents

Catchment monitoring methods

This report summarises the methods undertaken by the Catchment monitoring program that reports the catchment monitoring results required for the delivery of the Reef Water Quality Report Card 2021 and 2022. The Catchment Monitoring Program provides data to the Catchment Loads Modelling Program to validate progress towards achieving the Reef 2050 Water Quality Improvement Plan (Australian and Queensland governments 2018) 2025 water quality targets. The Catchment Monitoring Program also delivers Pesticide Risk Condition calculations for comparison of the risk posed by pesticides for each basin, region and the whole of the Great Barrier Reef catchment area, with the Pesticide Risk Baseline and pesticide target.

The water quality targets are:

- 60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads
- 20% reduction in anthropogenic end-of-catchment particulate nutrient loads
- 25% reduction in anthropogenic end-of-catchment fine sediments loads
- to protect at least 99% of aquatic species from pesticides at the end-of-catchments.

Monitoring sites

Catchment water quality was measured at more than 61 sites across 23 major catchments that discharge to the Great Barrier Reef lagoon (Figure 1) during the 2020-2021 monitoring year, and more than 68 sites across 24 major catchments (Figure 2) during the 2021-2022 monitoring year as part of an ongoing, long-term monitoring program. Water quality monitoring site numbers and locations vary slightly from year to year, due to various logistical, climatic and operational reasons.

During 2020-2021, 55 sites across 23 major catchments were monitored for total suspended solids and nutrients. Pesticides were monitored at 34 sites across 20 major catchments (pesticides were not monitored in the Cape York region). During 2021-2022, 56 sites across 23 major catchments were monitored for total suspended solids and nutrients. Pesticides were monitored at 38 sites across 21 major catchments.

Monitoring sites are classified as either end-of-catchment or sub-catchment sites. The end-of-catchment monitoring sites are located at the lowest point in a river or creek, where the discharge can be accurately measured, typically where gauging stations have been established and are being maintained by the Queensland Department of Natural Resources, Mines and Energy. Sub-catchment sites are located at the lowest point in a sub-catchment (tributary), mainly at existing gauging stations. Water quality samples collected at each monitoring site provide data related to land management activities in the catchment area upstream of the site. Both site types provide field data that are used to calibrate and validate catchment models.

Monitoring currently captures an estimated 92% of the total suspended solid load and 88% of the dissolved inorganic nitrogen load discharged to the Great Barrier Reef lagoon. Pesticides are monitored in all priority locations.

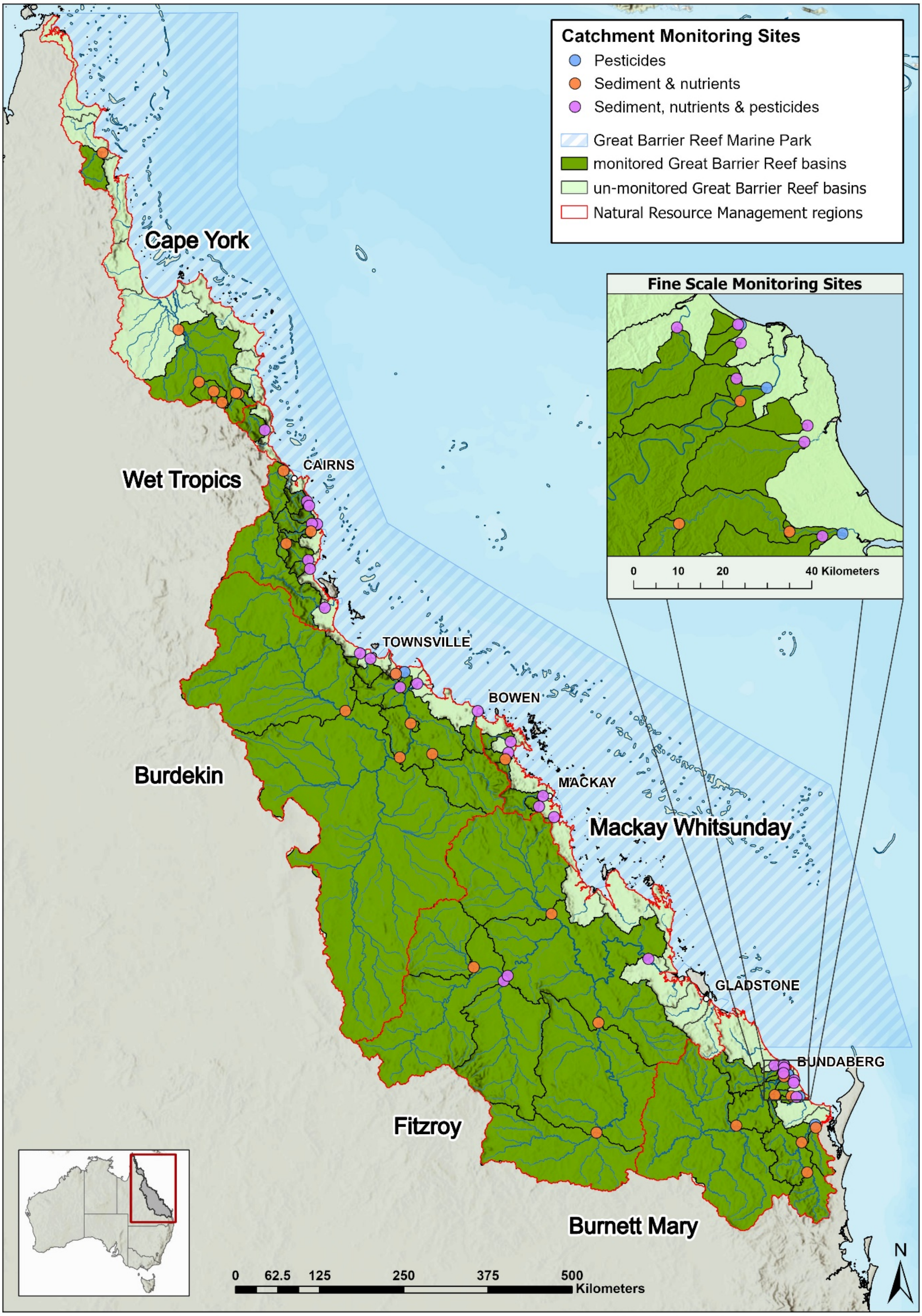

Figure 1: Map showing the location of 2020-2021 monitoring year catchment monitoring program sites in the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program.

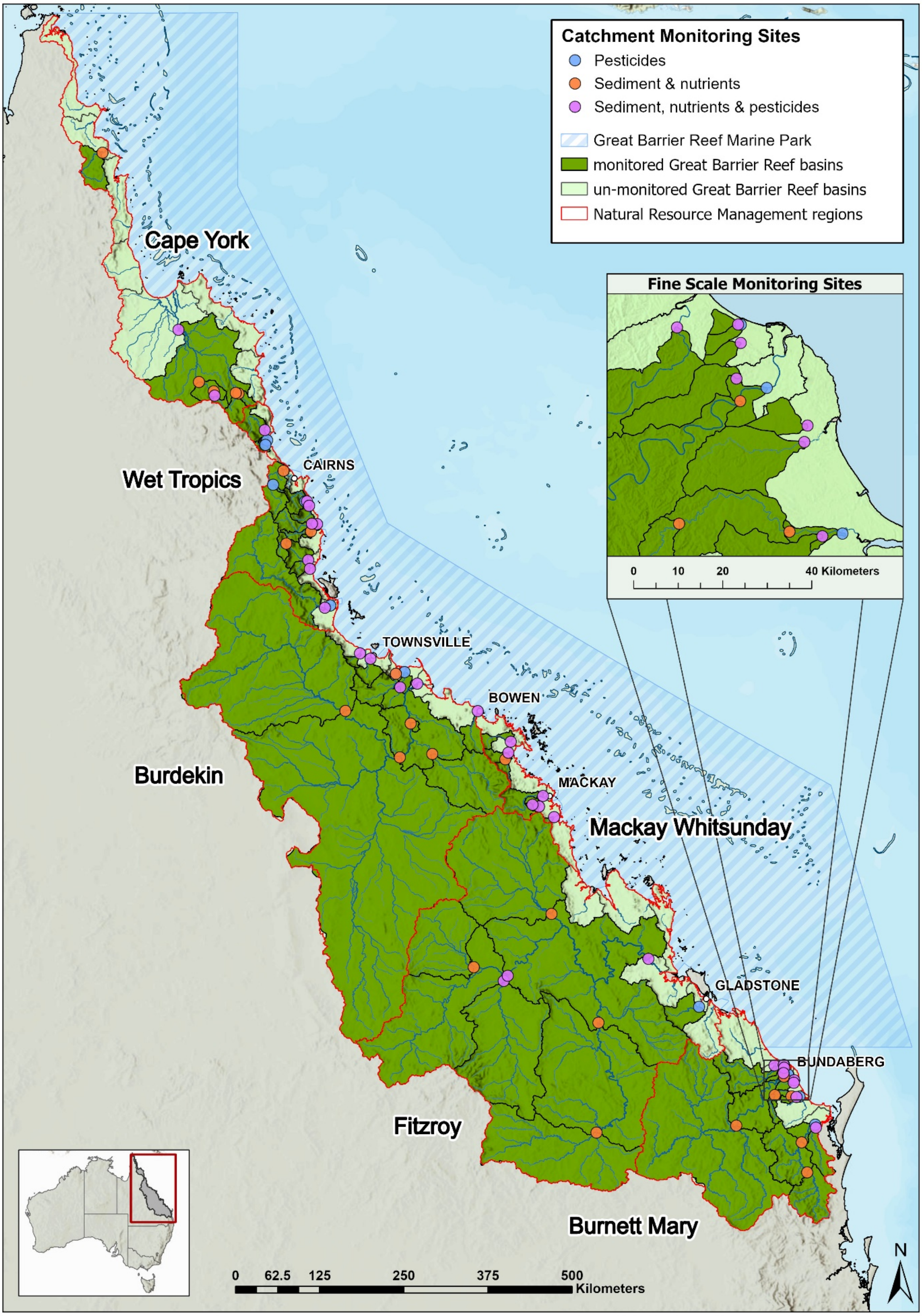

Figure 2. Map showing the location of 2021-2022 monitoring year catchment monitoring program sites in the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program.

Rainfall data

Rainfall totals and rainfall decile data comes from the Bureau of Meteorology National Climate Centre. These data are synthesised using geographic information system tools to display total annual rainfall and annual rainfall deciles for Queensland from 1 July to 30 June each year. The total annual rainfall and annual rainfall deciles provide contextual information regarding the state of the climate during the monitoring year and is described in detail in the annual Great Barrier Reef Catchment Loads Monitoring Program - Condition Report.

Water quality sampling

Water samples are collected, stored, transported and quality assured and quality controlled in accordance with the Environmental Protection (Water) Policy Monitoring and Sampling Manual 2018 (www.ehp.qld.gov.au/water/monitoring/sampling-manual). Water quality samples are collected using two methods: manual grab sampling and automatic grab sampling using refrigerated pump samplers. Intensive sampling (daily or every few hours) is conducted during high flow events and monthly sampling is conducted during low or base-flow (ambient) conditions. For pesticides, intensive sampling (daily or every few hours) is similarly conducted during high flow events and weekly to monthly sampling is conducted during low or base-flow (ambient) conditions over the wet season. For the purpose of sampling pesticides, the standardised wet season (i.e. for assessing the main pesticide exposure period) commences with the first run-off event and continues for 182 days (six months).

Where possible, total suspended solids, nutrients and pesticide samples were collected concurrently. Manual grab samples collected during low flow conditions, where sites are tidally influenced, were taken on the outgoing, low tide. Automatic grab samplers installed in tidal sites were activated during rainfall run-off events based on discharge measured with Horizontal Acoustic Doppler Current Profilers and conductivity and turbidity readings recorded *in situ*.

River discharge data

The volume of water flowing in the rivers is calculated using one of four methods, depending on the location and data availability:

- measured discharge from existing gauging station and extracted from Hydstra - the surface water database of the Department of Regional Development, Manufacturing and Water (Water Monitoring Information Portal);
- 'time and flow factored'[1] measured discharge from existing Department of Regional Development, Manufacturing and Water gauging station(s);
- modelled flows generated in the Source Catchments modelling platform using the Sacramento rainfall runoff model, where the Parameter Estimation Tool (PEST) was coupled with Source for the calibration process; or
- discharge measured by Horizontal Acoustic Doppler Current Profiler, with missing records and periods of low flow and/or strong tide influence infilled with daily modelled flow data.

The selected method for each site is reported annually in the Great Barrier Reef Catchment Loads Monitoring Program - Condition Report.

1 Time and flow factors adjust the flow by adding a time delay due to travel time from the upstream gauging station to the water quality sampling site, and to account for the change in discharge between the upstream gauging station and the end of catchment site due to differences in catchment area.

Water quality sample analysis

The Science Division Chemistry Centre (Dutton Park, Queensland) analyses water samples for total suspended solids and nutrients (Table 1). The Queensland Health Forensic and Scientific Services Organics Laboratory (Coopers Plains, Queensland) analyses water samples for pesticides (Table 2). Both laboratories are accredited by the National Association of Testing Authorities for the analyses conducted.

Table 1: Summary information for each reported analyte in the catchment monitoring program

Reported pollutants	Abbreviation	Measured analytes
Sediment (Total suspended solids)	TSS	Total suspended solids
Total nitrogen	TN	Total nitrogen as N
Particulate nitrogen	PN	Total nitrogen (suspended) as N
Dissolved organic nitrogen	DON	Organic nitrogen (dissolved) as N
Ammonium nitrogen as N	NH_4-N	Ammonium nitrogen as N
Oxidised nitrogen as N	NO_x-N	Oxidised nitrogen as N
Dissolved inorganic nitrogen	DIN	Ammonium nitrogen as N + Oxidised nitrogen as N
Total phosphorus	TP	Total phosphorus as P
Particulate phosphorus	PP	Total phosphorus (suspended) as P
Dissolved organic phosphorus	DOP	Organic phosphorus (dissolved) as P
Dissolved inorganic phosphorus	DIP	Phosphate phosphorus as P

Pesticide monitoring and reporting differs from nutrients and suspended solids due to the large range of pesticides used in agriculture and the variation in their use from one year to the next. For this reason, water samples are analysed for a general suite of pesticides. However, not all pesticides that are detected are reported each year. Other detected and non-detected pesticides are available in the Pesticide Reporting Portal. A sub-set of pesticides, referred to as the *reference pesticides*, were used to measure and compare the Pesticide Risk Condition of catchments, basins and the whole GBR catchment area against the Pesticide Risk Baseline and Reef 2050 pesticide target[2]. The reference pesticides (Table 2) were selected based on the frequency of detection in catchments, the availability of ecotoxicity data for individual pesticides as an indicator of risk, and the scope to model application and run-off of chemicals using Source Catchment models. The reference pesticides include herbicides and insecticides used in a range of agricultural land uses, including sugarcane, grazing, cropping and horticulture.

2 Note: The pesticide target encompasses all pesticides in GBR water bodies. All possible measures are taken to include as many pesticides in the metric to measure progress towards the target; however, measuring and modelling progress is reliant on other data (e.g. ecotoxicity and application data) not just concentration information, which is not available for all pesticides detected in catchments. For this reason, not all pesticides are included in the metric to measure progress towards the target. The number and types of pesticides included in the metric will expand over time as new data are collected.

Table 2: Pesticides included in Pesticide Risk Metric (not all of the listed pesticides were necessarily detected in collected water samples)

Reference pesticide	Pesticide type	Mode of action
Chlorpyrifos	Insecticide	Acetylcholine esterase (AChE) inhibitor
Fipronil	Insecticide	Gamma-aminobutyric acid (GABA) gated chloride channel blocker
Imidacloprid	Insecticide	Nicotinic receptor agonist
Haloxyfop	Herbicide	Acetyl-coenzyme A carboxylase (ACCase) inhibitor
Imazapic	Herbicide	Acetolactate synthase (ALS) inhibitor
Metsulfuron-methyl	Herbicide	
Pendimethalin	Herbicide	Microtubule synthesis inhibitor
Metolachlor	Herbicide	Very long chain fatty acid (VLCFA) inhibitor
Ametryn	Herbicide	Photosystem II inhibitor
Atrazine	Herbicide	
Terbuthylazine	Herbicide	
Tebuthiuron	Herbicide	
Simazine	Herbicide	
Diuron	Herbicide	
Terbutryn	Herbicide	
Hexazinone	Herbicide	
Metribuzin	Herbicide	
2,4-D	Herbicide	Auxin mimic (Phenoxy-carboxylic acid auxins)
MCPA	Herbicide	
Fluroxypyr	Herbicide	Auxin mimic (Pyridine-carboxylic acid auxins)
Triclopyr	Herbicide	
Isoxaflutole	Herbicide	4-hydroxyphenylpyruvate dioxygenase (4-HPPD) inhibitor

Calculating nutrient and sediment loads

The suitability of the generated water quality monitoring data for use in load calculations was assessed using a sample representivity rating. The annual rating of sampling representivity was assessed against two criteria:

1. the number of samples collected in the top five per cent of annual monitored flow
2. the ratio between the highest flow rate at which a water sample was collected and the maximum flow rate recorded.

The representivity was determined for each monitoring year by assigning a score using the system presented in Table 3.

Table 3: Scores assigned to total suspended solids and nutrients data to determine their representivity

Number of samples in top 5% of flow	Score	Ratio of highest flow sampled to maximum flow recorded	Score
0 – 9	1	0.00 – 0.19	1
10 – 19	2	0.20 – 0.39	2
20 – 29	3	0.40 – 0.59	3
30 – 39	4	0.60 – 0.79	4
>40	5	>0.80	5

The rating of sample representivity for each analyte was the sum of the scores for the two criteria. Sample representivity for each analyte was rated as 'excellent' when the total score was greater than or equal to eight, 'good' when the total score was six or seven, 'moderate' for total scores of four or five, or 'indicative' when the score was less than four. Furthermore, hydrographs were visually assessed to verify the representivity rating.

For nutrients and sediment, the concentration and flow data are used to determine the total load of each pollutant that is transported past the monitoring site in each catchment and sub-catchment. Annual and daily loads are calculated for total suspended solids and the nutrient analytes listed in Table 1, using the ReLo[3] loads calculation software developed by the Queensland Department of Environment, Science and Innovation. The loads estimation models incorporated in the software are consistent with Water Quality Analyser 2.1.2.6 (eWater 2012). The total suspended solids and nutrient loads were calculated using concentrations reported in milligrams per litre (mg L^{-1}).

One of two methods was used to calculate loads: the average load (linear interpolation of concentration) or the Beale ratio. Average load (linear interpolation of concentration) is the most accurate and reliable method, provided events are adequately sampled, with a representivity rating of excellent. For complex events or events with a representivity rating of good, moderate or indicative, the Beale ratio is one of the recommended methods (Joo et al. 2012).

Calculating the Pesticide Risk Metric

The Pesticide Risk Metric estimates the percentage of species protected from mixtures of pesticides detected during a standardised wet season. This period is typically when the vast majority of rain occurs and therefore the greatest probability that pesticides will be transported, either as soluble or bound forms, to waterways and their associated aquatic ecosystems. The wet season was defined as the six-month period (182 days) following the first flush in each monitored waterway.

The Pesticide Risk Metric was calculated from the monitored concentration data for the 22 reference pesticides (Table 2), and forms the basis of pesticide reporting in the Great Barrier Reef Catchment Loads Monitoring Program Condition Report and the Pesticide Risk Condition for the Reef Water Quality Report Card 2020. Pesticide Risk Condition can be used to assess distance from the Pesticide Risk Baseline[4]. Details of all the methods involved in the calculation of the Pesticide Risk Metric, Pesticide Risk Baseline and Pesticide Risk Condition are provided in Warne et al. (2020a), Warne et al. (2020b) and Neelamraju et al. (2021). A brief overview of the principal components of the Pesticide Risk Metric are provided below.

The 22 reference pesticides have multiple different modes of action (Table 2). The toxicity of pesticides with different modes of action was calculated using the independent action model of joint action (Plackett and Hewlett 1952) within the multiple-substance-potentially affected fraction (ms-PAF) method

3 ReLo is a software program developed by the Queensland Department of Environment and Science. The loads estimation models incorporated in this software are consistent with Water Quality Analyser 2.1.2.6 (eWater 2012). ReLo allows the batch processing of load calculations, a function that is not currently available within Water Quality Analyser (eWater 2012).

(Traas et al. 2002). The pesticide mixture toxicity was calculated for all samples collected over the wet season. Where there was more than one sample per day, a daily mean pesticide mixture toxicity value was calculated.

In order to express the concentration data for all 22 reference pesticides as a single number that represents the wet season pesticide risk to aquatic ecosystems, the mixture toxicity data (i.e. Pesticide Risk Metric values) for all water samples collected over the wet season were then summarised as a single value. This required estimating the daily average per cent of species affected for days that were not monitored during the wet season using a multiple imputation technique (Rubin 1996; Donders et al. 2006; Patrician 2002). This involved fitting a statistical distribution to the observed data for the wet season for the site. This distribution was then used to impute values to fill in the missing days in the 182-day period. The application of the Multiple Imputation method assumes that the distribution of sampling over the wet season encompasses the variability of pesticide concentrations over the wet season. This was usually ensured by having a good balance between ambient samples and event samples. Where that balance of ambient and event samples could not be achieved, then a decision was made about whether the calculated Pesticide Risk Metric was a reliable estimate of the wet season risk[5]. The resultant 182 days of data were then divided by 182 to obtain the Pesticide Risk Metric and ranked into five risk categories (Table 4). These categories were consistent with the ecological condition categories used in the Australian and New Zealand Water Quality Guidelines (ANZWQG) for Fresh and Marine Waters.

The Pesticide Risk Metric method was used to obtain pesticide risk values for four groups of pesticides - total pesticides (all 22 pesticides included in the Pesticide Risk Metric), insecticides, photosystem inhibiting (PSII) herbicides and other (non-PSII) herbicides.

Table 4: Risk categories used to assess pesticide risk

Pesticide Risk Metric value		Risk category	Ecological condition (ANZWQG)
% species affected	% species protected		
≤1%	≥99%	Very low	High Ecological Value
>1 to 5%	95 to <99%	Low	Slightly to Moderately Disturbed
>5 to 10%	90 to <95%	Moderate	Highly Disturbed
>10 to 20%	80 to <90%	High	
>20%	<80%	Very high	

Once the Current Basin Condition values were obtained for PSII Herbicides, Other Herbicides and Insecticides, they were converted from per cent species protected to per cent species affected (i.e., 100% - % species protected). The Current Basin Condition (per cent species affected) values for PSII Herbicides, Other Herbicides and Insecticides were summed. The relative contribution for PSII Herbicides was calculated for each basin using Equation 1.

Equation 1:

$$\text{Relative contribution (PSII)} = 100 \times \left(\frac{\%\ \text{affected}_{\text{PSII}}}{\sum \%\ \text{affected all groups}}\right) \quad (1)$$

where % affected$_{\text{PSII}}$ is the estimated per cent of species affected by PSII Herbicides for a basin and Σ % affected all groups is the estimated sum of the per cent species affected by PSII Herbicides, Other Herbicides and Insecticides for the same basin.

5 In the 2021-2020 monitoring year, a decision was made that the Current Pesticide Risk for the Don River basin would not be calculated for Reef Water Quality Report Card because the sampling across the wet season was biased toward event monitoring, and therefore not reflective of the risk across the wet season.

The relative contribution of Other Herbicides (OH) and Insecticides (I) of each basin were calculated using equations 2 and 3, respectively.

Equation 2:

$$\text{Relative contribution (OH)} = 100 \text{ x } \left(\frac{\%\ \text{affected}_{\text{OH}}}{\sum \%\ \text{affected all groups}}\right) \quad (2)$$

Equation 3:

$$\text{Relative contribution (I)} = 100 \text{ x } \left(\frac{\%\ \text{affected}_{\text{I}}}{\sum \%\ \text{affected all groups}}\right) \quad (3)$$

where % affected$_{OH}$ and % affected$_{I}$ are the estimated per cent of species affected by Other Herbicides and Insecticides, respectively for a basin.

Reporting on pesticides for the report card

Pesticide monitoring data from the Great Barrier Reef Catchment Loads Monitoring Program were used to calculate the Pesticide Risk Metric (expressed as a per cent of species protected) at each monitoring site. These data were weighted according to the size of the sub-catchment compared to the catchment they belong to. The weighted values were then used to modify the per cent of species protected values from the Pesticide Risk Baseline (Warne et al. 2020b) to estimate the Pesticide Risk Condition of each catchment. The same approach was applied to the regions and the entire Great Barrier Reef Catchment Area. This method does not enable reporting of progress to the pesticide target, as the Pesticide Risk Condition values are affected by annual variations in climatic conditions. The relative contribution of PSII herbicides, other herbicides and insecticides to the Pesticide Risk Metric values was also determined for each catchment. Details of all these calculations are provided in Neelamraju et al. (2021).

Semiquantitative confidence rankings for reporting on pesticides

Data confidence ●●●○○

A multi-criteria analysis was used to score the confidence in each indicator used in the report card from low to high (Australian and Queensland governments 2020). The approach combined expert opinion and direct measures of error for program components where available.

The methods used to calculate Pesticide Risk Condition, and distance from the Pesticide Risk Baseline, received a three-dot confidence ranking. The rationale for this confidence ranking is provided below.

Rationale for the confidence ranking

Maturity of methods

A score of three was awarded because the methods have now been thoroughly reviewed. This resulted in a final score of 1.5 when the 0.5 weighting factor was applied. The score of 1.5 applied to catchments, basins, regions and the GBRCA scales.

Validation

An overall score of two was awarded because the data used in the calculations have either been validated or are direct measurements from monitoring (analytical results), but the per cent of species protected have not validated in the field.

Representativeness

An overall score of two was awarded based on a representivity assessment for the predictions at the whole of the Great Barrier Reef scale. This value was awarded because the high-confidence monitoring data at the catchment scale was used to adjust values at the basin, region and whole of GBR levels.

Directness

An overall score of two was awarded because there are a series of four quantified relationships between land use, hydrological and climatic variables with pesticide mixture toxicity. A higher score was not awarded as the per cent of species protected at the end of catchments is not directly measured.

Measurement error

A score of two was awarded because some components do not have error quantified.

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Australian Government

Queensland Government

Catchment loads modelling methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

Citation

Australian and Queensland governments, 2024, *Catchment loads modelling methods, Reef Water Quality Report Card 2021 and 2022,* State of Queensland, Brisbane.

CONTENTS

Catchment pollutant delivery – Catchment loads modelling methods

This report summarises the data and methods used for reporting progress toward the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) (Australian and Queensland governments 2018) 2025 water quality targets. The catchment loads modelling program is one line of evidence used to report on progress in the Reef Water Quality Report Card 2021 and 2022.

The water quality targets are:

- 60% reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads
- 20% reduction in anthropogenic end-of-catchment particulate nutrient loads
- 25% reduction in anthropogenic end-of-catchment fine sediment loads
- pesticides: to protect at least 99% of aquatic species at the end-of-catchments.

Catchment loads modelling

Quantifying the impact of land management practice change on long-term water quality through monitoring alone is not possible at the whole Great Barrier Reef (GBR) scale. Models are, therefore, used in conjunction with the monitoring program to predict long-term changes in water quality.

The purpose of the modelling is to report annually on the progress towards the Reef 2050 WQIP 2025 load reduction targets for total suspended sediment (TSS), dissolved inorganic nitrogen (DIN), particulate phosphorus (PP) and particulate nitrogen (PN).

The ability to model progress towards the new pesticide target is in development. In the meantime, pesticide risk is reported through the catchment loads monitoring program.

This document provides a summary of the methods of the catchment loads modelling. A detailed outline of the modelling methods and outputs are available from McCloskey et al., 2021a and McCloskey et al., 2021b.

The eWater Source Catchments modelling framework (eWater, 2010) was modified to GBR Source (Ellis 2017) to enable the synthesis of management practice change, paddock monitoring and modelling, plus catchment monitoring data to estimate end-of-catchment pollutant loads. The catchment models generate pollutant loads for current and improved practices for each individual land-use. Modelling is conducted over a fixed climate period. This enables changes in water quality that are only due to the implementation of improved management practices to be modelled.

Baseline loads are estimated for the current (2016) management practice benchmark.

From the baseline, the reduction in loads resulting from improved management practice adoption is calculated by running the model with the new practice adoption layer for the same 28-year modelling period as the baseline. The difference in load is the load reduction for that investment year.

Pollutant loads are summarised in the report card for the 35 basins draining to the Great Barrier Reef lagoon. This catchment-scale water quantity and quality model uses a node link network to represent processes of generation, transportation and transformation of water and constituents within major waterways in a catchment (see Figure 1). The model generates estimates of run-off and pollutant loads for each functional unit. Functional units (FUs) – are areas within a sub-catchment that have similar behaviour in terms of run-off generation and/or nutrient generation e.g. land use within a sub-catchment. Run-off and pollutants are transported from a sub-catchment through the stream network, represented by nodes and links, to the end of the catchment. These components represent the sub-catchment and waterway network.

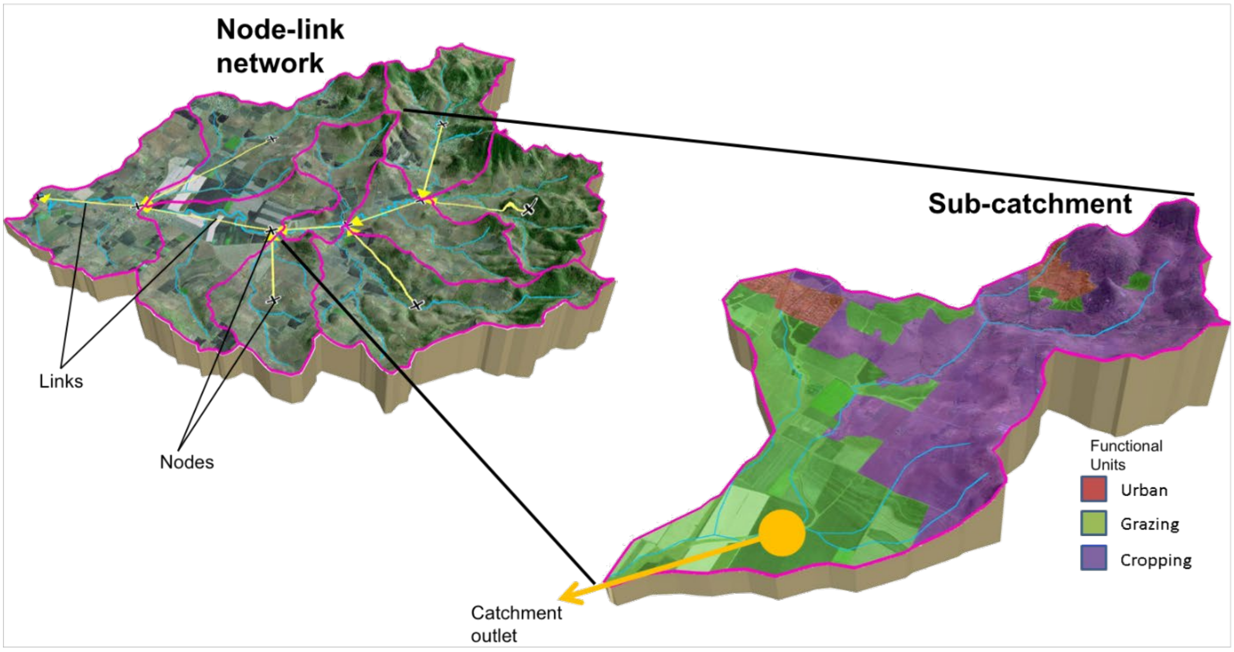

Figure 1: Example of a functional unit (FU) and node-link network generated in Source Catchments (source eWater).

The Source Catchment model runs at a daily time-step which enables the interactions of climate and land management to be reflected in modelled outputs. Aggregated average annual catchment loads are required for the report card. The model runs for a fixed climate period (1986 to 2014), to remove the influence of climate on estimated load reductions. The most current land-use mapping is incorporated when models are periodically updated (details of the mapping data can be found at: www.qld.gov.au/environment/land/management/mapping/statewide-monitoring/qlump/qlump-datasets).

The pollutants modelled were:

- fine sediment (TSS) and coarse sediment
- dissolved and particulate nutrients.

The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program) agricultural management practice adoption program has developed water quality risk frameworks for each agricultural industry. These frameworks articulate best management practice in relation to the Reef 2050 WQIP land and catchment management targets for agricultural management practice adoption. These practices are described in terms of their relative water quality risk, from low to high. See the Agricultural land management practice adoption methods report for more information about the water quality risk frameworks.

Representation of pre-agricultural land management scenario

It is important to note that the pre-development modelled loads were constructed to reflect a scenario prior to agricultural development. The aim was to enable load changes from management to be quantified. The scenario does not represent a true pre-development landscape. Off-shore coral coring and sediment tracing work suggests anthropogenic loads have increased anywhere from 2-10 times the current load (Bartley *et al.* 2018, Lewis et al 2014 and Hughes et al 2009, McCulloch et al 2003a). The modelled estimates of fine sediment fall within these ranges.

The assumptions made when modelling pre-development are:

- Hydrology was kept the same for baseline and the pre-agricultural land management scenarios with dams and weirs maintained.
- Ground cover was increased to 95% in grazing areas.
- With the exception of grazing, all other land uses reverted to nature conservation area.
- The foliage projected cover layer was increased to 95% riparian cover.
- Gully cross-section areas were reduced to 10% of their baseline values.
- Management factors for streambank models were adjusted to reflect a very low risk to water quality (https://www.reefplan.qld.gov.au/tracking-progress/paddock-to-reef/management-practices).

To reflect the modelled load reduction for each report card as a result of changes in adoption of improved agricultural management practices, three scenarios[1] are run:

- Pre-development load (prior to agricultural development) for the 28-year modelling period
- The baseline load for the 28-year modelling period (i.e. representing the agricultural management practice benchmark 2016)
- Change load for the 28-year modelling period with the proportion of land managed using improved practices adjusted to reflect the previous year's adoption.

The proportion of land managed using defined management practices is the only variable that changes between modelled scenarios. This allows for the relative load reductions attributed to the areas of improved agricultural management practices to be reported. Approximately 10 land uses are modelled in each region including grazing, sugarcane, grain cropping, horticulture and bananas.

Modelled load estimates were calibrated and or validated against field data collected through the Catchment Loads Monitoring program at 43 monitoring sites across 20 catchments that discharge to the Great Barrier Reef lagoon. For further information on the model calibration and validation processes and results, refer to McCloskey et al., 2021a and McCloskey et al., 2021b.

The Catchment Loads Modelling program undergoes an external peer review every three to four years. The program was reviewed in 2012, 2015 and 2019. Prior to the release of each report card, modelled load estimates are reviewed both internally and externally.

Management practice change

The Reef 2050 WQIP water quality risk frameworks describe and categorise farming practices according to recognised water quality improvements at the paddock scale. Improvements in water quality as a result of adopting improved management practices were determined by linking paddock model timeseries outputs to catchment models.

[1] *A scenario describes the major processes in a river system or catchment that are modelled. This includes catchment and sub-catchment definition, rainfall run-off and constituent generation models, data sets and parameters. You can create multiple scenarios to break complex projects into distinct parts or duplicate existing scenarios to conduct what-if experiments without disrupting the original. Any change to the definition of sub-catchments, node-link network, FUs, or the models within FUs, forms a new scenario. Similarly, a different set of inputs or parameters can be used to set up a new scenario, such as a change in land use or a climate change* (eWater Source User Guide 4.1).

Management practice change has been modelled for the sugarcane, grains, horticulture, banana and grazing areas of the Great Barrier Reef catchments. For details on how management practice changes are represented in the modelling, refer to McCloskey et al. 2017A and Waters *et al* 2014.

Improved management of gullies and streambanks are modelled to reflect activities such as gully restoration, excluding stock via fencing off gullies and streambanks, and installing off-stream watering points. Spatial data on investments in improved practices are provided by industry and the six natural resource management (NRM) bodies within each region to enable good spatial representation of where works occurred.

Modelling assumptions

- Loads reported for each report card reflect the relative change in modelled average annual loads for the specified model run period (1986 to 2014).
- Land use areas in the model are static over the model run period and are based on the latest available Queensland Land Use Mapping Program (QLUMP) data.
- Paddock model runs that are used to populate the catchment models represent 'typical' management practices for a given management class and do not reflect the actual array of management practices that occur year-to-year across the Great Barrier Reef catchments.
- Paddock model simulations represent the reported management practice adoption water quality risk frameworks as a set suite of practices.
- Application rates of pesticides and fertilisers that are used to populate the paddock models are derived through consultation with relevant industry groups and regional NRM bodies.
- Management practice adoption areas represented in the model are applied at the spatial scale of the data supplied by the delivery organisations and collated by the Department of Agriculture and Fisheries (DAF) Paddock to Reef Agricultural Management Practice Adoption program team annually.
- The water quality benefits from adopting a management practice change are assigned in the year that on-ground works were implemented, so time lags that may occur in the system are not accounted for.
- It is important to note that these modelled load reductions are based on improved land management adoption data supplied by organisations that receive Australian and Queensland government funding to increase the adoption of best management practices. Results are, therefore, indicative of the likely long-term water quality response due to adoption of improved land management practices for a given scenario, rather than a measured reduction in load.

Linking paddock and catchment models

The eWater Source Catchments model (www.ewater.org.au) was modified to incorporate hillslope constituent generation from the most appropriate paddock models for cropping, sugarcane and sugarcane areas, and the Revised Universal Soil Loss Equation (RUSLE) for grazing. Gully and streambank erosion and floodplain, channel and reservoir deposition processes added to the model were based on the SedNet/ANNEX approach (Wilkinson et al. 2014). The modified framework is referred to as P2R Source. A detailed description can be found in Ellis and Searle (2013) and Ellis (2017). The spatial and temporal representation of gully, streambank and in-stream erosion processes were incorporated to better represent the erosion processes observed in the summer-dominant rainfall areas of northern Australia.

Two approaches were used to represent improved land management practices in the Source Catchments model depending on the land use of interest. In the first approach, for sugarcane, bananas and cropping, the constituent time-series (e.g. load per day per unit area) for the given land use was supplied from a paddock model. Unique combinations of climate, soil type and defined management practices within each land use were identified and represented spatially in the paddock model simulations used to inform the catchment models. For cropping (grain cereal crops) and bananas, the HowLeaky model was used (Rattray et al. 2004). For sugarcane modelling, the Agricultural Production Systems sIMulator (APSIM) (Holzworth et al. 2014) was used. For load reduction representation, the defined management practice for a particular land use segment was altered between scenarios.

In the second approach, the RUSLE model was written into the Source Catchments model to model hillslope soil erosion in grazing lands. The cover term (C-factor) in the model is generated from remotely sensed ground cover satellite imagery seasonally (four scenes per year). The paddock-scale model GRASP (McKeon et al. 1990) was used to provide scaling algorithms for each scenario to account for changes in management in each identified land type; for example, shifting areas from moderate risk to moderate–low risk. These scaling algorithms were applied at the pixel scale to each ground cover satellite image for the modelling period. This is applied according to a spatial representation of areas of defined management practices as provided annually by regional NRM bodies. Calculations were performed pixel by pixel, with results accumulated to a single land use representation in each sub-catchment. All loads generated for each land use represented within a sub-catchment were then aggregated at the sub-catchment scale and routed through the stream network.

Total load

The **total baseline load** is the load modelled within each Great Barrier Reef catchment using the 2016 management practice benchmark. A pre-development land use map was also developed and modelled. The model was then run for a 28-year period to establish an average annual load for this period: **the pre-development load**. The **anthropogenic load** was calculated as the total baseline load less the pre-development load.

Load reductions

To reflect investment in improved management practices since 2016, the model was then re-run in each year for the same climate period using the proportions of lowest risk to high risk management practice areas in that year. The relative change in pollutant loads from the anthropogenic baseline after investment reflects the load reduction due to changes in management practices (see Figure 2).

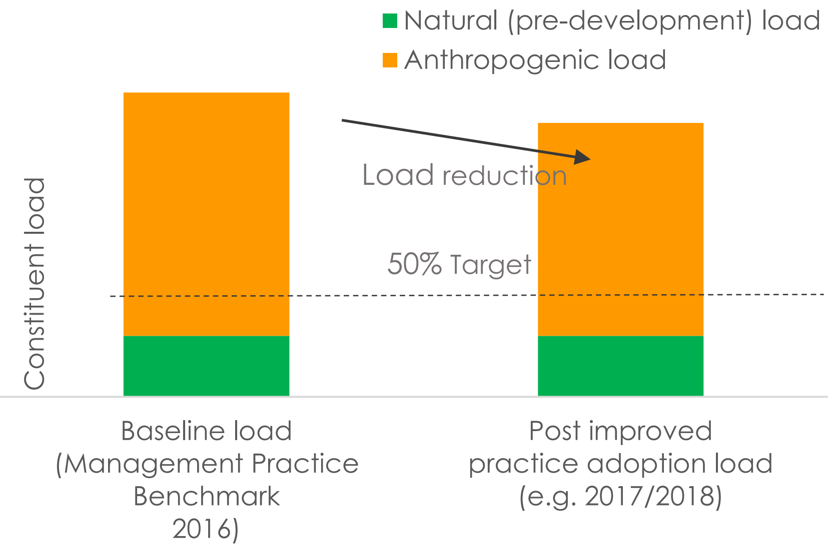

Figure 2: Example of modelled pre-development and anthropogenic pollutant loads, and the load reduction following investment in improved management practices.

Modelling improvements

In response to the independent external review of the program in 2015 and 2019, and recommendations from the Queensland Audit Office and the Great Barrier Reef Water Science Taskforce (GBRWST, 2016), improvements include:

- A desktop and field gully mapping program continues to improve the spatial representation of gully density and geometry in the models. Updated gully maps have been incorporated for selected areas within the Fitzroy region
- Annual monitoring/modelling validation workshops are held to compare model performance against monitoring data
- Updated land use mapping incorporated for the Fitzroy, Burdekin and Burnett Mary regions
- Research into parameter sensitivity/uncertainty in modelled inputs and outputs is continuing to guide future data collection and provide estimates of load uncertainty.

How the information is reported

Progress towards the targets is estimated by determining how much the modelled pollutant load has reduced from the average annual modelled anthropogenic baseline (total load less the pre-development load). This is calculated as a percentage reduction in average annual modelled load.

The average annual percentage reduction in load is calculated as:

$$\text{Reduction in load (\%)} = \frac{\text{(anthropogenic baseline load – anthropogenic change) x 100}}{\text{Anthropogenic baseline load}}$$

where, anthropogenic baseline load = total load less pre-development load

Modelled TSS, DIN, PN and PP at the end of the catchment are reported for the total Great Barrier Reef catchment, six regions and 35 sub-catchments.

Semiquantitative confidence ranking

Dissolved inorganic nitrogen	Particulate nitrogen	Particulate phosphorus	Sediment
●●○○○	●●●○○	●●●○○	●●●○○

A multi-criteria analysis was used to score the confidence in each indicator used in the report card, from low to high. The approach combined expert opinion and direct measures of error for program components, where available.

Sediment and particulate nutrients scored higher for confidence as the modelling for these parameters is based on well-established methods, particularly for hillslope erosion processes. Models are validated with data from more than 43 catchment loads monitoring sites and modelled relationships are based on published data from historic and ongoing research. Extensive gully mapping underpins the sediment modelling. The models undergo numerous quality assurance checks and research is currently underway to measure and report uncertainty within the models.

Dissolved inorganic nitrogen scored lower for confidence as the way in which nitrogen changes form as it moves from paddock to the Great Barrier Reef is more complex to represent within the modelling framework.

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Glossary

ANNEX: Annual Network Nutrient Export model is a static model that predicts the average annual loads of phosphorus and nitrogen in each link in a river network.

APSIM: Agricultural Production Systems sIMulator.

Agricultural land management practice adoption program: A component of the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program which develops rigorous estimates of management practice adoption and annual management practice change for the major agricultural industries of the Great Barrier Reef catchments: sugarcane, grazing, horticulture, grains and bananas.

Sediment: Sediments in water include clay, silt, sand and coarser particulate material, and are referred to as 'total suspended solids' (this is how they are measured in the water column) or 'total suspended sediment'. Sediments are characterised by different particle sizes. Not all sediment or particle size fractions present the same risk to the Great Barrier Reef, with **fine** (<20μm) **sediment** moving furthest into the marine environment, leading to increased turbidity and reduced light and, therefore, posing the greatest risk.

GRASP: Soil water pasture growth model.

HowLeaky: Agricultural system water balance and crop growth model based on PERFECT.

USLE: Universal Soil Loss Equation.

C-factor: Cover management factor (**C**) in the USLE that represents effects of vegetation and other land covers.

SedNet: Sediment River Network Model used to determine catchment sediment yields and sediment sources.

Australian Government

Queensland Government

Great Barrier Reef Marine Monitoring Program Methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

Citation

Australian and Queensland governments, 2024, Marine Monitoring Program Methods. Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

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Marine monitoring methods

This report summarises the coral and seagrass data and methods used for monitoring and reporting within the Great Barrier Reef Marine Monitoring Program (MMP) managed by the Great Barrier Reef Marine Park Authority and reported in the Reef Water Quality Report Card 2021 and 2022. Detailed methods are available in the Marine Monitoring Program annual technical report series that undergo independent peer review before being published in the Great Barrier Reef Marine Park Authority's eLibrary.

The Marine Monitoring Program was established in 2005 and assesses trends in ecosystem health and resilience indicators for the inshore Great Barrier Reef in relation to water quality and its linkages to end-of-catchment pollutant loads. The inshore Marine Monitoring Program has three sub-components:

Water quality (Moran *et al.* 2023);

Seagrass condition (McKenzie et al. 2023); and

Coral reef condition (Thompson *et al.* 2023).

The Marine Monitoring Program is one line of evidence describing the condition and trend of key coral reef and seagrass meadows used to report progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) (Australia and Queensland governments 2018) 2025 water quality outcome:

Good water quality sustains the outstanding universal value of the Great Barrier Reef, builds resilience, improves ecosystem health and benefits communities.

The Marine Monitoring Program objectives are:

Assess temporal and spatial trends in inshore marine water quality and link pollutant concentrations to end-of-catchment loads.

Monitor, assess and report the condition and trend of inshore coral reefs in relation to the extent, frequency and intensity of acute and chronic impacts.

Monitor, assess and report the condition and trend of inshore seagrass meadows in relation to the extent, frequency and intensity of acute and chronic impacts.

Since the 2015-2016 water year, the Reef Water Quality Report Card marine result has been based on averaging the scores for water quality from the eReefs model output (Robillot et al. 2018) with scores for coral and seagrass condition from the Marine Monitoring Program.

The inshore water quality component of the Marine Monitoring Program provides data on physico-chemical water quality parameters including nutrients and sediment concentrations in four Natural Resource Management (NRM) regions, and wet season flood plume exposure and risk to marine communities. Details are not provided in this report and can be found in the annual technical report for inshore water quality (Moran *et al.* 2023).

Seagrass condition

Approximately 77% of the Reef seagrass meadows occur in the inshore water body (Moran et al 2023). Seagrasses are fundamental to fisheries productivity and the main food source of dugongs and turtles. Monitoring was conducted at 75 sites across 35 locations during the 2021-22 monitoring period, (McKenzie et al. 2023) (see Figure 1). Five major seagrass habitat types (estuarine, coastal intertidal, coastal subtidal, reef intertidal and reef subtidal) are assessed where possible

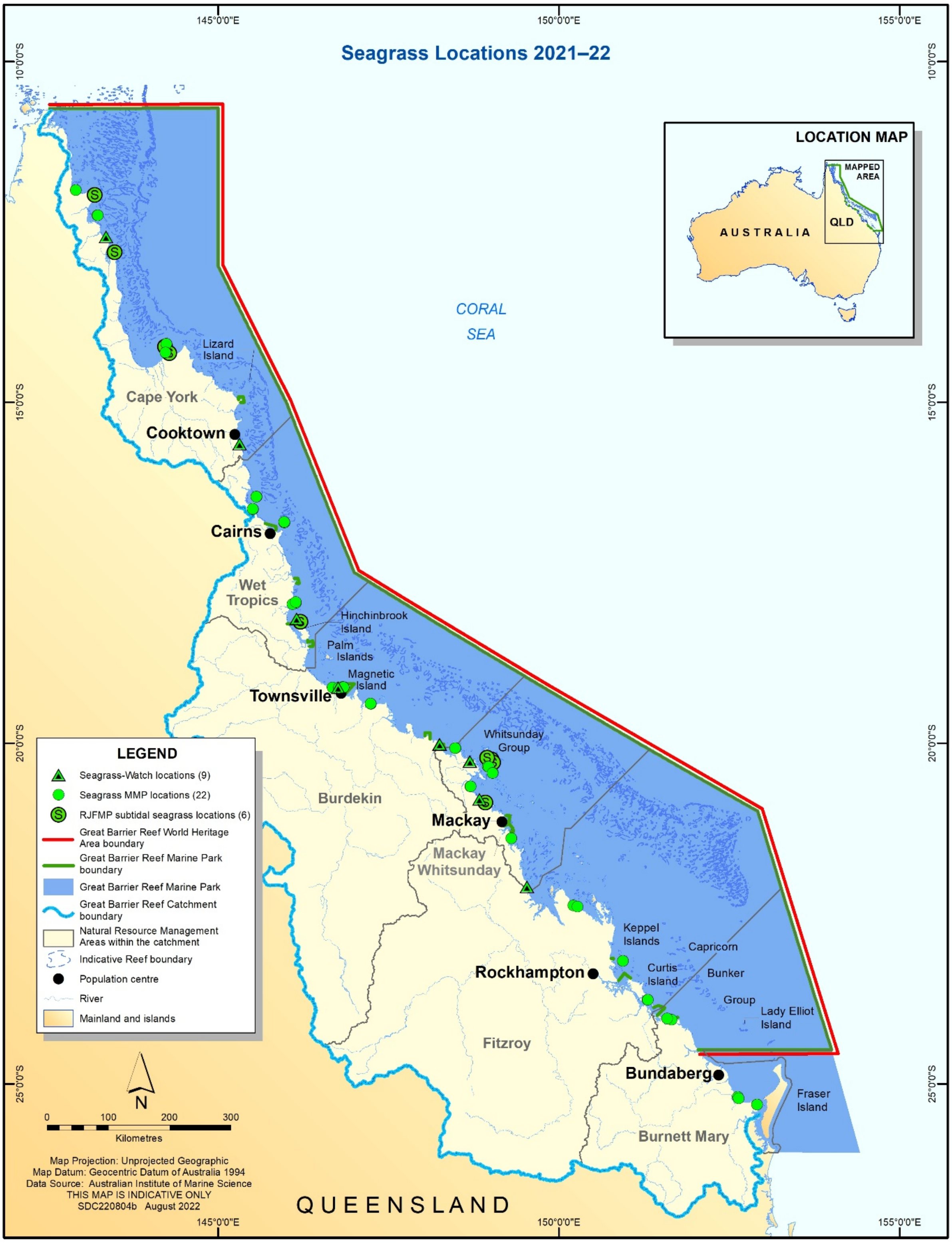

Figure 1. Marine Monitoring Program seagrass survey locations

(including Reef Joint Field Management Team and Seagrass-Watch). *Not all sites are surveyed every year.* Source: (McKenzie et al. 2023).

Sampling was undertaken at fifteen coastal, four estuarine and twelve reef locations (i.e. two or three sites at each location). Reef intertidal sites in the Burdekin and Wet Tropics were paired with a subtidal site. At each location, with the exception of subtidal sites, sampling included two sites nested within 500m of each other. Subtidal sites were not always replicated within locations. Intertidal sites were defined as a 5.5ha area within a relatively homogenous section of a representative seagrass community/meadow. Monitoring occurred in the late dry season (September-November 2021) and late wet season (March-May 2022).

Two indicators were assessed:

- Seagrass abundance (per cent cover) is an assessment of the average per cent cover of seagrass at a monitoring site in relation to the Seagrass Abundance Guidelines (McKenzie 2009)
- The resilience indicator takes a subset of measurable characteristics for which long-term data is available to develop a score and includes seagrass meadow species composition, relative abundance and reproductive status, and was backdated to 2005. The resilience score was determined using a multi-faceted resilience metric informed by existing metrics, historical data, and a conceptual understanding of resilience. Resilience can be considered as having two main elements (e.g. Timpane-Padgham et al. 2017; Connolly et al. 2018): an ability to resist disturbance; and the capacity to recover from disturbances. A decision tree approach was developed, which includes thresholds defining the splits, and methods for calculating scores. The methods used to arrive at each step are outlined in detail in Collier et al. (2021), and describe the following two components working both individually and in collaboration to provide the best estimate of resilience:
    - a ‘resistance’ component that assesses the seagrass meadow capacity to cope with disturbance based on their seagrass abundance and species composition. A low resistance site is one that has very low abundance based on the history of that site and/or has a high proportion of colonising species. These meadows are considered to be highly vulnerable to disturbances and, therefore, to have very low resilience.
    - a ‘reproduction' component that is based around likelihood of producing seed banks given the presence and count of reproductive structures. These are scored based on the levels of expected reproductive effort given the life history strategy of the species present. For example, some ‘persistent’ species such as *Thalassia* are not expected to have a high number of reproductive structures, and nor does it depend on them quite as much for long-term survival compared to ‘colonising’ species.

Additional indicators of seagrass condition and resilience include species composition, relative meadow extent and density of seeds in the seed bank (McKenzie *et al.* 2023).

Environmental pressures are also recorded including within-canopy water temperature, within-canopy benthic light, sediment composition as well as macroalgae and epiphyte abundance.

- Within-canopy benthic light is compared to long-term recorded light levels at individual sites as well as daily light thresholds likely to support long-term growth requirements of the species in these habitats (Collier *et al.* 2016)
- Within-canopy temperature is considered in context of the number of days above 35°C. Growth reduction can occur in some species from prolonged warm water exposure (Collier *et al.* 2011; Collier *et al.* 2016). The critical canopy temperature threshold for photoinhibition and acute temperature stress for seagrass is 40°C (Campbell *et al.* 2006)
- Changes in sediment composition can be an indicator of broader environmental changes (such as sediment and organic matter loads and risk of anoxia) and an early-warning indicator of changing species composition.

Additional data on climate and water quality is obtained from the Bureau of Meteorology and from the Marine Monitoring Program inshore water quality component (Moran *et al.* 2023).

Coral reef condition

Coral reefs comprise 7% of total area of the Great Barrier Reef Marine Park, 3.6% of coral reefs are in the inshore water body.

Monitoring of inshore coral reef communities occurs routinely in the dry season at reefs adjacent to four regions: Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy (see Figure 2). No reefs are included in Cape York due to logistic and occupational health and safety issues relating to diving in coastal waters in this region.

Thirty reefs are monitored biennially at two depths under the program, with an additional six inshore reefs monitored at single depths under the Australian Institute of Marine Science – Long Term Monitoring Program. All are included in the annual assessment of coral condition, although not all reefs are sampled every year (Thompson *et al.* 2023).

Figure 2: Marine Monitoring Program coral survey locations. Reefs were scheduled to be monitored biennially. Purple dots indicate locations monitored as part of the Long Term Monitoring Program conducted by the Australian Institute of Marine Science. Source: (Thompson *et al.* 2023).

Two sites at each reef are permanently marked with fence posts at the beginning of five, 20m-long transects with smaller steel rods at the midpoint and end of each transect. Monitoring is conducted by divers along these transects. They assess community attributes including hard and soft coral cover, the number of hard coral juvenile colonies (up to 5cm in diameter), proportion (per cent) of macroalgae cover, rate of change in coral cover (as an indication of the recovery potential of the reef following a disturbance) and coral community composition (Thompson *et al.* 2023).

Assessing status against the objectives

Improved seagrass condition

Seagrass indicators were changed for reporting in 2021, with tissue nutrient status being removed, abundance remaining and reproductive effort being calculated as part of a new resilience decision-making tree and relevant resilience indicator, backdated to 2005. This change was driven by scientific concern about the Great Barrier Reef's seagrass meadow resilience, and the lack of specific relevance of the tissue nutrient status indicator with the need to develop a more representative metric for management purposes.

Resilience can be described as the capacity of an ecosystem to cope with disturbance (Connolly *et al.* 2018), and to adapt to change without switching to an alternative state (Holling 1973; Unsworth *et al.* 2015). For monitoring and reporting, *'a set of measurable biological characteristics that exemplify seagrass meadows' resistance to pressures and essential mechanisms for recover'* are required to assess resilience (Udy *et al.* 2018).

Hence, two indicators are used to assess and report inshore seagrass condition: abundance, and resilience. Further detail about the selection and scoring of these indicators is available in the annual technical report (McKenzie *et al.* 2023).

The overall grade is the average of the scores of the two indicators for the monitoring year (colour-graded coaster) for the inshore Reef and regions. To calculate the overall score for seagrass, the regional scores were weighted by the relative proportion of World Heritage Area seagrass (shallower than 15m) within that region (see Table 1).

*Table 1: Area of seagrass shallower than 15m in each region within the boundaries of the Great Barrier Reef World Heritage Area**

Region	Area of seagrass (km^2)	Weighting factor (per cent)
Cape York	2,078	60
Wet Tropics	207	6
Burdekin	587	17
Mackay Whitsunday	215	6
Fitzroy	257	7
Burnett Mary	120	3
World Heritage Area	3,464	100

* Derived from (McKenzie, Yoshida, Grech *et al.* 2014; McKenzie, Yoshida, and Unsworth 2014; Carter *et al.* 2016; Waterhouse *et al.* 2016).

The online Report Card also shows a graph of the abundance indicator over time (dark blue circles) for the inshore Reef and regions.

Improved coral condition

Five indicators are used to assess and report on inshore coral reef condition: coral cover, coral cover change, juvenile coral density, coral community composition and proportional macroalgae cover.

Further detail about the selection and scoring of these indicators is available in the annual technical report (Thompson *et al.* 2023).

The overall grade is the average of the scores of the five indicators for the monitoring year (colour-graded coaster) for the inshore Reef and regions. To calculate the overall score for coral, the regional scores were weighted by the relative proportion of the total inshore Reef area in the Great Barrier Reef Marine Park that is represented by each of the four monitored regions (see Table 2).

*Table 2: Area of inshore reef in each region within the Marine Park**

Region	Area of inshore reef (km^2)	Weighting factor (per cent)
Cape York	265	
Wet Tropics	64	20.9
Burdekin	28	9.2
Mackay Whitsunday	117	38.1
Fitzroy	98	31.8
Burnett Mary	5	
Marine Park	577	100

* Area statistics supplied by the Authority's Spatial Data Centre, 2011

The online Report Card also shows a graph of the coral cover indicator over time (light blue circles) for the inshore Reef and regions.

Synthesis and integration of data and information

The Reef Water Quality Report Card 2021 and 2022 provides scores for the condition of inshore water quality, seagrass and coral at Great Barrier Reef-wide and regional scales.

Reef-wide and regional marine scores are unweighted averages of these three indicator scores.

The Marine Monitoring Program provides the coral and seagrass scores, based on annual technical reports published in the Great Barrier Reef Marine Park Authority's eLibrary.

The eReefs Marine Modelling Program provides the water quality metric for the inshore Reef score based on open coastal waters (Robillot *et al.* 2018).

Semiquantitative confidence rankings

A multi-criteria analysis was used to score the confidence in each indicator used in the report card from low to high. The approach combined expert opinion and direct measures of error for program components where available. Seagrass and coral both received a four-dot confidence ranking (see Figure 3).

Seagrass	Coral
Data confidence	Data confidence
●●●●○	●●●●○

Figure 3: Semiquantitative confidence rankings for seagrass and coral scores. Source: Refer to Appendix A.

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Appendix A: Derivation of confidence ranking

A multi-criteria analysis approach was endorsed by the Independent Science Panel in July 2016 and used to score the confidence for each key indicator used in the report card. The approach enables the use of expert opinion and measured data.

A multi-criteria analysis identifies the key components that contribute to a problem. These are known as criteria. Each criterion is then scored using a defined set of scoring attributes. If the criteria are seen to have different levels of importance for the problem being addressed, they can be weighted accordingly. The strengths of this approach are that it is repeatable, transparent and can include contributions from a range of sources.

The determination of confidence for the report card used five criteria:

Maturity of methodology (the score is weighted half for these criteria so not to outweigh the importance of the other criteria)

Validation

Representativeness

Directness

Measured error

Seagrass

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Survey with no ground truthing	Less than 10% of population survey data	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	Survey with ground-truthing (not comprehensive)	**10%-30% of population survey data**	Measurement of data that have a quantifiable relationship to reported indicators	**10-25% error**
Established methodology in published paper	**Survey with extensive on ground validation or directly measured data**	30-50% of population	**Direct measurement of reported indicator with error**	Less than 10% error
3 x0.5 = 1.5	3	2	3	2

Bolded and grey shading in cells indicates assessment ranking. Total score = 11.5, equates to **Four dots**.

Coral

Maturity of methodology (weighting 0.5)	Validation	Representativeness	Directness	Measured error
New or experimental methodology	Survey with no ground truthing	Less than 10% of population survey data	Measurement of data that have conceptual relationship to reported indicator	Error not measured or >25% error
Peer reviewed method	Survey with ground-truthing (not comprehensive)	**10%-30% of population survey data**	Measurement of data that have a quantifiable relationship to reported indicators	**10-25% error**
Established methodology in published paper	**Survey with extensive on ground validation or directly measured data**	30-50% of population	**Direct measurement of reported indicator with error**	Less than 10% error
3 x0.5 = 1.5	3	2	3	2

Bolded and grey shading in cells indicates assessment ranking. Total score = 11.5, equates to **Four dots**.

Glossary

Ecosystem: dynamic complex of plant, animal and microorganism communities and their non-living environment interacting as a functional unit.

Ecosystem health: ecological processes, biodiversity and function of biological communities is maintained.

eReefs: coupled hydrodynamic and biogeochemical models of water quality and ecosystem condition for the Marine Park <https://research.csiro.au/ereefs/models/>.

Guideline value: a measurable quantity (e.g. concentration) or condition of an indicator for a specific community value below which (or above which, in the case of stressors) there is considered to be a low risk of unacceptable effects occurring to that community value.

Inshore: the enclosed coastal and open coastal water bodies combined. These terms are defined and mapped under schedules in the Environmental Protection (Water) Policy.

Marine Park: Great Barrier Reef Marine Park.

Pollutant: a substance that is present in concentrations that may harm organisms or exceed an environmental quality standard. In this program, the term refers primarily to nutrients, sediment and pesticides.

Reef 2050 WQIP: Reef 2050 Water Quality Improvement Plan.

Reef 2050 Plan: Reef 2050 Long-Term Sustainability Plan.

Australian Government

Queensland Government

Marine modelling methods

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

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Citation

Australian and Queensland governments, 2024, Marine modelling methods, Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

Contents

Marine modelling methods

The Marine Modelling Program (Waterhouse et al. 2018) directly supports the 2050 outcome of the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP) (Australia and Queensland governments), which states:

“Good water quality sustains the outstanding universal value of the Great Barrier Reef (GBR), builds resilience, improves ecosystem health and benefits communities.”

The Marine Modelling Program was established in 2016 to:

- Assess trends in ecosystem health for the Great Barrier Reef in relation to water quality and its linkages to end-of-catchment loads by predicting, assessing and reporting trends in inshore water clarity (secchi depth) and concentrations of chlorophyll *a*
- Predict physical and biogeochemical properties of Reef waters under a range of scenarios to assess the impact of management practices and contribute to the establishment or review of basin-level water quality targets
- Support regional and whole-of-Great Barrier Reef water quality risk assessments by predicting the impact of rivers on the Great Barrier Reef waters under a range of conditions.

Given the scale of the Great Barrier Reef, it is impractical to measure and report water quality through the entire area and at a reasonable frequency using monitoring data alone. Satellite imaging is employed for extensive spatial coverage but can be less accurate in shallow areas and susceptible to seasonal influences such as cloud cover and smoke haze. Consequently, the eReefs marine modelling framework combines monitored data and satellite observations to extend water quality assessments across the entirety of the Great Barrier Reef. This eReefs marine model framework is used to derive the GBR marine water quality metric.

Marine models which integrate physical processes and ecosystem responses play an integral part in supporting resilience-based management and linking science and observations to policy and decision making.

In this context, the marine component of eReefs delivers and operates numerical models capable of simulating and predicting the physical hydrodynamic state, sediment transport, water quality and basal ecology of the Great Barrier Reef lagoon <https://research.csiro.au/ereefs/models/>. Together, these models provide the ability to simulate the transport and fate of waterborne material, from the ocean or land, and assess its impact on Reef water quality (Skerratt et al., 2019a).

In 2015-2016, as part of National Environmental Science Programme (NESP) Project 3.2.5, eReefs models were used for the first time to report on chlorophyll *a* (productivity linked to nutrient concentrations) and Secchi depth (proxy for water clarity and presence of fine sediments) across the entire Great Barrier Reef (Robillot et al., 2018). These measures underpinned a new water quality metric for the Reef water quality report cards. The metric considered all six regions in calculating the Reef-wide score and is based on open coastal waters. The approach to calculating Reef water quality indices and overall scores was independently peer-reviewed as part of NESP Project 3.2.5.

The metric is underpinned by the eReefs biogeochemical model and integrates multi spectral data from Sentinel 3a/b, and VIIRS for improved accuracy in what is commonly referred to as data assimilation (Baird et al., 2016, Jones et al., 2016). The eReefs marine model has also been used to determine various scenario catchment loads impacts on marine water quality in the GBR (Baird et al 2021) and 67 papers have been published using the eReefs model water quality outputs since the establishment of the 2016 marine modelling program.

The eReefs model has been assessed extensively against *in situ* observations with detailed assessment findings available in the previous technical assessment of the eReefs biogeochemical simulation against observations (Skerratt and Mongin 2023 and Skerratt et al. (2019) (B2p0) and Skerratt et al., 2019 (B3p0).)

This report describes the methods and changes to the eReefs model reanalysis simulation used to generate the marine water quality metric for the period 1 October 2020 to 30th September 2022 (water year 2020-2022).

In this report we present the results of the Reanalysis of the 4 km resolution coupled hydrodynamic – biogeochemical model for the period Oct 1, 2020 – Sep 30, 2022 (designated gbr4_H3p5_BARRAr2_BRAN2020_G2G_B4p1_Cq4b_rean). A brief description of the modelling system is given, with an emphasis on changes since the previous year's report card simulations (Report Card 2020; Table 1).

Table 1 Report Card numbering and water years.

	YEARS DOCUMENTED	YEAR REPORT PUBLISHED
Report Card 2016	Oct 1, 2015 – 30 Sep 2016	2017
Report Card 2017 and 2018 (2 years)	Oct 1, 2016 – 30 Sep 2018	2019
Report Card 2019	Oct 1, 2018 – 30 Sep 2019	2020
Report Card 2020	Oct 1, 2019 – 30 Sep 2020	2022
Report Card 2021 and 2022 (2 years)	Oct 1, 2020– 30 Sep 2022	2024

eReefs coupled hydrodynamic biogeochemical model

Water quality on the GBR is driven by meteorological factors such as winds, waves, and solar radiation, as well as large-scale ocean currents and nutrient and sediment loads from the catchments. In order to accurately model water quality, a comprehensive approach is therefore needed. This involves using a coupled catchment-hydrodynamic-biogeochemical model that is driven by global atmospheric and ocean models. The eReefs Project, developed collaboratively by CSIRO, DESI, AIMS, and BoM, provides such a model (Figure 1). This integrated system allows for a more holistic understanding of water quality dynamics.

The eReefs coupled hydrodynamic, sediment and biogeochemical modelling system involves the application of a range of physical, chemical and biological process descriptions to quantify the rate of change of physical and biological variables.

The process descriptions are generally based either on a fundamental understanding of processes or on actual measurements when a specific process was able to be isolated and studied. The model also requires external inputs, such as observed river flows and pollutant loads (Figure 1 and 2).

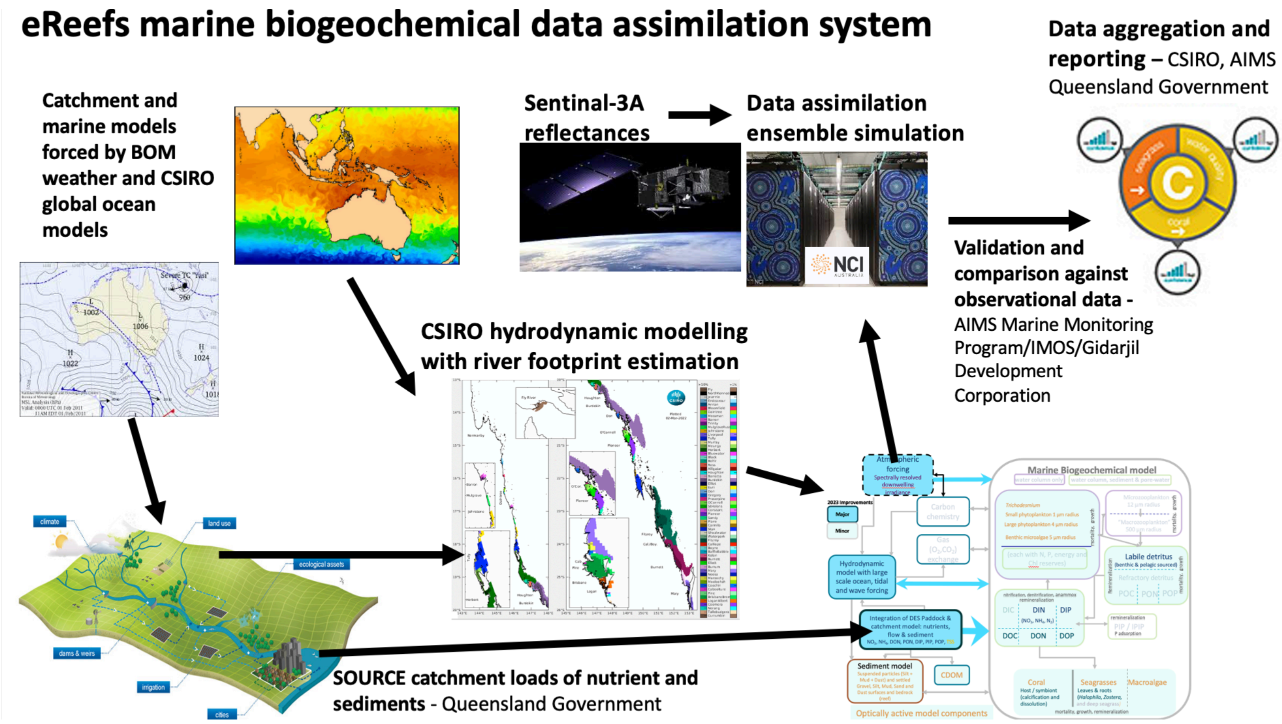

Figure 1 Schematic of the eReefs marine modelling system illustrating the modelling and observational products that are assembled to generate the data assimilating ensemble simulations that are implemented on the National Computing Infrastructure and aggregated to form the Report

Card scores. Enlargement of BGC model in figure 2 dark blue with dark blue arrows showing major process improvements and minor improvements shaded in light blue.

The four main components of the marine model described in more detail later in the report are:

- The hydrodynamic 3-D model based on Herzfeld, 2006 and 2015 which now incorporates improved oceanic and atmospheric forcing and increased river boundaries (Langlais, 2023)

- The sediment transport model, which is a multilayer sediment bed to the hydrodynamic model grid and simulates sinking, deposition and resuspension of multiple size classes of suspended sediment (Margvelashvili, 2009, Margvelashvili et al., 2016)

- The biogeochemical model, which simulates optical, nutrient, plankton, benthic organisms (seagrass, macroalgae and coral), detritus, chemical and sediment dynamics across the whole GBR region, spanning estuarine systems to offshore reefs (Baird et al., 2020) Figure 2)

- The data assimilating biogeochemical model which incorporates remote sensing observations into the marine biogeochemical model to produce the BGC reanalysis (described below).

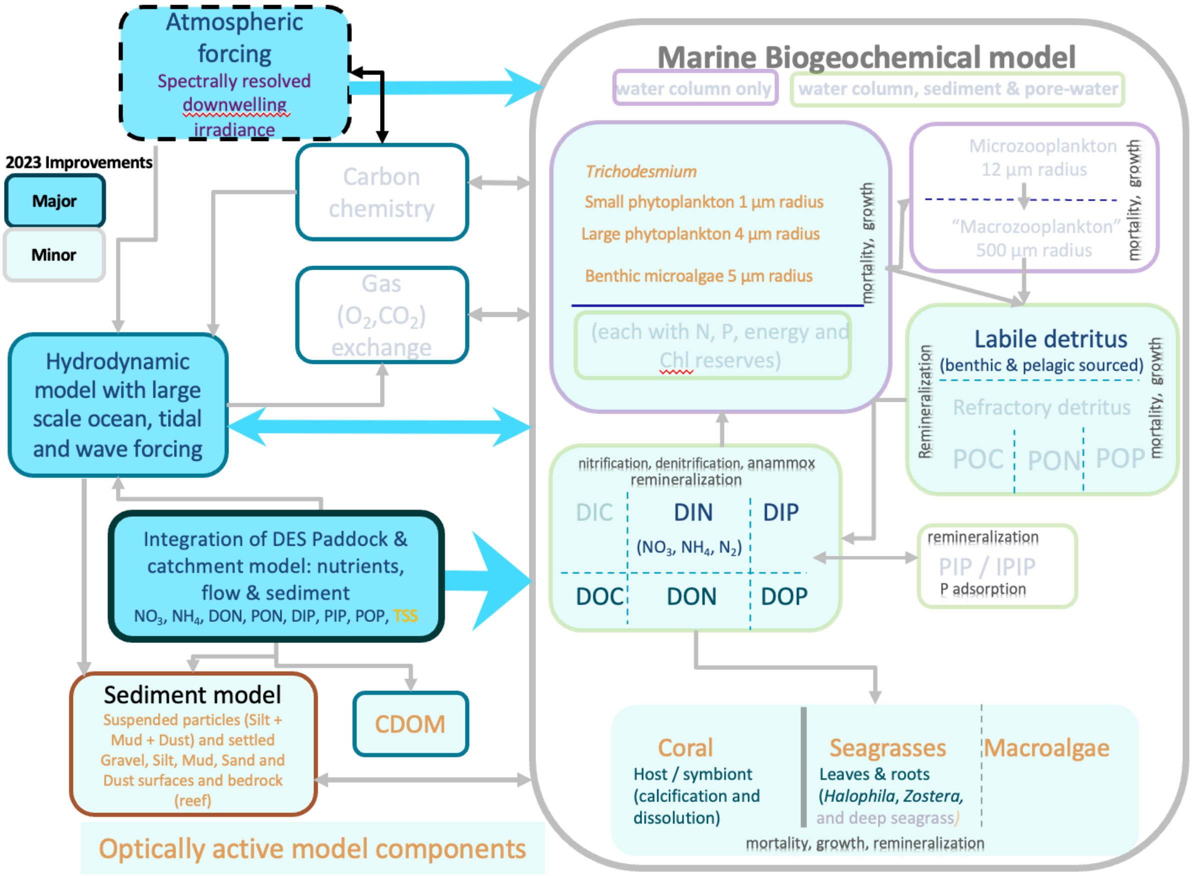

Figure 2. The eReefs marine biogeochemical model conceptual framework with major improvements for this report card shaded in dark blue with dark blue arrows showing major process improvements and minor improvements shaded in light blue. Orange variables are optically active (i.e., either scatter or absorb light) this allows the model to make use of and incorporate remote sensing data.

Briefly, the biogeochemical model considers four groups of microalgae (small and large phytoplankton, *Trichodesmium* and microphytobenthos), two zooplankton groups, four macrophytes (seagrass types corresponding to *Zostera sp.*, two *Halophila sp.* types, and macroalgae) and coral communities.

Photosynthetic growth is determined by concentrations of dissolved nutrients (nitrogen and phosphorus) and photosynthetically active radiation. Overall, the model contains 23 optically active constituents (Baird et al., 2016, 2020). The biogeochemistry model also considers ultrafine sediment particles and their impact on matters such as water clarity (Baird et al., 2020).

The model is currently forced with freshwater inputs from rivers along the GBR that enter at the river mouths (Figure 3). River flows for 67 rivers are obtained from The Bureau of Meteorology (BOM) Grid to grid (G2G) model. There are an additional 44 rivers entering as point sources along the coast (i.e. fluxes with load but no flow). The nutrient and sediment loads for all 109 rivers (and 4 river flows for Cape York region) are from the SOURCE catchment model through the Queensland Department of Environment, Science and Innovation (DESI), and the Queensland Department of Resources. For rivers outside the GBR region flows are from the gauging stations supplied by the above QLD department's gauging network. Nutrient concentrations flowing in from the ocean are obtained from the CSIRO Atlas of Regional Seas (CARS) 2009 climatology (Ridgway et al., 2002). 90% of nutrient and sediment loads are delivered with flow and the remaining 10% are as fluxes.

Figure 3 River entrances in blue along the GBR with marine monitoring sites used to compare and validate the marine model in black. Outline of GBR1 and the GBR World Heritage Area shown in blue and hashed respectively. Coral mapping in brown. The 6 NRM (land) catchment areas shown as outlines.

River pollutant loads were obtained from the SOURCE catchments modelling outputs (Ellis and Searle, 2013) up to 1st November 2022 (Figure 3). These provide daily time series prediction of pollutant loads past 30 April 2020, pollutant generation models are used that estimate daily loads through varying monthly concentrations. These monthly concentration outputs allow the model predictions to be extended by providing daily rainfall run-off model inputs (i.e., the run-off of the day), without the need to update many thousands of farm scale sub-models.

Data assimilation/Reanalysis

The eReefs model can be run without ingesting observations from the marine environment, which is referred to as a non-assimilating simulation. However, optimally configured data assimilation systems provide the best estimate of the biogeochemical state of the Reef by combining model predictions with observations (Jones et al., 2016). The assimilation of observations improves the model's predictive skill (Skerratt et al., 2019). Data assimilation methods can be thought of as using a model to dynamically interpolate between observations.

For shallow inshore waters, using remote sensing observations to estimate in-water properties is challenging due to the interactions between chlorophyll *a*, sediment, coloured dissolved organic matter and benthic communities, which all absorb and scatter light in the blue, green and red wavebands. Instead of using remote sensing to estimate in-water properties, the water quality metric is based on the optical calculations of the biogeochemical model, which simulates the normalised remote-sensing reflectance. The data assimilation system uses the mismatch between observed and modelled remote-sensing reflectance to constrain the biogeochemical model (Jones et al., 2016).

The use of data assimilating biogeochemical models to quantify the state of marine ecosystems is becoming an important management tool globally (Jones et al., 2016; Fennel et al., 2019). The eReefs Project has developed a sophisticated data assimilating system (Figure 1) based on the eReefs 4 km configuration of a coupled hydrodynamic - biogeochemical model. The output of such a data assimilating system is described as a **reanalysis**. A biogeochemical reanalysis was used to estimate spatially and temporally resolved water quality properties for the previous Great Barrier Reef (GBR) Water Quality Report Cards (Robillot et al., 2018, Baird et al, 2020). For naming see Table 1.

For the GBR, only remote sensing platforms provide the density of observations required to undertake a large-scale data assimilation (see <eReefs home page | eReefs>). The data assimilation system combines model simulations with data obtained from the European Space Agency (ESA) Sentinel-3A and 3B ocean colour sensors and Visible Infrared Imaging Radiometer Suite (VIIRS) sensors (Figure 1). Specifically, the data assimilation system uses the mismatch between satellite-derived remote-sensing reflectance and the simulated remote-sensing reflectance in a 100-member ensemble of simulations to alter the state of the biogeochemical model ensemble thus providing a better estimate of water quality than can be obtained from either models or observations alone.

The dynamic 100 member ensemble is then sub-sampled by selecting all members that have a lower independently calculated (i.e. observations that are not assimilated), in-situ root mean square (RMS) and Bias than the non-assimilating control run. In this case 21 members were used. The estimate of the biogeochemical state used in the report card is the mean of these 21 members. While the model assimilates ocean colour data from satellite, it is independently assessed against the *in situ* observations of chlorophyll *a* concentration, from which the skill of the system can be quantified.

For more information on the eReefs simulations see biogeochemical -simulation naming protocol (https://research.csiro.au/ereefs/models/models-about/biogeochemical-simulation-naming-protocol/)

The data assimilation technique used in this report is described as an Ensemble Kalman Filter (EnKF). We utilized a 100-member ensemble, which was informed by observed ocean colour data collected by the Sentinel-3A/B and VIIRS satellites. The system is described in detail in Jones et al. (2016). When the ocean colour data is assimilated, it means that the data is incorporated or ingested into the model. In this case, the model incorporates the ocean colour data from satellite observations to update and adjust the relevant variables in order to improve the accuracy of the model's predictions. The model adjusts several optically active in situ variables, including phytoplankton concentration, in all the ensemble members in a way that aligns with the internal properties of the biogeochemical model. The model's performance was then evaluated against in situ observations of chlorophyll concentration (monitored water samples and sensor networks), which allowed us to quantify the system's accuracy.

River exposure

The calculation of river footprints is not required for the biogeochemical data assimilation but is used in this report to explain the model behaviour. The calculation of river footprints is explained in detail in Baird et al. (2017) and Skerratt et al (2023) and river footprint examples are shown in Figure 1.

In this modelling approach, each river flow is assumed to have a unit concentration, for example a concentration of 100%. This assumption allows for a proportional relationship between the flow of each river and the corresponding pollutant load. The outflow from the rivers is then transported and dispersed by the hydrodynamic model. For instance, the example of a mid-shelf grid cell with concentrations of Burdekin = 7 and Haughton = 2 while all other river tracers are negligible. This indicates that 7% of the water in that cell at that time entered the model through the Burdekin River, and 2% entered through the Haughton River since the start of the simulation. The remaining 91% represents ocean water, either because it originated in the ocean at the beginning of the simulation or entered through offshore ocean boundaries.

The river plume extents predicted from Jan 1, 2011 to 2022 are given here.

Major improvements in the eReefs marine model system 2023

The eReefs coupled hydrodynamic-biogeochemical model is a variant of the CSIRO Environmental Modelling Suite, which is utilized for various applications in fields such as Defence, Aquaculture, and Coastal Management (Baird et al., 2020, Steven et al., 2019). The model is regularly updated and improved both within the eReefs Project and from other applications (Figure 1 and 2).
Summary of relevant changes in the hydrodynamic model (Langlais 2023):

1. Increased coastal distribution for the 109 rivers along the coast.
2. Improved large-scale circulation for shelf break currents upwelling and chlorophyll signature.

Summary of relevant changes in the data assimilation system were:

1. Use of a revised 2023 SOURCE catchments run with updated catchment condition.
2. The input of an atmospheric source of dissolved inorganic phosphorus (DIP) at the Redfield ratio.
3. Improved the data assimilation system through:
    a. Addition of Sentinel 3B satellite data stream (Oct 2019 onwards)
    b. Updated version of EnKF-C data assimilation software (v2.4.0)
    c. Assimilation update vector limited to top 50 m and includes DIN, DIP, Large and Small Zooplankton biomass, and 3 sediment classes (mineral, carbonate and dust)
    d. Hybrid ensemble used to prevent ensemble collapse, requiring addition of 94 static members to the existing 100 dynamic members
    e. Simplified the (data assimilation) analysis step with an analytical expression to update the DIN and DIP nutrient field
    f. Run on a 2d cycle (previous reanalysis runs prior to 2023 used a 10d cycle).

Present reanalysed fields as the mean of the 21members [#0, 1, 3, 16, 23, 28, 31, 36, 42, 44, 45, 47, 48, 53, 57, 59, 70, 83, 91, 93, 94, 95] closest to the MMP in situ chlorophyll extractions.

How the metric is calculated, and information reported

The Reef water quality report card marine water quality metric is calculated as follows:

1. Chlorophyll *a* concentration and Secchi depth data are extracted from the assimilated eReefs biogeochemical model at a 4km spatial resolution and daily temporal resolution (midday snapshot) for the entire Reef

2. The data is partitioned temporally into water years (from 1 October to 30 September of the reporting year) and spatially into zones representing combinations of regions and cross-shelf water bodies (i.e. open coastal, mid-shelf and offshore waters; defined in GBRMPA, 2010). The enclosed coastal water body is excluded due to limitations associated with the 4 km model resolution near the coastline.

3. The site-level data (4 km x 4 km) for each of the three measures are standardised to indices on a continuous scale of zero (very poor) to 100 (very good). This is done by assessing individual values relative to the appropriate water quality guideline value according to a ‘modified amplitude indexation routine’ (fsMAMP: base 2 logarithm of the ratio of observed value to threshold)

4. Scores for each parameter are aggregated (averaged) temporally over the water year into annual scores and spatially in the open coastal reporting zone. The resulting scores for chlorophyll *a* and Secchi depth are then averaged to generate a single score for each region

5. A Reef score is calculated as the weighted (relative areas) average of regional scores

6. All reported scores are mapped onto a five-point (A–E) colour-coded grading scale (see Table 1).

Table 2: Marine water quality metric score to grade scale

Grade	Status	Range	Colour
E	Very poor	0–20	Red
D	Poor	21–40	Orange
C	Moderate	41–60	Yellow
B	Good	61–80	Light green
A	Very good	81–100	Dark green

Semiquantitative confidence ranking

Data confidence

●●●○○

A multi-criteria analysis was used to score the confidence in each indicator used in the report card, from low to high. The approach combined expert opinion and direct measures of error for program components where available. Marine modelling received a three-dot confidence ranking.

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Australian Government

Queensland Government

Human dimensions methods

Individual factors influencing agricultural management practice adoption

Reef Water Quality Report Card 2021 and 2022

Reef 2050 Water Quality Improvement Plan

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Citation

Australian and Queensland governments, 2024, Human dimensions methods - Individual factors influencing agricultural management practice adoption. Reef Water Quality Report Card 2021 and 2022, State of Queensland, Brisbane.

CONTENTS

Special thanks to Tracy Schultz, and the Human Dimensions Working Group for their valuable contributions in this Methods statement.

HUMAN DIMENSIONS: INDIVIDUAL FACTORS INFLUENCING AGRICULTURAL MANAGEMENT PRACTICE ADOPTION

This report summarises the method to collect, assess and report the individual factors that influence agricultural management practice adoption against the 2025 Human Dimensions target in the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP; Australian and Queensland governments 2018). The results of the 2020-2021 and 2021-2022 social monitoring data are outlined, and recommendations are made for the presentation format for these data.

Out of scope of this statement is the supporting communication regarding the release of this data which will be handled as part of the Reef Water Quality Report Card 2021 and 2022 communication strategy.

Background

Why monitor human dimensions?

The Reef 2050 WQIP recognises that a range of human dimensions (i.e., social, cultural, institutional, and economic factors) play a role in shaping outcomes associated with water quality and the Great Barrier Reef (Australian and Queensland governments 2018a pg. 20). The Scientific Consensus Statement 2017 also recognised that 'further consideration of economic and social dimensions is needed in the development and implementation of programs to improve water quality' (Waterhouse et al., 2017, p. 8). Further, achievement of the land management targets to improve the quality of water flowing to the Great Barrier Reef will only be delivered by supporting industries and communities to build a culture of innovation and environmental stewardship towards agricultural land management adoption (Australian and Queensland government 2018a, p. 7). Accordingly, the Reef 2050 WQIP set the human dimension target as follows:

- *Active engagement of communities and land managers in programs to improve water quality outcomes is increased.*

How do we monitor human dimensions?

The effectiveness of the Reef 2050 WQIP, including the human dimension target, is monitored and reported through the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Paddock to Reef program). The Paddock to Reef social monitoring survey was introduced in 2019, and the first year of data, collected from a suite of cane and grazing projects, is presented in the Reef Water Quality Report Card 2020.

The social monitoring data tracks responses regarding agricultural management practice adoption and identifies any trends evident over time that can both give context to and help inform and improve progress towards the land management and water quality targets of the Reef 2050 WQIP targets. Two subsequent years of data have been collected and results for cane and grazing projects will be presented in the Reef Water Quality Report Card 2021 and 2022. Additionally, there will be data presented from the social and economic long-term monitoring project (Hobman, et al., 2022) and regional report cards (Curnock, et al., 2022) expanding the picture of the agricultural industry and for the first time including the perceptions of residents of the Great Barrier Reef catchment.

The individual factors that influence agricultural management practice adoption

As the lead agency for developing a human dimension baseline, the Office of the Great Barrier Reef and World Heritage (OGBRWH), Department of Environment, Science and Innovation, funded a project to identify the human dimension indicators of agricultural innovation and stewardship behaviours (Hobman and Taylor, 2018). The project identified key 'themes' and social monitoring questions to include in the existing Paddock to Reef agricultural management practice adoption questionnaire for the cane, grazing, grains, horticulture and banana industries. These thematic variables (refer Table 1) demonstrated both strong conceptual validity and supporting empirical evidence.

Table 1. Identified themes that influence agricultural management practice adoption (Hobman and Taylor, 2018)

Theme	Description
Attitudes (towards the practice)	How attractive, beneficial/advantageous (relative to the current practice), and/or risky the practice is.
Perceived behavioural control	How easy or difficult it is to perform the practice (self-efficacy/capability), and whether it is within one's control (perceived control).
Perceived barriers (control beliefs)	The extent to which one perceives that certain barriers are impeding performance of the practice.
Motivation	How motivated one is to perform the practice, and whether this is for intrinsic or extrinsic reasons.
Behaviours (past and future)	Whether the practice (or precursor practices) has been used in the past, and whether there is a stated intention to trial or use certain practices in the future, in a particular situation, at a particular time.
Group norms	Whether other land managers/ farmers in the community (with whom one has strong ties) approve of and perform the practice themselves.
Trust	Level of trust in information sources and advice networks related to improved practices.
Cultural norms and artefacts	Community- and industry-level norms that encourage/facilitate innovation and stewardship practices.

Except for cultural norms and artefacts, the identified themes are classified as 'individual factors' that measure the human dimensions that directly influence land management practice adoption.

Methods

Practice change project social monitoring

The Paddock to Reef Integrated Monitoring, Modelling and Reporting Program: Program Design 2018-2022 (Australian and Queensland governments 2018b, p. 47-49) outlined a phased approach for the addition of questions that assess the social monitoring factors. The approach included development, testing and consultation in the 2022 Paddock to Reef program design review. The following section sets out the method for developing, testing and consulting on the social monitoring survey and it remains consistent with the method as presented for the 2020 report card.

Questions format and design

The themes identified by Hobman and Taylor (2018) were tested in a pilot project, with extensive stakeholder consultation to guide the format and design of Paddock to Reef social monitoring questions. The questions are intended to be asked of the same individual at two time points – prior to the practice change and after. In addition to the social monitoring questions, a project extension officer records:

- whether the survey is being completed before or after a practice change
- project ID - a unique identifier
- project description – ascribes the survey to a program/delivery agent

- specific Great Barrier Reef catchment
- specific agricultural commodity
- management practice - nominated practice (Table 2) the landholder is considering changing (at the commencement of the project) or has changed (at the end of the project).

Table 2. Agricultural management practice options for each commodity

Commodity	Management practice
Cane	• changing my fertiliser management • changing my soil management • changing my pesticide management • changing my irrigation management • becoming BMP accredited
Grazing	• changing my pasture management • changing the way I manage streambanks • changing the way I manage gullies
Grains	• changing my soil management • changing my fertiliser management • changing my pesticide management • becoming BMP accredited
Horticulture	• changing my soil management • changing my fertiliser management • changing my pesticide management • becoming BMP accredited
Bananas	• changing my soil management • changing my fertiliser management • changing my pesticide management • changing my irrigation management • having 60% covered ground, living or dead, • becoming BMP accredited

The nominated management practice is the focus for the remaining social monitoring questions. The management practice options for each commodity are based on the water quality risk frameworks. It is important to note that there can be a large variation in the individual practices that may fall under each management practice option. Landholders are asked to respond as follows:

Attitude. On a five-point scale (1 = strongly agree to 5 = strongly disagree, 'don't know' or 'decline to answer') to the statement *"I think this farming practice is a positive thing to do on my farm".*

Self-efficacy. On a five-point scale (1 = strongly agree to 5 = strongly disagree, 'don't know' or 'decline to answer') to the statement *"I feel that this farming practice is easy to do on my farm".*

Group norm. On a five-point scale (1 = strongly agree to 5 = strongly disagree, 'don't know' or 'decline to answer') to the statement *"Most farmers in my local area and industry have adopted this farming practice".*

Motivation. Select up to three (3) *"main reason/s for implementing this farming practice"*. The options are:

- I received government funding (e.g., a grant or incentive)
- It will increase profitability
- It will increase production
- To save time
- To save money
- To comply with regulations
- It will benefit local water quality
- It will benefit the environment

- For my family
- There are no reasons to change
- Other landholders in my area have adopted this practice
- I don't know/I need more information to answer this question
- I'd prefer not to answer
- Other (free response)

Barriers. Select up to three (3) *“main challenge/s in relation to implementing this farming practice”*. The options are:

- I am worried about a reduction in production
- I am worried about a reduction in profitability
- I do not have the time
- I need more information before I can make a change
- It costs too much
- I don't think it will make a positive water quality impact
- It is not the way I have managed my farm in the past
- Weather and seasonal issues
- I tried it before and I was not happy with the outcome
- Lack of family support
- I am constrained by the availability of contractors and/or contractors equipment
- There are no challenges/difficulties
- I'd prefer not to answer
- I don't know/I need more information to answer this question
- Other (free response)

Attribution. A free-response question, landholders are asked to list *“all people, projects, grants or events that have helped with or contributed to you adopting this farming practice”.*

Data privacy and informed consent

The program complies with the *Information Privacy Act 2009* and the privacy of the landholders completing the Paddock to Reef Management Practice Adoption questionnaire is protected. Social monitoring data is linked to de-identified management practice adoption data through a unique identifier (Project ID) created by the delivery agent. At no stage does the OGBRWH have access to, or receive, the ‘spatial layer’ data or any other identifying information.

Answering the social monitoring questions is voluntary for landholders and participation is initiated through an informed consent process. The delivery agent advises landholders of the data use and data management which ensures landholder privacy. An example of the statement provided to delivery agents for use in this process is provided in Appendix 1.

Data management

Social monitoring data from 2019 to the end of 2022 was collected and recorded using Survey123 for ArcGIS[1], an online platform for creating and collecting survey data. Data was downloaded from Survey123 and stored in secure server folders on password protected computers. The OGBRWH reviews the raw data, including:

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[1] Hard copies of surveys are provided to delivery agents at their request to aid in the collection of data with landholders, all collected data is to be recorded and transferred to Survey123 for ArcGIS and sent electronically to the OGBRWH for analysis and reporting purposes.

- Assessing and addressing data quality issues, including missing data and/or data handling errors
- Assessing that assumptions for data analysis have been met, including minimum sample sizes.

Program specific raw data is provided to delivery agents to cross-check quality. The ISP review the aggregated results for each program area prior to public release.

Social and economic long-term monitoring program and regional report cards

The Social and Economic Long-Term Monitoring Program (SELTMP) collects primary data on a subset of Great Barrier Reef (GBR) human dimension indicators relating to social, economic, cultural, and governance aspects of the GBR (Hobman, et al., 2022), as described within the Reef 2050 Long Term Sustainability Plan (Reef 2050 Plan, Australian & Queensland governments, 2021).

The construct that was selected to support Human Dimensions reporting from the SELTMP survey was 'Importance of GBR interventions' which presented a range of options and a ten-point scale from 1= not important at all to 10 = extremely important, with the option of 'I don't know/I am unsure'. The options included 'Improved land management to improve GBR water quality (i.e., efforts to reduce sediments, nutrients and pollution flowing into the sea)'.

The 2021 survey included for the first time, a subset of demographic questions that enabled identification of GBR residents who selected (from a list of options) their main work as being in the agricultural sector. Those who selected this option were then directed to two further questions; the first to select the agricultural commodity/ies farmed, and the second to identify which, if any, support programs they have participated in, or if they have improved practices without being in a program or have done nothing to reduce run-off from their farm.

The supporting SELTMP module for the Regional Report Cards of the Great Barrier Reef which focuses on human dimension indicators of waterway health (Curnock, et al., 2022), includes a construct 'Relative importance of recreation and industry uses of regional waterways' gauging the extent to which respondents valued direct uses of waterways in their region, including uses by different industry sectors, were elicited using a series of items and the same 10-point rating scale (1 = 'I don't value this at all', 10 = 'I value this extremely highly'). Options included supporting agriculture ('the waterways support local agriculture').

These data sets and methods are publicly available via the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Data Access Portal.

Applications of the data

The primary purpose of the social monitoring data is to track responses regarding agricultural management practice adoption and identify any trends evident over time that can both give context to and help inform and improve progress towards the Reef 2050 WQIP targets in the Reef water quality report card. While reporting against the other targets in the Reef Water Quality Report Card identifies if, and how much, change has occurred, the social monitoring data can provide insights into why (or why not) landholders are making particular land management decisions and the differentiating factors.

The data also has several other important applications including:

- Inform the design of future water quality investment programs by using the knowledge of the drivers and barriers of management practice adoption by landholders and providing an assessment to identify areas for improvement
- By tracking progress over time, the data will provide an indication of likely trajectory of practice change

- Comparing and understanding the effectiveness of different interventions across region, commodity, and program scales
- Providing feedback to delivery organisations on the drivers and barriers of change which can be used to adaptively manage the program design and delivery to meet the needs of involved landholders and achieve greater outcomes
- Providing opportunities to align the data with the regional report cards with regards to how the stewardship behaviours are reported and monitored across industries
- Informing and creating a data flow to the Reef Integrated Monitoring and Reporting Program human dimensions reporting process
- Providing internal reports to the Queensland and Australian governments on the social impacts of their respective investment.

Presenting the Reef Water Quality Report Card 2021/2022

The planned reporting scale, assumptions and issues associated with the data were extensively workshopped with the Human Dimensions Working Group and an expert was engaged to assist with reporting (Dr Tracy Schultz).

Reporting scale

The Reef Water Quality Report Card for 2021 and 2022 will present the results of the 2020/21 and 2021/22 survey data set. The pathway for reporting social monitoring data in the Reef water quality report card will remain the same as for the 2020 report card. The current content management system (CMS) capability does not sufficiently allow for the intricacies of social monitoring reporting including interactivity, so a visually simple approach will once again be employed.

Data have been collected from projects with grazing, cane, banana and horticulture industries. The minimum reporting threshold is set at 50 records per region and commodity, which was considered a reasonable level to ensure a greater level of confidence in the data and farmer cohort anonymity. Banana and horticulture industry data did not meet the threshold, so it remains the case that only the grazing and cane industries have sufficient data for inclusion. Mackay Whitsundays region did not meet the threshold, and there is considerable variation in data from other regions so a regional breakdown will not be presented.

Depending on data availability and granularity, emerging trends and the content management system (CMS) capability, future report cards will be able to include banana and horticulture industry data and representation of all regions.

Most cane data relate to the landholders' perceptions of the selected practice change 'changing my fertiliser management' and for grazing it is for 'changing my pasture management'. Therefore, presenting specific fertiliser and pasture management data in the infographic enables a less generic representation of the data for each commodity.

The key social findings from the Human Dimensions program will be presented in the Reef Water Quality Report Card 2021 and 2022 as an infographic showcasing the following highlights from:

- cane fertiliser management and grazing pasture management practice change project social monitoring:
    - motivations (before engagement in the project), barriers, attitudes and self-efficacy (after engagement in the project) related to specific practice types, and
- Social and Economic Long Term Monitoring Project (SELTMP) core module:

    - importance of Great Barrier Reef interventions as ranked by all respondents
    - agricultural respondents' efforts to improve land management to reduce farm run-off.
- SELTMP Regional Report Cards of the Great Barrier Reef supporting module:
    - importance of recreation and industry uses of regional waterways as ranked by all respondents.

Further data (graphs) supporting the infographic will be linked from the infographic and will show:

- representation of results by industry
- SELTMP and Regional Report Cards dashboard.

Group norm and attribution data are not presented as part of the report card due to the high level of potential error, specifically non-response bias, present in these items. Non-response bias occurs when there is potential that those who have not answered a question could have provided responses different from those who have answered, making the results non-representative. The potential for non-response bias to be present with the group norms data is evidenced through higher "don't know" responses (26%) than other questions, indicating the scale was not appropriate. For attribution data, the potential for non-response bias is evidenced through a higher non-response rate (33%) to this question than other questions. These issues have been addressed for both items for future monitoring and reporting (see Table 3 below).

Future Reef water quality report card considerations

Future Reef water quality report cards will seek to include:

- Aggregated paired data at the deidentified landholder level 'before' and 'after' engagement
- A five-year trend of cumulative data reporting, aligning with the Paddock to Reef program design which also allows for program design reviews at those points in time
- Data at a commodity level and by Reef region
- Infographics to communicate social monitoring data at the higher level
- Updated grading scales
- Further testing with stakeholders and users of report cards.

Reviewing the human dimensions action

The Reef 2050 WQIP highlighted that the human dimension target was to be further refined as indicators or measures relevant to Reef water quality were identified and a baseline developed (Australian and Queensland governments 2018a, p. 20). The following action was set from the Reef 2050 WQIP:

- Develop a baseline for a variety of practice, behavioural and attitudinal drivers that influence Reef water quality. The baseline will be consistent with related Reef 2050 Plan Targets (Action 7.3, p. 50-51).

In addition, the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program: Program Design 2018-2022 indicated that the phased approach to the addition of social factors to the Paddock to Reef Management Practice Adoption questionnaire would be fully operational by March 2019 and that a baseline would be developed using existing monitoring and evaluation datasets (p. 48-49).

However, due to the small number of datasets available across commodities and poor alignment between the available datasets and the identified social factor themes, a baseline was unable to be established (Jarvis, Taylor and Hobman, 2018) prior to survey implementation in 2019.

The human dimensions target is currently being reviewed as part of the Reef 2050 WQIP review and in addition, as of March 2023, a new and expanded social monitoring survey has been introduced following extensive consultation, review and refinement. Further, the OGBRWH has recently completed a social monitoring benchmark survey project (at June 2023) which provides data from agricultural landholders who are not engaged in projects. As such, while trends can be observed from the three years of survey data now available for cane and grazing, it is expected that future reporting against the human dimensions target in the report card will be derived from a more complete data set, and that consideration will then be given to creating a baseline.

Data limitations

Agricultural practice change project social monitoring to support the 2025 Human Dimensions target in the Reef 2050 WQIP has been in place since mid-2019 and is continuously developing and both data collection and reporting is improving. Table 3 below outlines current limitations and how they are being minimised for presentation in the current report card and future report cards.

Table 3. Limitations of data collection approach

Limitations of this approach:	How will this be addressed:
Relies on delivery organisations appropriately collecting social monitoring data	• Training. • Cross validation with qualitative survey data. • Established quality assurance and quality control processes (see section below). • Expert review with Human Dimensions Working Group and delivery agents.
Potential for response bias due to existing relationships between the landholders and those delivery agents administering the questionnaire	• Training on the role of response bias and strategies to minimise. • Landholder consent processes to establish the purpose of the study and reassurances regarding data confidentially.
Data of *participating* landholders is captured with no mechanism to report non-participating landholders. This limits the generalisability of the results; however, the current reporting still yields valuable behavioural insights.	• Acknowledgement and appropriate use of the data. • Collecting similar data from other lines of evidence (e.g., a benchmarking project on broader industry perceptions of practices). • Seek other opportunities to collect and collate data from a range of stakeholders in the practice change value chain (i.e., SELTMP, regional report cards, etc.).

Limitations of this approach:	How will this be addressed:
Data is collected from landholders in Queensland or Australian Government funded programs: some regions and commodities will not have any social monitoring data reported against the Human Dimensions target.	• Data will not be included where no or limited data (below 50 records) exists for a commodity. • Data collection under contracted arrangements should see thresholds met for all commodities and regions for future report cards
Minimum standards for data quality and assumptions for analysis, including minimum sample sizes, may not be met.	• Data will not be published if data quality standards and assumptions for analysis are not met.
Data collection mechanism issues including difficulty in data pairing at the landholder level.	• From 2023, the survey will be collected and accessed through the P2R Projector which will allow for improved data pairing at the landholder level.
Survey questions limitations.	• The survey questions and scales have been reviewed and updated and future report cards will reflect the updated survey. Specifically, some of the questions and scales have changed (including group norms) and the attribution question has been removed. • Demographic data is included in the updated survey.
Database limitations involving download and transfer processes posing risks to integrity.	• From 2023, the survey will be accessible through P2R Projector which will allow for improved data integrity.

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Appendix 1

Privacy statement

(Example organisation), on behalf of the Department of Environment, Science and Innovation, is collecting the information in this survey assessing land management practices to evaluate and report how effective the actions taken through the (Example project) have been in improving water quality in the rivers and creeks that flow to the Reef, as part of the Reef 2050 Water Quality Improvement Plan 2017-2022.

Some of the information is provided to the Office of the Great Barrier Reef, the Department of Agriculture and Fisheries and/or the Department of Resources to support annual reporting of progress towards land management and water quality targets. Your personal information, including address, geographical location or any information that can make your identity apparent, will not be disclosed to any other parties unless clearly and expressly authorised or required by law. Individual property data is not published or made public in any way. If you would like further privacy information visit www.des.qld.gov.au/legal/privacy or email privacy@des.qld.gov.au.