Australian Government

Queensland Government

Methods

Reef Water Quality Report Card 2020

Reef 2050 Water Quality Improvement Plan

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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 currently in place or are planned. They include programs which aim to improve management of ground cover levels appropriate to the regional conditions such as:

- the Grazing Resilience and Sustainable Solutions (GRASS) program, which 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 management 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. Furthermore, there are a number of commercial platforms now providing access to the same ground cover information with additional functionality, such as 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 higher 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 essentially 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'.

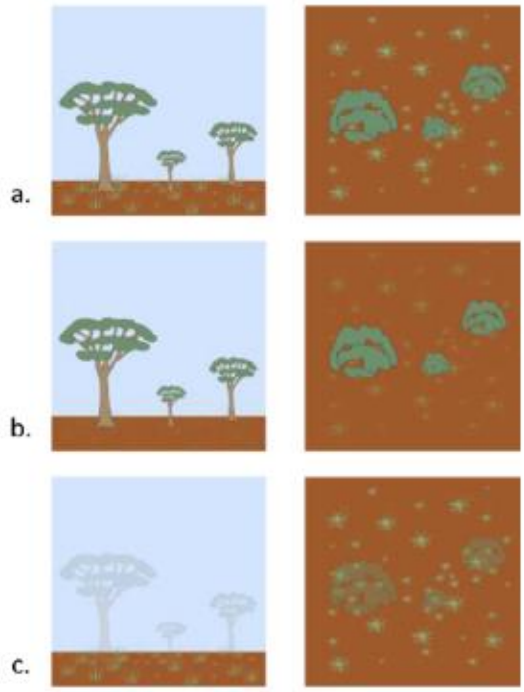

Figure 1: Schematic representation of the correction of the fractional cover data to estimate the fractional ground cover used for reporting (Trevithick et al, 2014). (a) Fractional cover measures all vegetation cover including trees, shrubs and ground cover, as well as bare ground. The ground cover 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 certain 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 current version of the fractional ground cover product was developed using around 2,000 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 4,000 field observations collected using the same field protocols across Australia, and a re-calibrated and revised fractional cover model is being developed. It is expected that this updated version will help to address some known limitations in the current version (e.g. in bright soil areas) and will be incorporated into reporting in the future, following assessment of the accuracy and degree of difference to the current reporting. Re-processing of previous years will be undertaken to produce reporting statistics which are based on a single, consistent product.

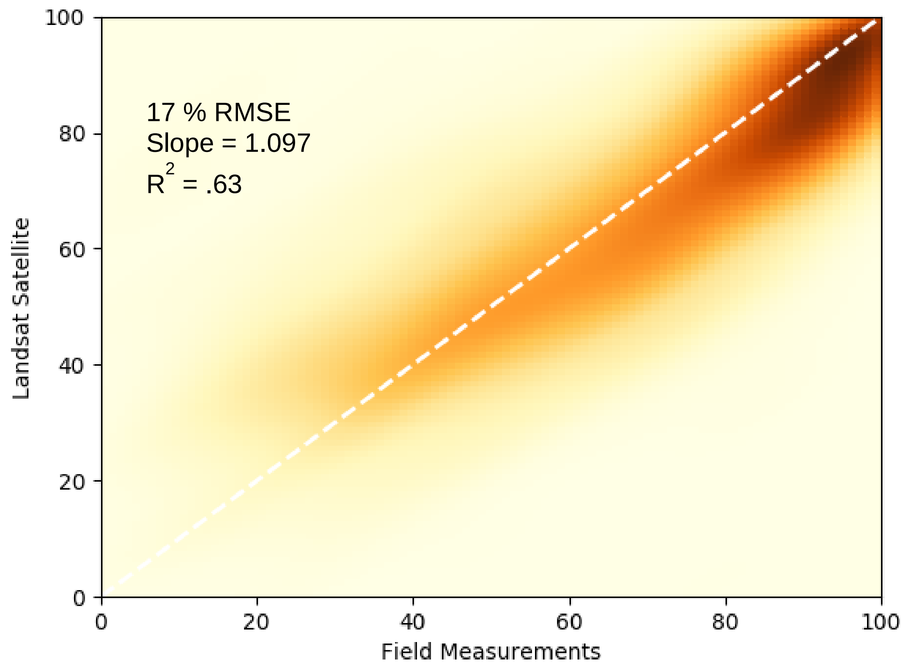

Figure 2: Comparison of field measurements of fractional cover with Landsat derived fractional ground cover for 2047 sites across Australia. The linear regression shows an overall Root Mean Square Error (RMSE) of 17%.

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 (NRM) 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 the most recent land use data provided by the Queensland Land Use Mapping program (DSITIA, 2012). The most recent version of the mapping for Burdekin and Wet Tropics is 2016, with the Fitzroy and Burnett Mary current to 2017. Cape York and the Wet Tropics are current to 2013 and 2015, respectively.

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). Therefore, the mean ground cover reported is 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 Water Quality 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% 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.

Qualitative confidence ranking

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A multi-criteria analysis is used to qualitatively score the confidence in each indicator used in the Reef 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.

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

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

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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 2020.

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.

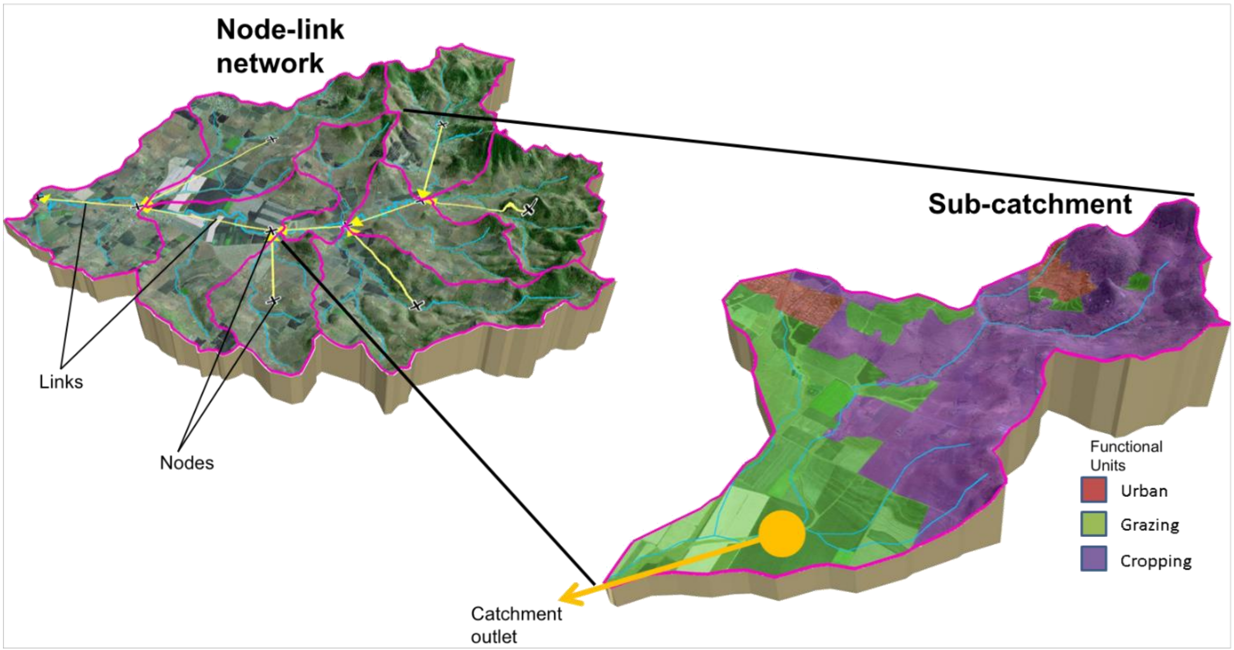

Figure 2: Example of a functional unit (FU) and node-link network generated in Source Catchments (source eWater).

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.

[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).

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.

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).

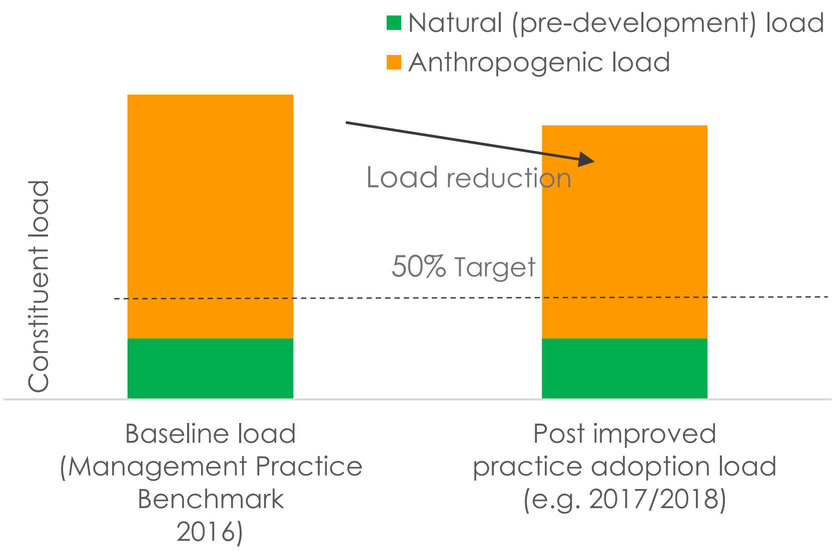

Figure 2: Example of modelled pre-development and anthropogenic pollutant loads, and the load reduction following investment in improved management practices.

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:

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

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.

Qualitative confidence ranking

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

A multi-criteria analysis was used to qualitatively 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.

Catchment loads monitoring methods

The Great Barrier Reef Catchment Loads Monitoring Program was implemented in 2005 to monitor and report on loads of total suspended solids and nutrients, with pesticide monitoring added to the program in 2009. This report summarises the methods undertaken by the Catchment Loads Monitoring Program to report results required for the delivery of the Reef Water Quality Report Card 2020. The Catchment Loads Monitoring Program provides data to the Catchment loads modelling program to validate progress towards achieving the Reef 2050 Water Quality Improvement Plan 2025 water quality targets (Australian and Queensland governments 2018). The Catchment Loads 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 Reef 2050 Water Quality Improvement Plan 2017-2022 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 is measured at more than 61 sites across 23 major catchments that discharge to the Great Barrier Reef lagoon (Figure 3) as part of the ongoing, long-term Paddock to Reef Integrated Monitoring, Modelling and Reporting Program. Water quality monitoring site numbers and locations vary slightly from year to year due to various logistical, climatic and operational reasons. Total suspended solids and nutrients were monitored at 26 end-of-catchment sites, 21 sub-catchment sites and seven fine-scale monitoring sites. Pesticides were monitored at 23 end-of-catchment sites, five sub-catchment sites and seven fine-scale monitoring sites.

Monitoring sites were classified as either end-of-catchment, sub-catchment or fine-scale monitoring sites. The end-of-catchment monitoring sites were 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 were maintained by the Queensland Department of Regional Development, Manufacturing and Water (DRDMW). Sub-catchment sites were located at the lowest point in a sub-catchment (tributary), mainly at existing gauging stations. Fine-scale monitoring sites typically occur off the main channel of a waterway, have relatively small catchment areas, and may experience lower or intermittent flows compared to the dominant river system.

Water quality samples collected at each monitoring site provide data related to land management activities in the catchment area upstream of the site. All three site types potentially 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.

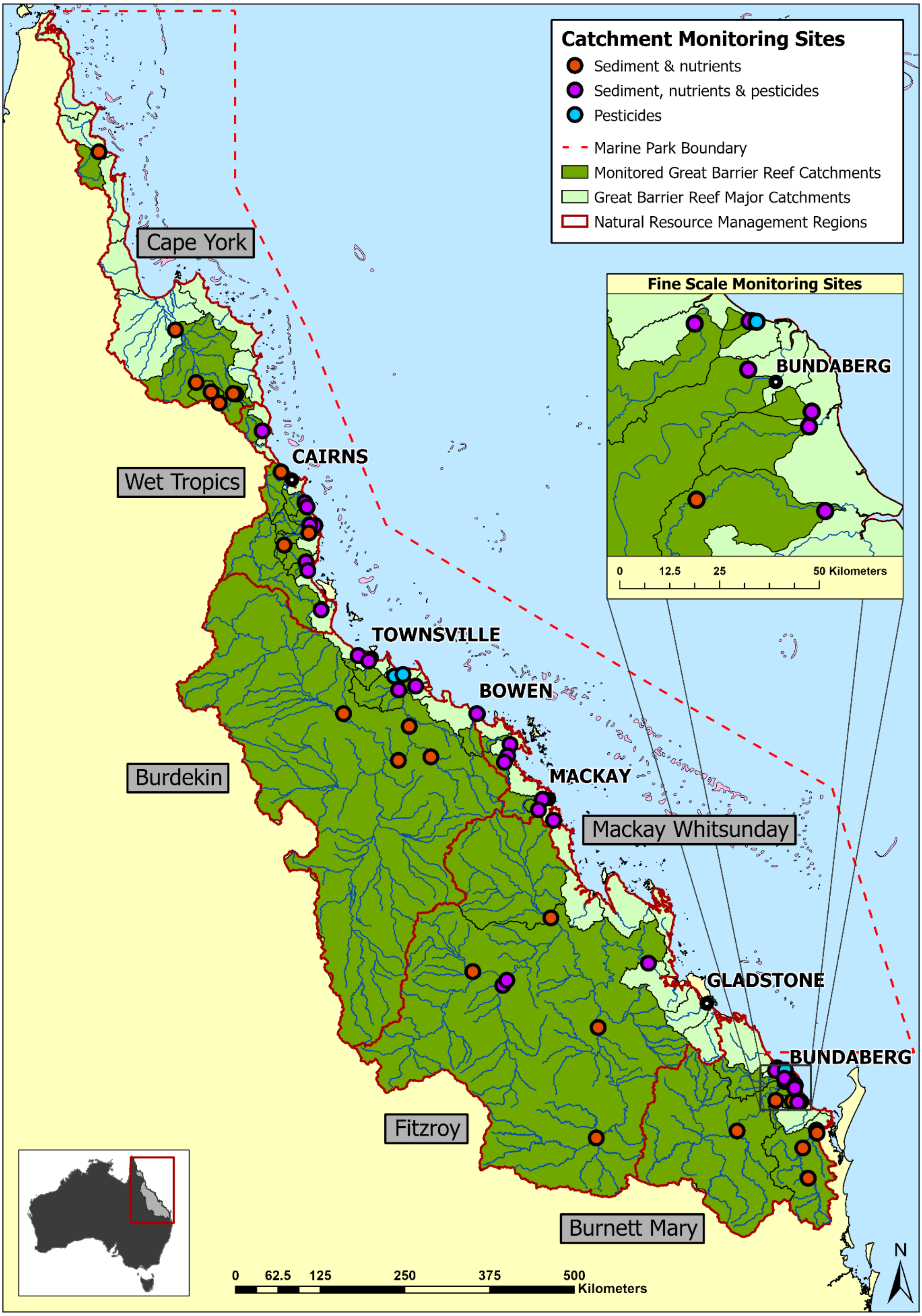

Figure 3: Map showing the location of catchment monitoring sites in the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program.

Rainfall data

Rainfall totals and rainfall decile data come from the Bureau of Meteorology National Climate Centre (BoM 2021). 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 are described in detail in the annual [Great Barrier Reef Catchment Loads Monitoring Program - Condition Report](#).

Water quality sampling

Water samples were collected, stored, transported, quality assured and quality controlled in accordance with the Environmental Protection (Water and Wetland Biodiversity) Policy Monitoring and Sampling Manual 2018 (www.ehp.qld.gov.au/water/monitoring/sampling-manual). Water quality samples were collected using two methods: manual grab sampling and automatic grab sampling using refrigerated pump samplers. Intensive sampling (daily or every few hours) was conducted during high-flow events and monthly sampling was conducted during low or base-flow (ambient) conditions. For pesticides, intensive sampling (daily or every few hours) was 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. At tidally influenced sites, manual grab samples collected during low flow conditions 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 (DRDMW).
- 'Time and flow factored'[2] measured discharge from existing RDMW gauging stations.
- Modelled flows generated in the Source Catchments modelling platform using the Sacramento rainfall run-off model, where the Parameter Estimation Tool (PEST) was coupled with Source for the calibration process.
- 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 in the annual Great Barrier Reef Catchment Loads Monitoring Program - Condition Report.

[2] 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 Queensland Government Science and Technology Division Chemistry Centre (Dutton Park, Queensland) analysed water samples for total suspended solids and nutrients (Table 1). The Queensland Health Forensic and Scientific Services Organics Laboratory (Coopers Plains, Queensland) analysed 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 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[3]. 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.

3 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
Ametryn	PSII Herbicide	Photosystem II inhibitor
Atrazine	PSII Herbicide	
Terbuthylazine	PSII Herbicide	
Tebuthiuron	PSII Herbicide	
Simazine	PSII Herbicide	
Diuron	PSII Herbicide	
Terbutryn	PSII Herbicide	
Hexazinone	PSII Herbicide	
Metribuzin	PSII Herbicide	
Haloxyfop	Other herbicide	Acetyl-coenzyme A carboxylase (ACCase) inhibitor
Imazapic	Other herbicide	Acetolactate synthase (ALS) inhibitor
Metsulfuron-methyl	Other herbicide	
Pendimethalin	Other herbicide	Microtubule synthesis inhibitor
Metolachlor	Other herbicide	Acetolactate synthase (ALS) inhibitor
2,4-D	Other herbicide	Auxin mimic (Phenoxy-carboxylic acid auxins)
MCPA	Other herbicide	
Fluroxypyr	Other herbicide	Auxin mimic (Pyridine-carboxylic acid auxins)
Triclopyr	Other herbicide	
Isoxaflutole	Other 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, concentration and flow data were used to determine the total load of each pollutant that was transported past the monitoring site in each catchment and sub-catchment. Annual and daily loads were calculated for total suspended solids and the nutrient analytes listed in Table 1 using the Loads Tool component of the 'ReLo' loads calculation software developed by the Queensland Department of Environment and Science[4]. 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[5]. 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 multisubstance-potentially affected fraction (ms-PAF) method (Traas et al. 2002).

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4 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).

5 The Pesticide Risk Baseline was generated using a suite of models that can predict the pesticide mixture toxicity from monitored sites to the whole catchment, region and Great Barrier Reef scales. The Pesticide Risk Baseline was developed using Catchment Loads Monitoring Program data collected from monitoring sites across Queensland from 2015 to 2018. The model build compared the monitored pesticide trends to spatial, climate and land use characteristics at those sites. The Pesticide Risk Baseline then used the relationships developed to predict the current estimate of percent species protected from mixtures of 22 reference pesticides in major catchments discharging to the Great Barrier Reef (Warne et al. 2020).

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 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	

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. 2020) 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).

Qualitative confidence rankings for reporting on pesticides

A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the Great Barrier Reef 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 four-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 Great Barrier Reef catchment area scales.

Validation

An overall score of 2.7 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 been validated in the field.

Representativeness

An overall score of 2.8 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 1.8 was awarded because some components do not have error quantified.

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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 2020. 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, including pesticides (Waterhouse *et al.* 2021)
- Seagrass condition (McKenzie *et al.* 2021)
- Coral reef condition (Thompson *et al.* 2021).

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 (Waterhouse *et al.* 2021).

Seagrass condition

77% of seagrass meadows are in the inshore water body. They are fundamental to fisheries productivity and the main food source of dugongs and turtles. Monitoring was conducted at 69 sites at 31 locations in six regions during 2019–2020 by three field teams (McKenzie et al. 2021) (see **Error! Reference source not found.**). Five major seagrass habitat types (estuarine, coastal intertidal, coastal subtidal, reef intertidal and reef subtidal) are assessed where possible.

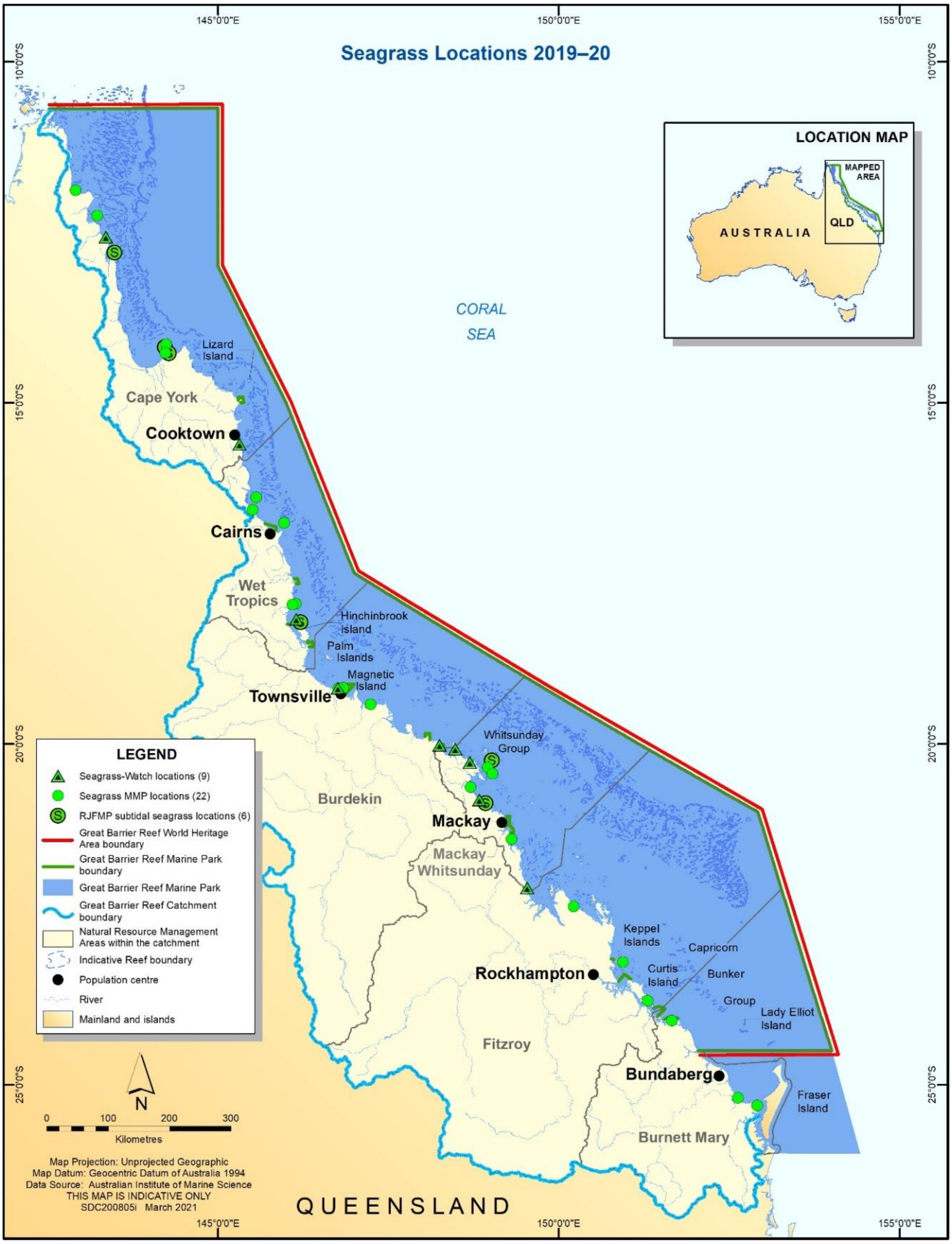

Figure 4. Marine Monitoring Program seagrass survey locations (including Reef Joint Field Management Team and Seagrass-Watch). *Not all sites are surveyed every year.* Source: (McKenzie et al. 2021).

Sampling was undertaken at 14 coastal, four estuarine and 12 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 2019) and late wet season (March/April 2020).

Three 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).
- Reproductive effort is the ratio of the average number of reproductive structures (spathes, fruits, female and male flowers) of plants on an area basis relative to the long-term average, and provides an indication of the capacity for meadow recovery following disturbances.
- Tissue nutrient composition is an indicator of nutrient enrichment relative to light available for growth (McKenzie *et al.* 2021).

Additional indicators of seagrass condition and resilience include species composition, relative meadow extent and density of seeds in the seed bank (McKenzie *et al.* 2021).

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 (Waterhouse *et al.* 2021).

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 5). 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.

31 reefs are monitored biennially at two depths under the program, with an additional eight 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.* 2021).

Figure 5: 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. 2021).

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.* 2021).

Assessing status against the objectives

Improved seagrass condition

Three indicators are used to assess and report inshore seagrass condition: abundance, reproductive effort and tissue nutrient status. Further detail about the selection and scoring of these indicators is available in the annual technical report (McKenzie *et al.* 2021).

The overall grade is the average of the scores of the three 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 5).

Table 5: 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 macroalgal cover. Further detail about the selection and scoring of these indicators is available in the annual technical report (Thompson *et al.* 2021).

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 6).

Table 6: 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 2020 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).

Qualitative confidence rankings

A multi-criteria analysis was used to qualitatively score the confidence in each indicator used in the Reef Water Quality Report Card 2020, 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 6).

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

Figure 6: Qualitative 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 qualitatively 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. The attributes are ranked from those that contribute weakly to the criteria to those that have a strong influence. 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 weaknesses are that it can be subjective and open to manipulation.

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.

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, 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 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 would be impractical to measure and report water quality through the entire area and at a reasonable frequency using monitoring data alone.

Satellite imaging can be used to cover this wide spatial area but is generally considered to have lower accuracy and is seasonally affected by cloud cover. Therefore, the eReefs modelling framework is used in conjunction with the monitored information and satellite observations to extrapolate water quality across the entire Great Barrier Reef. The model is used to generate the marine water quality metric.

This report describes the methods used to generate the marine water quality metric for the period 1 October 2019 to 30 September 2020 (water year 2019-2020).

Marine modelling methods

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 new metric is underpinned by the eReefs biogeochemical model and integrates true-colour data from satellite images for improved accuracy in what is commonly referred to as data assimilation (Baird et al., 2016). This integration of multiple streams of data to measure and report on water quality differs from the previous metric, which relied exclusively on model predictions of water quality variables like chlorophyll and suspended sediments derived from satellite data.

The eReefs model has been assessed extensively against *in situ* observations with detailed assessment findings available in the Technical assessment of the eReefs biogeochemical simulation [gbr4_H2p0_B3p0_Chyd_Dcrt] against observations (Skerratt et al., 2019b). The approach to calculating Reef water quality indices and overall scores was independently peer-reviewed as part of NESP Project 3.2.5.

eReefs coupled hydrodynamic - biogeochemical model

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.

The three components of the model are:

- The hydrodynamic 3-D model as defined by Herzfeld (2006, 2015).
- The sediment transport model, which adds 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 Great Barrier Reef region, spanning estuarine systems to offshore reefs (Figure 1. Skerratt et al., 2019a).

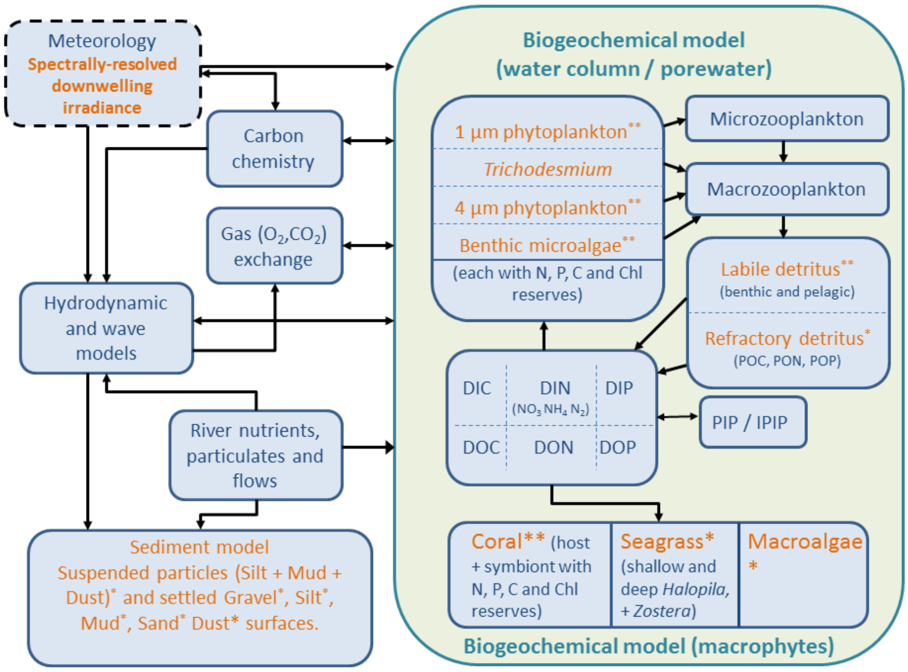

Figure 1: Conceptual framework of the eReefs coupled hydrodynamic-biogeochemical model. Orange variables are optically active (i.e. either scatter or absorb light), influencing the vertical attenuation of light and the bottom light field. The model is forced by rivers along the Reef with nutrient and sediment loads (Baird et al., 2016) using the Source Catchments model. Source: Skerratt et al., 2019a.

Briefly, the biogeochemical model considers four groups of microalgae (small and large phytoplankton, *Trichodesmium* and microphytobenthos), two zooplankton groups, four macrophytes types (seagrass types corresponding to *Zoster 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). The biogeochemistry model was updated in 2018 to specifically consider ultrafine sediment particles and their impact on matters such as water clarity.

The model is currently forced with freshwater inputs from rivers along the Great Barrier Reef. River flows for 17 rivers are obtained from the Queensland Department of Natural Resources, Mines and Energy 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).

River pollutant loads are obtained from the Source Catchments modelling outputs (Ellis and Searle, 2013) up to 30 April 2020. To 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.

The eReefs model can be run without using observations from the marine environment, which is referred to as a non-assimilating simulation. However, data assimilation provides the single best estimate of the biogeochemical state of the Reef by combining modelling and observations (Jones et al., 2016), and also improves the skill of the model to make predictions (Skerratt et al., 2019a, b). Data assimilation systems can be thought of as using a model to interpolate between observations.

For the Great Barrier Reef, only remote sensing provides the density of observations required to undertake a large-scale data assimilation (see <eReefs home page | eReefs>).

For shallow inshore waters, using remote sensing 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 and green 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).

A 100 member Ensemble Kalman Filter (EnKF) assimilation system is used informed by observed ocean colour from the NASA MODIS Aqua, VIIRS and ESA Sentinel-3A satellites (Jones et al., 2016). When the ocean colour data is ingested, the model shifts a number of optically-active *in situ* quantities, and in particular phytoplankton numbers, in all ensemble members in a manner that is consistent with the statistical properties of the biogeochemical model.

The estimate of the biogeochemical state by the assimilation system is the mean of the 100 ensemble members. While the model assimilates ocean colour data from satellite, it is assessed against the *in situ* observations of chlorophyll *a* concentration, from which the skill of the system can be quantified.

Modelling improvements

The modelling system was initially developed under the eReefs Project and NESP 3.2.5 Project, and improved for Report Card 2017 and 2018. Significant improvements in Report Card 2020 include:

- Incorporating catchment load estimates using the new SOURCE Catchments code with 2020 vegetation cover.
- Improved pre-processing of river loads before input into the model by 'capping' to prevent large river concentrations due to large loads relative to small flows. Loads that cannot be included at the time predicted by SOURCE Catchments are released at the next flow event: this allows concentrations to be below the cap. This mostly affected the O'Connell River due to large ungauged sections of the catchment.

- SOURCE Catchments total suspended sediments were allocated to FineSed (90%) and Dust (10%), replacing constant concentration for Dust of 20 g/m3 used in previous simulations. This reduced the total riverine suspended solids slightly and increased the fraction of ultrafine sediments during large flows.
- From 1 January 2018, Sentinel-3A atmospherically-corrected remote-sensing reflectance was used for the data assimilation.
- Optical properties of suspended inorganic particles were updated based on analysis in Soja-Wozniak et al. (2020). These new values, obtained at Lucinda Jetty Coastal Laboratory, were more representative of the Great Barrier Reef-wide suspended inorganic particles but less representative of coastal embayments.

The revised model has been assessed over a period of eight years and compared to the previous model configuration to confirm it maintained all the properties and skill required to predict water quality.

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 7: 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

Qualitative confidence ranking

Data confidence

●●●○○

A multi-criteria analysis was used to qualitatively 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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Catchment condition – wetland condition monitoring methods

This report describes methods used to produce the Reef Water Quality Report Card 2020 wetland condition results. Within the Paddock to Reef Integrated Monitoring, Modelling and Reporting Program, the Wetland condition monitoring program tracks progress towards the Reef 2050 Water Quality Improvement Plan (Reef 2050 WQIP), improved wetland condition objective.

The program design is described in the Great Barrier Reef (GBR) catchments wetland monitoring pilot study: assessment methods and monitoring design (Tilden et al., 2015) and the proposed program analysis methods are set out in detail in the Great Barrier Reef catchments wetland monitoring program: analysis methods (Tilden and Vandergragt, 2017).

Between 2018 and 2020, the Program's assessment instrument, Wetland Tracker (WT), underwent a major method update, including:

- the development of a new set of pressure subindices, based on classes of pressure identified in a landscape-scale study of hazards to wetlands (DSITI 2015)
- changes to the scoring scales, reducing their complexity.

These methods changes are described in more detail in sections to follow.

Methods

The analysis methods document (Tilden and Vandergragt, 2017) identified a number of activities to be carried out in 2020. The aims were to:

- Assess wetland condition, and change in wetland condition, in Great Barrier Reef freshwater floodplain wetlands[6].
- Test for any indication that multiple assessments of panel 1 wetlands are affecting the condition of the wetlands in that panel. A panel is a group of wetlands with the same schedule of repeat assessments across years. Potential effects of annual visits are that the wetlands of panel 1 are being degraded in some way (unlikely) or alternatively, that the average condition of panel 1 wetlands has improved because their landholders have managed aspects of wetland condition brought to their notice by the program (preferential management). In either case, the wetlands in panel 1 would then no longer be representative of the program subpopulation. The null hypothesis is that both panels (panel 1 and panel 4) still sample wetlands from the same subpopulation, despite panel 1 having been assessed five times and panel 4 just once.
- Test for trend in pressure and state, provided there is sufficient power to do so.

[6] In 2020, due to COVID-19 restrictions, field assessments could not be completed in Cape York wetlands. Instead, scores for field indicators in Cape York were imputed, based on data from previous years. Field assessments were able to be carried out as usual in all other regions.

Baseline data for pressure on wetland values and the state of wetland values were reported in 2016. Wetland condition was reported for 2018, along with an analysis of change between 2016 and 2018. Great Barrier Reef-wide analyses reported for 2020 are:

- Tests for change in wetland condition (**state** of environmental values and anthropogenic **pressure** on wetlands) between 2018 and 2020.
- Tests for change in wetland condition between the 2016 baseline study and 2020.
- Tests for differences between panel 1 and panel 4 data gathered in 2020 to look for effects associated with multiple assessments.

Trend assessment was not performed due to lack of power to detect trend after five years of repeat assessments on 19 wetlands (see White 2019, Starcevich et al, 2018).

Progress with Great Barrier Reef-wide monitoring design

Table 1 shows the Great Barrier Reef wetland condition monitoring program sample design – an augmented serially alternating design comprising one panel[7] of 20 wetlands assessed every year, and four panels of 20 assessed in alternate years following a pattern that repeats every eight years. The total sample size is 100 wetlands, comprising a spatially balanced random sample of wetlands selected using the Generalised Randomised Tessellation Stratified[8] method. The sub-population sampled for the Great Barrier Reef-wide monitoring program is natural freshwater floodplain wetlands in high-density assemblages (see Figure 1).

Table 1. Panel design for the GBR catchments wetland condition monitoring program*.

Panel	Year										
	2016	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
1	20	20	20	20	20	20	20	20	20	20	20
2	20		20						20		20
3		20		20						20	
4					20		20				
5						20		20			
Year total	40	40	40	40	40	40	40	40	40	40	40
Total sample	**40**	**60**	**60**	**60**	**80**	**100**	**100**	**100**	**100**	**100**	**100**

*Some wetland sample sizes per panel differ from the planned n=20 due to factors such as attrition and replacement. For example, panel 1 originally comprised 21 wetlands, and 21 were assessed in both 2018 and 2020, but only 19 wetlands have been assessed five times. Two have dropped out and been replaced.

Testing for change between 2018 and 2020 is complex, due to the program's augmented serially alternating panel structure, designed to optimise both status and trend assessment in a long-term monitoring program (Tilden et al, 2015). The particular pattern of alternating panels was chosen so the 40 wetlands assessed in 2016 (baseline) would be reassessed in 2018. This made it possible to test for change, with the power to detect change in 2018 after the program had been running for just three years. Each year, with this design, ≈ 40 wetlands are assessed for status reporting but only one panel of ≈ 20 wetlands is repeated *every* year throughout the program.

[7] A panel is a group of wetlands with the same schedule of repeat assessments across years.
[8] Generalised Randomised Tessellation Stratified sampling

While it is possible to test for trend with only these 20 wetlands, the power and economy of the program design for trend detection is not fully realised until other panels have been repeatedly tested in order for their results to be included in the trend analysis.

For the years being compared in 2020, the design mixes dependent and independent sampling – all wetlands are from the same population. However, while panel 1 wetlands are assessed in all years, the 20 wetlands in panel 2 (assessed in 2016 and 2018) and the 19 in panel 4 (assessed in 2020) are independent samples. Consequently, for the 2020 wetland condition report card the analysis of change between 2018 and 2020 is based on panel 1 wetlands only (n=21). Likewise, the comparison between the baseline (2016) and the condition of wetlands in 2020 is based on the 19 panel 1 wetlands assessed in both years.

Data collection

Wetland assessment data were collected in two ways:

- desktop analysis based on imagery and spatial data using a range of data sets for 14 indicators, primarily related to the pressure index
- field-based data collection methods for 10 indicators primarily related to state.

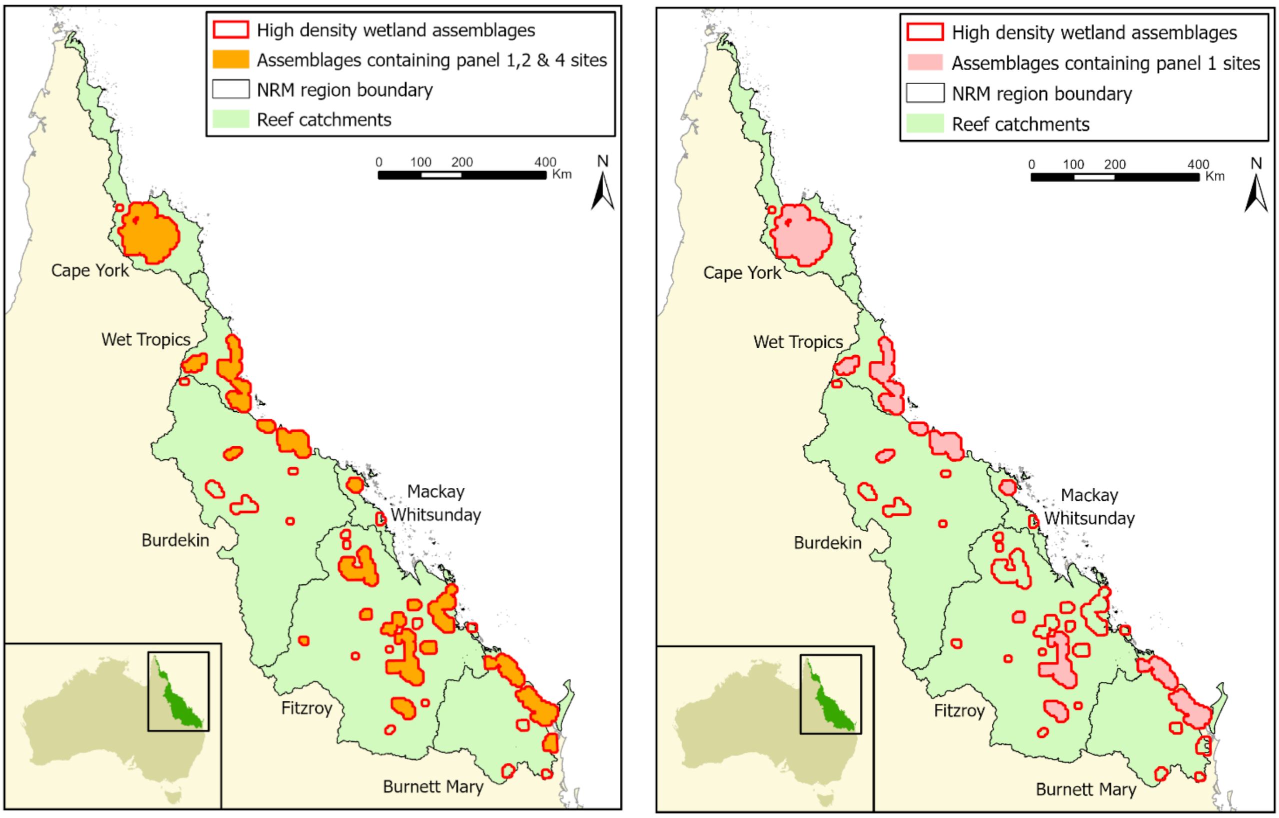

Figure 1: High-density wetland assemblages containing panel 1, panel 2 and panel 4 wetlands assessed in 2018 and 2020 (left) and panel 1 wetlands assessed all years from 2016 to 2020 (right, n=19).

Calculating summary statistics – Wetland Tracker updated

A major update of Wetland Tracker brought changes to the structure of the instrument, with new sub-indices for assessing anthropogenic pressure on wetlands and new scoring scales for arriving at summary statistics and report card grades.

For each wetland, the condition assessment tool, Wetland Tracker (WT) produces overall scores for the **state** of wetland environmental values and for anthropogenic **pressure** on wetlands plus scores on four wetland environmental value (WEV) sub-indices of state, and four pressure class (PC) sub-indices.

The wetland environmental value sub-indices of state remain unchanged from the previous version of Wetland Tracker. They are:

- biotic integrity: the biological health and diversity of the wetland
- local physical integrity: the wetland's natural physical state and integrity
- local hydrology: the wetland's natural hydrological cycle
- connectivity: the natural interaction of the wetland with other ecosystems including other wetlands.

The new pressure sub-indices are based on pressure classes derived from a landscape-scale assessment of land-use hazard to freshwater wetlands in the Great Barrier Reef catchment area (Department of Science, Information Technology and Innovation, 2015):

- biological introduction pressure (e.g. plant pests and animals changing the wetland)
- habitat disturbance and alteration pressure (e.g. loss of natural vegetation around the wetland)
- pressure towards change to water regime (e.g. natural wetland water levels being altered by a dam or levee)
- pollutant input pressure (e.g. land use associated with the likelihood of chemicals and nutrients going into the wetland).

The structure of version 2 of Wetland Tracker with indices, sub-indices, indicators and their relationships is shown in Figure 2.

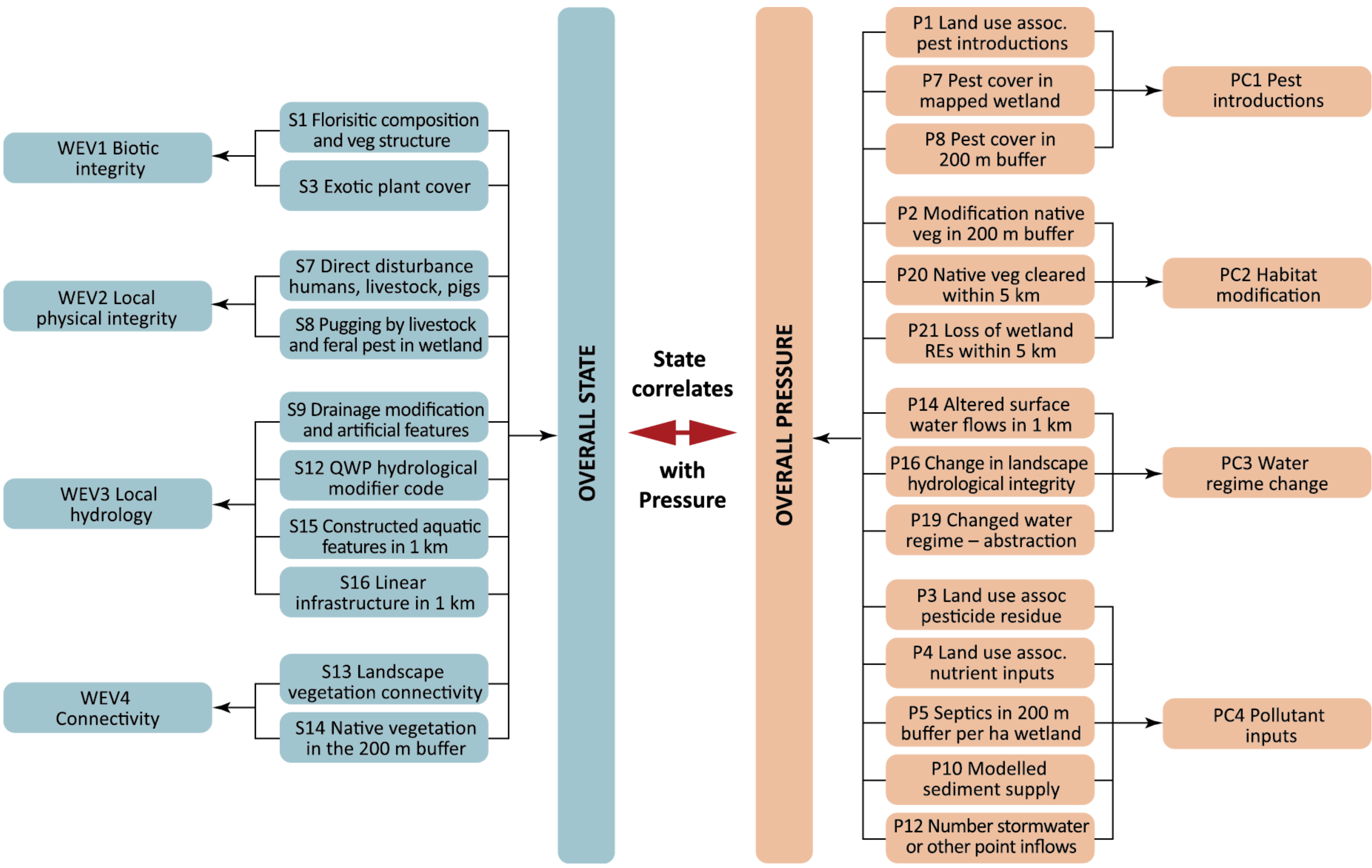

Figure 2: Structure of Wetland Tracker rapid assessment method, showing individual indicators (10 state, 14 pressure), sub-indices (4 state and 4 pressure) and overall index scores (state and pressure). Index and sub-index scores are calculated independently.

The status assessment for 2020 focuses on the 40 freshwater floodplain wetlands in the Great Barrier Reef catchments assessed that year (panels 1 and 4 in Table 1), while the assessment of change between 2018 and 2020, and between 2016 and 2020, includes solely wetlands assessed in both years (panel 1). Descriptive parametric and non-parametric statistics were calculated. Mean and variance of scores for overall wetland state and pressure were used to characterise the level of anthropogenic disturbance to Great Barrier Reef natural freshwater floodplain wetlands in 2020, along with the mean and variance per sub-index for state and pressure. Norman (2010) summarises work supporting the use of parametric statistics on aggregated ordinal data.

Scoring scales for assessing, analysing and reporting wetland condition

Prior to the major update of Wetland Tracker, generating Great Barrier Reef scale wetland condition scores (pressure and state) was a five-step process. This process was not only complex, it also lost information from the data gathered because numeric scores were converted to integers before being analysed. The scoring process has since been simplified:

Step 1. Scores per indicator: Individual indicators (pressure and state) are assessed on ordinal scales with **integer** scores generally 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 sub-index scores: The indicator scores are aggregated into sub-index **numeric scores** on a scale of one to five for each of the eight sub-indices per wetland: *biotic integrity*, *local physical integrity*, *local hydrology* and *connectivity* for state; *and biological introductions, habitat disturbance and alteration, changes to water regime and pollutant input* for pressure. Independently, the indicator scores are aggregated to generate an overall **numeric** pressure and state (OP and OS) score per wetland, also on a scale of one to five (not on a scale of one to 13, as previously recorded).

Step 3. Great Barrier Reef wide scores: At the Great Barrier Reef-wide scale individual sub-index pressure and state scores and overall pressure and state scores are calculated by averaging the **numeric** values obtained from the individual wetlands. All resulting average scores range from one to five.

Step 4. Report card grades: All variables are reported as raw score decimal values on a scale of one to five. Wherever report card grades are given, the cut-offs for grades are as follows:

Wetland environmental value sub-index cut-offs (1–5 scale)	<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

As a result of changes in scoring scales, precision criteria set at the beginning of the program to determine the minimum sample size needed to detect a change between two assessment times have been recast. With the original 13-point scoring scale we aimed for an 80 percent likelihood that a change in score of less than one point meant there little to no change between two times (alpha = 0.05, power = 0.80). With the new five-point scoring scales for overall pressure and overall state, the equivalent change between two assessment times is 0.38 (alpha = 0.05, power = 0.80).

Back scoring data to maintain comparability across five years of monitoring

The major upgrade of Wetland Tracker maintained, as far as possible, the continuity of year-on-year monitoring data. Improvements to individual indicators were made in such a way that back scores could be calculated for the program's previous years of data gathering (2016 to 2019). New indicators and the new pressure sub-indices were also able to be back scored. Back scores for all years to date are reported in the Reef Water Quality Report Card 2020 along with 2020 scores derived from 2020 wetland assessments using the new methods.

In 2020, all comparisons among summary statistics for different assessment years use back scored results for index and sub-index scores (state and pressure).

Assessments of change between 2018 and 2020

Tests for change between 2018 and 2020 analysed aggregated wetland assessment scores.

Paired-sample t-tests were used to test for any statistically significant differences in aggregated state and pressure scores (index and subindex) between the 2018 and 2020 survey periods ($p \leq 0.05$). All assessments of change used back scored results. Paired-sample t-test results are for the $n = 21$ wetlands that were surveyed in both 2018 and 2020.

All paired-sample t-tests were two-tailed and were performed using the 't.test' function from the 'statsr' package in the R language and environment for statistical computing (R Core Team, 2018). 95% confidence intervals were computed for all t-tests. The hypothesis of 'no change' was accepted if the value of zero fell within the computed confidence interval. Narrower confidence intervals provide stronger confidence in accepting the null hypothesis of 'no change'.

Assessments of change between baseline (2016) and 2020

Tests for change between 2016 and 2020 also analysed aggregated wetland assessment scores.

Paired-sample t-tests were used to test for any statistically significant differences in aggregated state and pressure scores (index and sub-index) between the 2016 and 2020 survey periods ($p \leq 0.05$). All assessments of change used back scored results. Paired-sample t-test results are for the $n = 19$ wetlands that were surveyed in both 2016 and 2020.

All paired-sample t-tests were two-tailed and were performed using the 't.test' function from the 'statsr' package in the R language and environment for statistical computing (R Core Team, 2018). 95% confidence intervals were computed for all t tests. The hypothesis of 'no change' was accepted if the value of zero fell within the computed confidence interval. Narrower confidence intervals provide stronger confidence in accepting the null hypothesis of 'no change'.

Analysis by land use type

The aims of this analysis are to:

- Determine if, in 2020, there were any significant differences in state or in pressure scores between wetlands surrounded by conservation land uses and those surrounded by other land use categories.
- Determine if land use intensity (LUI) in the wetland and the surrounding area affects change in scores between 2018 and 2020.

Wetland condition scores – aggregated state and pressure scores for both indices and sub-indices as well as their corresponding report card grades – were calculated for all wetlands assessed in 2018 and 2020.

Students t-tests were used to test for any statistically significant differences in aggregated state and pressure scores (index and sub-index) between wetlands surrounded by conservation lands and those surrounded by other land uses.

To test the significance of changes in average scores by land use category between 2018 and 2020, we used paired-sample t-tests (two-tailed, $p \leq 0.05$) to analyse panel 1 data only ($n = 10$ for wetlands surrounded by conservation land use and $n = 11$ for wetlands surrounded by all other land uses). For each land use category, comparisons between 2018 and 2020 were made at the overall state or pressure score level, as well for individual sub-index state or pressure scores.

95% confidence intervals were computed for all t-tests. The hypothesis of 'no change' was accepted if the value of zero fell within the computed confidence interval. Narrower confidence intervals provide stronger confidence in accepting the null hypothesis of 'no change'.

Comparing panels 1 and 4 for differences attributable to frequent testing

Students' t-test were used to compare the average condition of 21 wetlands in panel 1 with 19 in panel 4. By 2020, panel 1 wetlands had been assessed in five consecutive years, while panel 4 wetlands had had their first assessment. The null hypothesis under test was that the two panels of wetlands were independent samples from the same population. No indices or sub-indices had significantly different scores in the two years (alpha = 0.05).

For all variables tested, the computed 95% confidence intervals for the difference between panel 1 wetlands and panel 4 wetlands include the value of zero, however the confidence intervals are wide. Based on this test, there is no evidence that the two panels were not drawn from the same population, although confidence in this statement is reduced by the width of the confidence intervals around the mean differences between panels.

Non-response bias

The 2016 Reef wetland condition report established that there was a non-response bias in the program's wetland assessment data related to the intensity of land use surrounding wetlands. Managers of wetlands surrounded by high-intensity land uses such as cropping and manufacturing were less likely to agree to monitoring than managers of wetlands surrounded by conservation land uses, with intermediate acceptance rates for wetlands surrounded by land use of intermediate intensity.

For wetlands assessed in 2020 (panels 1 and 4), this difference remains highly significant in a test for a trend in differences among acceptance rates by land use intensity (chi-square for trend in proportions = 11.57, $p < 0.001$, see Figure 3).

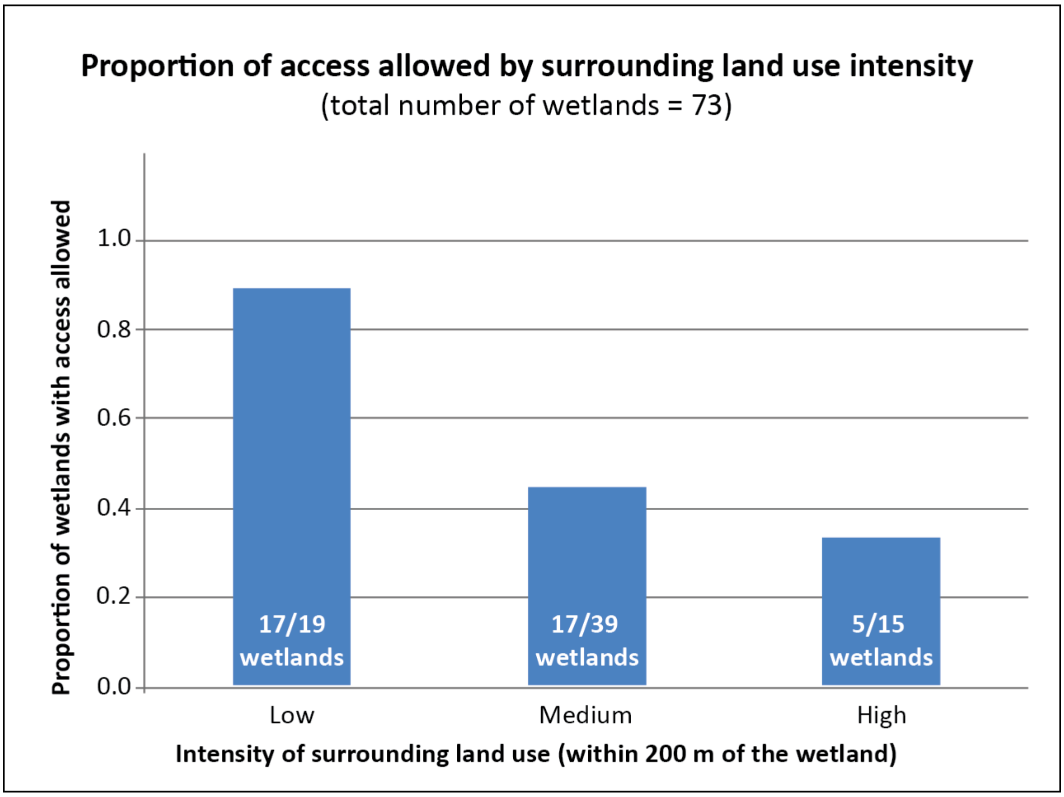

Figure 3. Relationship between non-response rate and land use intensity, illustrating a non-response bias. The more intense the land use surrounding a wetland, the less likely land managers are to grant access.

The effect of this bias would be to overestimate (towards the better end of the assessment scoring scale) the average condition of freshwater floodplain wetlands in the Great Barrier Reef catchment area.

To at least partially correct for this bias, adjustment weights were calculated by dividing the expected proportions of wetlands in each land use intensity class (high, moderate and low) by the observed proportions, and inverting the resulting values. All aggregated scores for the state of wetland environmental values and anthropogenic pressure on wetlands were adjusted using the resulting weights, and summary statistics were recalculated. Both adjusted and unadjusted results are given in the 2020 wetland condition results report. Only unadjusted scores were used in analyses of difference between times.

It is recognised that such adjustments are an approximation, and because the proposed source of the bias is correlated with the response variables measuring wetland condition, the adjustment weights calculated would only partially compensate for the effect of the bias. However, this is adjustment using weights based on observed non-response rates is preferable to no adjustment. For future reports, model-based methods of estimating non-response bias will be explored.

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Glossary

Aggregated wetland assessment scores: The wetland assessment method uses scores at three levels – *indicators* are aggregated into four *subindices* based on wetland environmental values (WEVs). The WEV subindices are aggregated into two *indices*, overall pressure and overall state. The aggregation methods average the scores of indictors to derive subindex scores, which are in turn averaged to derive index scores.

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 section 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 subsequently acquired data. In the case of the wetland condition monitoring component of the Reef Report, baseline data for the wetland results reported here 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).

Generalised Randomised Tessellation Stratified (GRTS) sampling: A method for selecting a spatially balanced random sample of natural resources defined as areas, lines or points.

Non-response bias: A non-response bias occurs when randomly selected subjects (wetland managers) choose not to be involved in a study (wetland assessment), not at random, but in ways that are meaningful to the phenomenon under study.

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.

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/sub-index/sub-indices: The Wetland Condition Monitoring Program assesses two indices of wetland condition, overall anthropogenic **pressure** and overall **state** of wetland environmental values. Sub-indices of pressure are classes of pressure on wetlands (PCs), defined as: biological introductions, habitat disturbance and alteration, changes to water regime and pollutant input pressures. State sub-indices 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 wetlands' natural environmental values and the state of those values under a Driver, Pressure, State, Impact, Response (DPSIR) conceptual framework.

Human dimensions: social factors influencing agricultural management practice adoption

This report updates the method to collect, assess and report the social 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). This report outlines the results of the 2019-2020 social monitoring data and recommends 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 2020 communication strategy.

Introduction

The Reef 2050 WQIP recognises that a range of human dimensions (i.e., social, cultural, institutional, environmental and economic factors, see Figure 1) play a role in shaping outcomes associated with water quality and the Great Barrier Reef (Australian and Queensland governments 2018a, p. 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 governments 2018a, p. 7). Accordingly, the Reef 2050 WQIP set a human dimension target as follows:

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

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 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:

- 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).

Methods

As the lead agency for developing a human dimension baseline, the Office of the Great Barrier Reef (OGBR), Department of Environment and Science, funded a project to understand the human dimension indicators of agricultural innovation and stewardship behaviours (Hobman and Taylor 2018). The project identified key 'themes' and six 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. The quantitative measures will inform a social monitoring baseline against the Human Dimensions target for future Reef water quality report cards.

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[9]. The approach included development, testing and consultation in the 2022 Paddock to Reef program design review.

First year data, collected from a suite of cane and grazing projects, is presented in the Reef Water Quality Report Card 2020 with supporting communication handled through the Reef Water Quality Report Card 2020 communication strategy.

Applications of the data collection

The primary purpose of the human dimensions data is to provide a measurement of the social monitoring responses regarding agricultural management practice adoption and to create a baseline plus ongoing trend data to report progress towards the Reef 2050 WQIP human dimension target in the Reef water quality report card. The data also has several other important applications including:

- Providing insights into why (or why not) landholders are making particular land management decisions and the differentiating factors.
- Informing the design of future water quality investment programs by utilising 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 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.

[9] 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 (MPA) 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). This necessitated delays in expected delivery timeframes.

Social factors that influence agricultural management practice adoption

In the review of human dimension factors that are directly related to agricultural management practice change, Hobman and Taylor (2018) identified seven themes to help develop the social monitoring, and recommended measures. 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 is the practice.
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, or 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 'social factors' that measure the human dimensions that directly influence the capacity, motivations and barriers of landholder engagement and management practice adoption.

The themes were tested in a pilot project, with extensive stakeholder consultation to guide the format and design of Paddock to Reef questions (Appendix 5 and 6).

Question/s format and design

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 3) the landholder is considering changing (at the commencement of the project) or has changed (at the end of the project).

Table 3. 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 Best Management Practice (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. Landholders are asked to respond as follows:

Attitude. 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 (perceived behavioural control). A five-point scale (1 = strongly agree, 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. 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. Landholders are asked to 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. Landholders are asked to 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. As 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"*.

Reef Water Quality Report Card 2020 – social monitoring reporting

Social monitoring to support the 2025 Human Dimensions target in the Reef 2050 WQIP has been in place since mid-2019 and, as such, is still in early stages and continuously developing and improving both data collection and reporting. The planned reporting scale, assumptions and issues associated with the data was extensively workshopped with the Human Dimensions Working Group and experts were engaged to assist with reporting (Dr Tracy Schultz and Dr Angela Dean).

Reporting scale

The pathway for reporting social monitoring data in the Reef water quality report card will vary slightly from year to year, depending on the data availability and granularity, emerging trends and the content management system (CMS) capability. The current CMS does not allow for interactivity details, so a visually simple approach has been chosen. New features including interactivity and a split of data per region and other commodities will be added in future reports.

Data have been collected from the grazing, cane and banana industries. However, only the grazing and cane industries have sufficient data for inclusion in Report card 2020. Banana industry data will be included in future report cards. The granularity of data collected from the grazing and cane industries varies across Reef regions and in some regions, numbers are well below the threshold. The threshold for minimum reporting is set at 50 records per region and commodity, which is considered a reasonable level to ensure a greater level of confidence in the data and farmer cohort anonymity.

Case studies

In addition to social monitoring data, the Reef Water Quality Report Card 2020 will also include narrative case studies to share examples of individual practice change journeys and personal grower stories.

Data collection issues

The current data collection mechanism is still under development to increase functionality of pairing data from one year to the next. Further, social monitoring is voluntary and farmers can choose to report in one year but not the next. For this reason, and to report on industry trends, data is aggregated to present the results of a whole cohort, while noting that the individuals in the cohort may potentially be different. The relevant information is presented at a project level and only projects that have provided ‘before’ and ‘after’ data are included in analysis. Those that have provided only ‘before’ data will be reported in future report cards. This limits the current size of the data set; however, it presents an approach more consistent with the management practice adoption reporting.

The key social findings from the Human Dimensions program will be presented as follows in the Reef Water Quality Report Card 2020:

- Two infographics (grazing and cane) showcasing motivations (before engagement in the project), barriers, attitudes and self-efficacy (after engagement in the project),
- Data (graphs) supporting the two infographics (Appendix 1).

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 data at the higher level.
- Updated grading scales: social monitoring data should not be reported in an ABCD grading scale as this has been identified as inappropriate for this type of social monitoring.
- Further testing with stakeholders and users of report cards.

Data limitations

Table 5. Limitations of data collection approach

Limitations	**How is it 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 reassurance regarding data confidentially.
Data of *participating* landholders is currently 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. extension officers) • Seek other opportunities to collect data from a range of stakeholders in the practice change value chain (i.e. potentially as part of Management Practice Adoption baseline reset in 2022).

Limitations	How is it addressed:
Data is collected from landholders in Australian or Queensland government funded programs: some regions and commodities will not have social monitoring data reported against the Human Dimensions target.	• Where no or limited data (below 50 records) exists for a region and/or commodity, this will be stipulated in the report card as N/A (Not Applicable).
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 inability for data pairing at the landholder level.	• Investigate options to facilitate pairing of data. • Other data collection mechanisms will be considered. Data pairing is important to report and adapt programs based on changes that happen at the landholder level, to accurately reflect their engagement in the practice change journey.
Survey questions limitations, including scale and demographic and refinements needed.	• Consult with extension providers and industry in advance to determine changes that are required to the social monitoring questions. This will be completed in time to inform the Paddock to Reef program design review.
Database limitations involving download and transfer processes posing risks to integrity.	• Investigate database options that allow upload and download efficiencies as well as effective analysis and reporting.

Data privacy and informed consent

The program complies with the *Privacy Act 1988* 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 Office of the Great Barrier Reef 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.

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