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Final Report

Evaluating services provided by ponded pasture wetlands in Great Barrier Reef catchments – Tedlands case study

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JAMES COOK UNIVERSITY AUSTRALIA

Evaluating services provided by ponded pasture wetlands in Great Barrier Reef catchments – Tedlands case study

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Cover photographs: (front) Tedlands wetland, Sarina; (back) Field staff deploying high frequency water quality logger in ponded pasture wetland. Images: Nathan Waltham.

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ACRONYMS

ALA............... Atlas of Living Australia
DES............... Department of Environment and Science
EC................. Electrical conductivity
GBR.............. Great Barrier Reef
NESP............ National Environmental Science Program
NATA............ National Analytical Testing Accreditation
TWQ.............. Tropical Water Quality
UAV.............. Unattended Automated Vehicle

ABBREVIATIONS

ha.................. hectare
km^2/yr .... kilometres squared per year
mg/L .... milligrams per litre
SE................. standard error
TN year^{-1}....... Total Nitrogen per year

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EXECUTIVE SUMMARY

1. Coastal floodplain wetlands provide essential habitat for a range of flora and fauna that hold/support cultural, social and economic values. However, not all wetlands provide the same values and services. Understanding the different values and stakeholder expectations is, therefore, critical to effectively managing wetlands. A 'one size fits all' approach can often lead to inappropriate management and restoration outcomes that are poorly aligned with project objectives.
2. Ponded pasture wetlands, created by tidal bunding, is extensive across the Great Barrier Reef catchment coastline. Primarily developed to provide late dry season forage for cattle, these wetlands now support freshwater ecological communities, on what was previously estuarine habitat. There is also increasing interest to remove tidal bund walls to allow seawater inundation, promote estuarine habitat and support blue carbon initiatives. Understanding the values ponded pasture wetlands currently hold/support will be critical to having informed decision making and reducing the probability of unintended consequences from any bund removals.
3. This study collates existing data, and presents new data, on the ecological values supported at the Tedlands wetland complex and the adjacent Marklands and Lloyds wetland complexes. All three of these wetlands are ~45 km (Euclidian distance) south of Mackay and were created by tidal bunding. Data collated covers water quality, vegetation extent, fish assemblages, and seawater.
4. The Tedlands wetland complex holds/supports considerable freshwater biodiversity and potential water quality improvement values. In addition to being home to many water and shore birds, the complex also supports at least 15 species of fish, such as the commercially valued barramundi and the southern purple-spotted gudgeon. The complex is also estimated to potentially remove, on average, 12-15 tonnes of nitrogen each year from watercourses draining agricultural catchment and flowing to the Great Barrier Reef. In addition, it provides a freshwater habitat over 150 different water bird species that have been recorded in the wetland and nearby.
5. Further, more comprehensive biodiversity, water quality and carbon assessments are required to understand the impacts of altered hydrology on the vegetation assemblages in downstream mangrove; examine how habitat enhancement and green engineering could further support biodiversity values; and identify the economic, social and cultural values held by stakeholders.
6. Freshwater wetlands provide incredible services and values, even when they established following landscape modification, and worth protecting in their own right particularly when so many have been lost or modified.

1.0 INTRODUCTION

Coastal floodplain wetlands provide essential habitat for a range of flora and fauna that hold/support cultural, social and economic values, delivering diverse amenity and ecosystem services (Elliott et al., 2016; Elliott & Whitfield, 2011; Gorski et al., 2011; Waltham & Fixler, 2017). Approximately 10% of global animal biodiversity is associated with freshwater ecosystems, which occupy <1% of Earth's surface (Dudgeon, 2019). Their low-lying position makes them vulnerable to runoff from urban, agricultural and industrial sites (Barbier et al., 2011; Creighton et al., 2015), sea level rise from climate change (S. Lee et al., 2019; Rogers et al., 2019), and drainage and reclamation (Coleman et al., 2008). Global floodplain wetland loss is estimated at 95 km^2/yr (Coleman et al., 2008; Davidson, 2014). Furthermore, a global assessment predicts that climate change will likely or highly likely exacerbate the impacts of habitat loss and fragmentation for 100% of all wetland ecosystems; by comparison, rainforests (the next most impacted ecosystem) are predicted to have a substantially lower proportion (45%) exacerbated (Segan et al., 2016). There is, however, an increasing global movement to halt this loss and degradation, and to commence large-scale programs to repair and restore coastal wetland ecosystem habitat and connectivity (Barbier, 2013; Van Coppenolle & Temmerman, 2019). The United Nations General Assembly declared 2021-2030 as the Decade of Ecosystem Restoration, embedded within multiple global Sustainable Development Goals, including the universal provision of clean water access, the sustainable management of land and water ecosystems, and climate action (United Nations General Assembly, 2015).

Like the rest of the world, Australia faces a legacy of degraded freshwater ecosystems, despite a small population and a relatively short 200 years of urban, industrial and agricultural development (Creighton et al., 2016). Between 2001 and 2017, the Great Barrier Reef (GBR) catchment experienced net loss of 740 ha of coastal floodplain wetland. While contemporary loss has been relatively small, since European arrival approximately 77 500 ha of palustrine wetland has been lost, much of which from freshwater floodplain systems. Artificial/highly modified wetlands, however, increased substantially over this period, increasing by 21 690 ha, much of which was created through bunding (8299 ha) (Department of Environment and Science, 2019; Environmental Protection Agency, 2005). This loss of natural habitat, and the degradation of remaining habitat, is also reducing the GBR's resilience to pressures via on-going pollutant runoff (Adame, Arthington, et al., 2019; MacNeil et al., 2019; Waterhouse et al., 2016), and reduced habitat availability for species with freshwater life stages (Adame, Arthington, et al., 2019; Arthington et al., 2015). Not only do coastal freshwater floodplain wetlands support diverse biological communities, they support connected ecosystems as they provide habitat for migratory species, regulate flows, reduce sedimentation and reduce nitrogen runoff (Bainbridge et al., 2009; Brodie & Waterhouse, 2012; Waterhouse et al., 2016). While artificial/highly modified wetlands are unnatural, their creation may be mitigating impacts of freshwater floodplain wetland loss that has occurred since European arrival – though little examination of this has occurred. This has sparked management goals seeking to maintain and improve the extent and condition of wetlands (Box 1; State of Queensland 2018).

The push for restoration of coastal wetlands has been met with optimism by scientists (Waltham et al., 2020); however, to date, many restoration projects have been unable to demonstrate success, in part, due to the lack of scientific guidance and data (Paschke et al., 2019; Waltham et al., 2019; Weinstein et al., 2019). For instance, removing non-native macrophytes is common regardless of whether the goal of the restoration is to improve water quality or to increase biodiversity (Zedler & Callaway, 2000). If biodiversity outcomes are expected, the removal of non-native macrophytes could be important, as they reduce oxygen availability in the water column, which results in reduced fish habitat (Perna et al., 2012; Waltham & Fixler, 2017). However, macrophyte removal efforts might be conducted differently if the goal is improvement of water quality, as denitrification will decrease if the macrophytes are removed (Alldred & Baines, 2016). Therefore, a 'one size fits all' approach can often lead to inappropriate restoration outcomes that are poorly aligned with project objectives (Hobbs et al., 2009; Hobbs & Harris, 2001). Inappropriate applications of restoration methods can be prevented by examining their outcomes on the services provided by the wetlands where they have been applied previously and then using those learnings to assess the suitability at future restoration sites. The Queensland Government's *Wetlands of the Great Barrier Reef Catchment Management Strategy (2016-2021)* has a framework to assist practitioners evaluate the components and processes of the target ecosystem, and to assist in setting values and services as targets for restoration (Box 1).

The removal of tidal bunds to restore estuarine habitats has become an attractive option for coastal restoration managers in Australia (Kelleway et al., 2017), including the GBR catchments, to capitalise on carbon sequestration potential (Bell-James & Lovelock, 2019; Stewart-Sinclair et al., 2020). This change to wetland management has occurred with little attention given to the consequences of methane and nitrous oxide emissions changing ponded pasture to mangrove in nutrient-laden waters (Grinham et al., 2018; Kreuzwieser et al., 2003; Rosentreter et al., 2018). Tidal bund walls were initially constructed in many places along the GBR coastline to provide stock with ponded pasture as late dry season forage. The exclusion of saline sea water permitted the growth of freshwater macrophytes, including Para grass (*Urochloa mutica*), Aleman grass (*Echinochloa polystachya*) and Olive hymenachne (*Hymenachne amplexicaulis*), allow the health and condition of livestock to be maintained throughout the dry season – saving on brought-in supplementary feed and improving farm resilience to drought (Abbott et al., 2020; Challen & Long, 2004; Hyland, 2002). Whilst they provide on-farm benefit, ponded pastures also support a range of other values and processes; whether those processes are deemed positive or negative is context dependent on the beneficiary being considered. There have been minimal new ponded pastures since a moratorium on ponded pastures was introduced in 1991, and since replaced by the *Ponded Pastures Policy (2001),* Fisheries Act (1994), Coastal Protection and Management Act (1995) and the Planning Act (2016). Understanding these values and processes, and those provided by an altered system where tidal bunds have been removed to allow seawater ingress, would be critical in deciding whether tidal bund removal at ponded pasture wetlands is a suitable restoration technique for future coastal wetland repair projects (Abbott et al., 2020).

Ponded pasture wetlands are primarily freshwater ecosystems, with the potential to support a range of aquatic fauna, either for all or part of their lifecycle, aquatic vegetation, and may improve water quality draining to the GBR by trapping sediment and removing nutrients. Ponded pasture wetlands have the potential to provide floodplain habitat for freshwater species and may compensate some of the loss of natural floodplain freshwater wetlands. Though, the extent to which the values are realised depends on the nature and design of the wetland. If the tidal bund wall becomes a direct barrier to flow and biots, then this could effectively limit available habitat for some species to complete lifecycles, for example, diadromous fish (e.g., mangrove jack). On the central Queensland plains, it has been estimated that more than

16,000 ha of ponded areas occur adjacent to important fish nursery areas (Houston & Duivenvoorden, 2002). This estimate, however, was made before effective mapping was established (Environmental Protection Agency, 2005). With high aquatic plant growth/high organic load and warm water conditions associated with the bund walls, the stagnant waters can (though not always) also become anoxic (Burrows et al., 2012). While these conditions may be favourable for denitrification of nutrient runoff, resulting black water events can contribute to fish kills not only in the pond itself (Butler & Burrows, 2007), but extend downstream into estuaries (Burrows et al., 2012; Burrows & Perna, 2005). Ponded pastures could also trap sediment that would otherwise be transported to the reef. While this may be a positive for reef health (as sedimentation requires reduction) (Brodie et al., 2017; Hairsine, 2017; Wolanski & Duke, 2002), it may also be a negative for downstream estuaries that can become sediment-starved, causing bank erosion and channel incision (Sheaves et al., 2007). The provision and desirability of these processes will inevitably depend on local values and be a determinant on whether bund removal for restoration is a suitable technique for a particular repair project.

Effectively managing wetland values within the GBR catchment has, in part, been constrained by a lack of understanding on biodiversity patterns and ecosystem service provision (Boer, 2010; Burley et al., 2012; Shoo et al., 2014). Informed decision making can reduce the chance of unintended consequences; in the context of bund wall removal, which requires understanding the values of existing ponded pasture wetlands and those of the potential replacement ecosystem. If ponded pastures are providing habitat on floodplains to freshwater species and mitigating (to some degree) the loss of natural freshwater floodplain wetlands, then their loss may result in undesirable outcomes for freshwater biodiversity. To assist with this knowledge gap, here we collate existing data, and collect new data, on the values provided by the Tedlands wetland complex – one of the largest ponded pasture wetlands in the GBR catchment, and two adjacent ponded pasture wetlands – Marklands and Lloyds.

Box 1. GBR wetlands management framework.

Legislation governing Australia's Great Barrier Reef (GBR), a World Heritage Area and National Marine Park, reflect a desire for coastal wetland restoration. In response to the loss of coastal wetlands that are reducing the GBR's resilience to future disturbance, the overarching framework for managing the GBR, the *Reef 2050 Long-term Sustainability Plan* (Reef 2050 Plan hereafter), and its subordinate *Wetlands in the Great Barrier Reef Catchments Management Strategy 2016-2021* (Reef wetlands strategy) and *The Reef 2050 Water Quality Improvement Plan 2017-2022* (Reef WQ Plan), all recognise the need to maintain and improve the net extent and condition of wetlands, within a whole-of-system catchment management approach. In addition to the Reef 2050 Plan framework, there are numerous laws regulating the development or disturbance of coastal habitats, including the Australian Government's *Environment Protection and Biodiversity Conservation Act 1999* and the Queensland Government's *Environmental Protection Act 1994*, *Fisheries Act 1994*, *Marine Parks Act 2004*, *Planning Act 2016*, *Vegetation Management Act 1999* and *Water Act 2000*. While the *Queensland Environmental Offsets Act 2014* provides a framework to facilitate environmental offsets that may lead to restoration of degraded habitats or creation of wetlands with demonstrable benefits.

Whole-of-system catchment management is an integrated approach to catchment management and the protection, maintenance and restoration of wetland systems (catchment strategy). The approach integrates information on natural and human values of a wetland with catchment functioning. Most wetlands have multiple values and managing wetlands effectively involves balancing these values to achieve the best outcomes economically, socially and environmentally. Restoring wetland services first requires defining the values desired, for example, bird habitat, fish habitat, water quality, carbon abatement, hydrology, or cultural. These values will differ between stakeholders and locations. Ecosystem repair strategies seem to be most effective when values of all stakeholders are incorporated, a process best facilitated through discussions to set objectives early in the project lifecycle. Often there will be trade-offs between values, for example, wetlands designed for high nitrogen attenuation are often poor for carbon abatement. The nature of the catchment can heavily influence the ability of a wetland to support given values, integrating desired values with catchment functioning is, therefore, critical to successful restoration. Once the values are set and agreed to by relevant stakeholders, wetland restoration projects can then be prioritised and implemented in a way that supports the identified values and catchment constraints, maximising the likelihood of a successful restoration that is generally accepted.

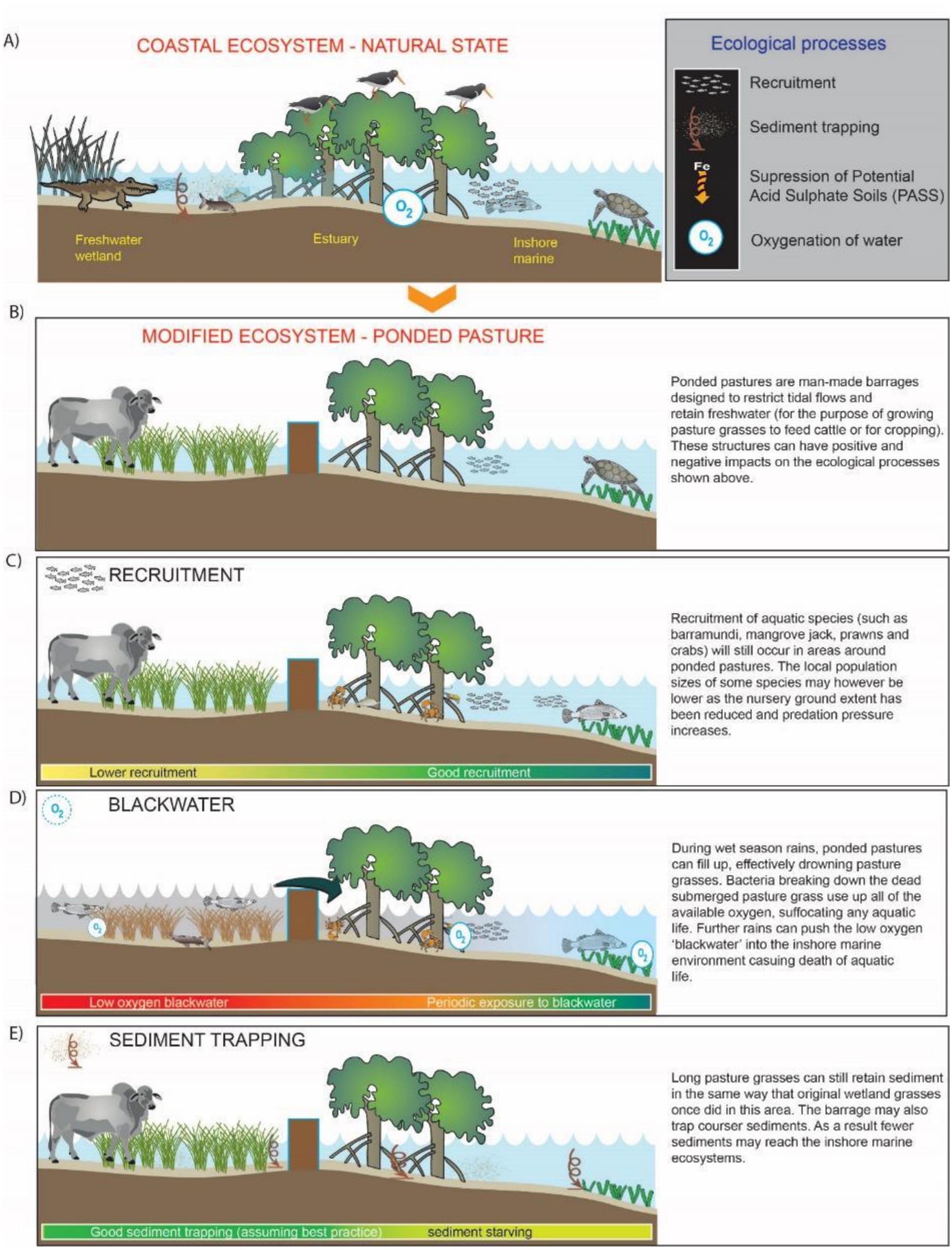

Figure 1: Conceptual diagram of bund walls in coastal wetlands (Source: Paul Groves, Great Barrier Reef Marine Park Authority)

1.1 Case study sites

All three sites examined are largely palustrine wetlands, created with earth tidal bunds largely preventing salt water intrusion, and are largely used for ponded pasture. Prior to the construction of tidal bunds, the wetland would have been estuarine and supported mangroves, salt flats and saltmarshes, similar to the adjacent wetlands on the creek side of the bund (Department of Environment and Science, 2019; Environmental Protection Agency, 2005). The three sites are typical of those occurring along the GBR coastline, and contain para grass (*Urochloa mutica*), olive hymenachne (*Hymenachne amplexicaulis)*, Aleman grass (*Echinochloa polystachya)*, salvinia (*Salvinia molesta)*, and water hyacinth (*Eichhornia crassipes*). All are declared weeds and spread either by spore/seed or asexually through fragmentation, with their growth often exacerbated by nutrient enriched runoff and spread by cattle movement (Abbott et al., 2020).

Tedlands (149.299319 E, -21.562048 S) is a 293 ha wetland complex located near the outflow of Rocky Dam Creek at the end of Landings Road, approximately 20 km south of Sarina in Central Queensland (Figure 2). In 2007, Conservation Volunteers Australia completed $2 million enhancement project that included feral pig exclusion fencing from parts (though not all and pigs are still visible in places now), controlled burning of exotic grasses, and aquatic fauna surveys (Queensland Wetlands Programme & Australian Government, 2009). In 2019, Catchment Solutions Ltd rejuvenated the existing fish ladder at Tedlands to improve performance as it was showing signs of poor efficacy. The eastern ladder also underwent repairs in 2020. These were necessary as bund walls can inhibit fish passage and may reduce the occupancy of fish within the wetland.

Marklands (149.28002 E, -21.5291 S) is a 672 ha wetland complex located off a tributary draining the western catchments into the outflow of Rocky Dam Creek. Most of the complex is highly ephemeral, with a small lagoon (~300 m^2) behind the bund wall that is permanent (Figure 3).

Lloyds (149.362834 E, -21.552702 S) is a 53 ha wetland complex located to the east of Rocky Dam Creek, draining first order streams directly to the coast. In the absence of the bund wall, the wetland would have been similar to the estuarine salt flats and saltmarshes directly downstream of the bund wall (Figure 3).

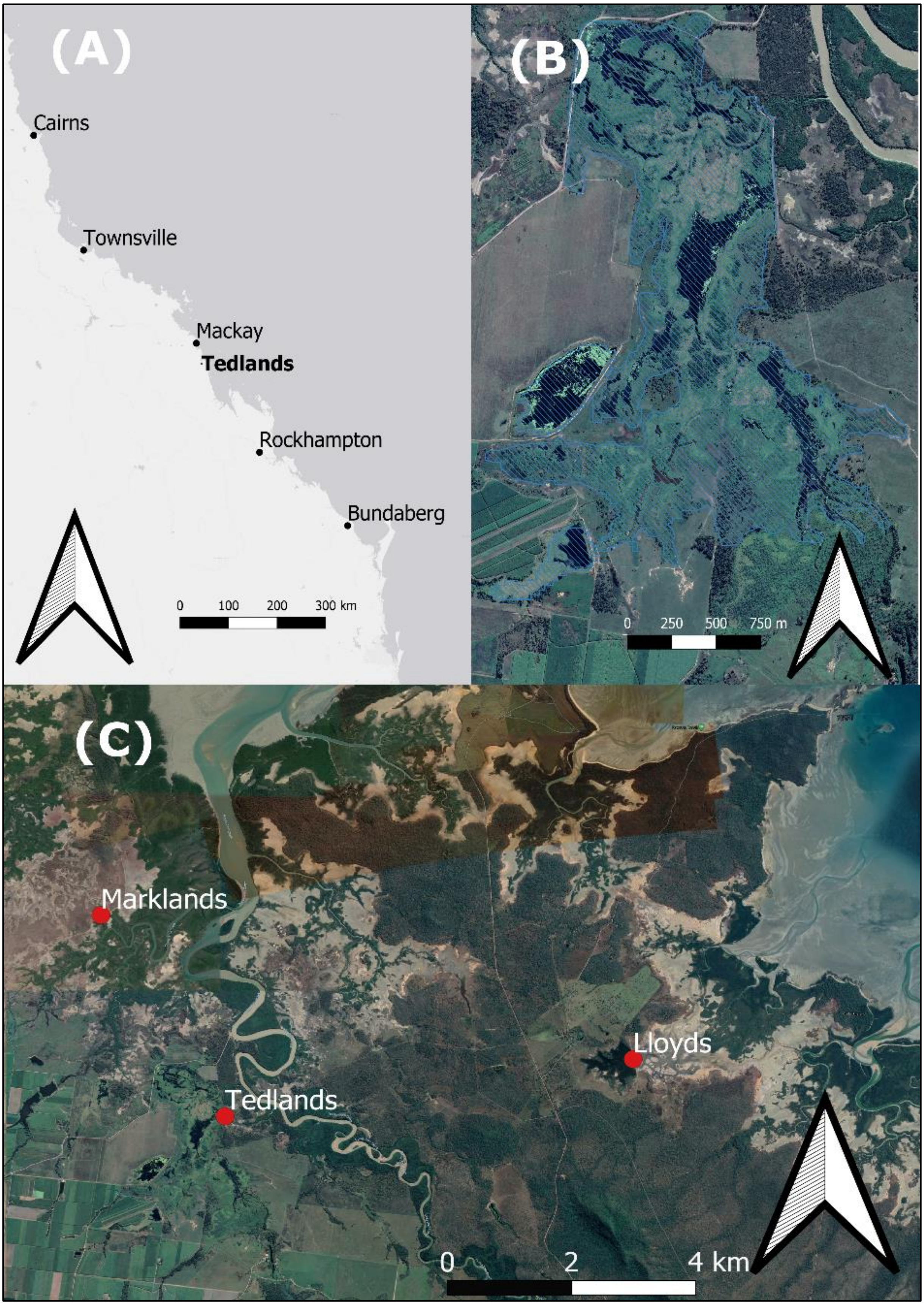

Figure 2: The (A) location and extent; (B) of the Tedlands wetland complex, and (C) the locations of the three continuous data loggers at the Marklands, Tedlands and Lloyds wetlands.

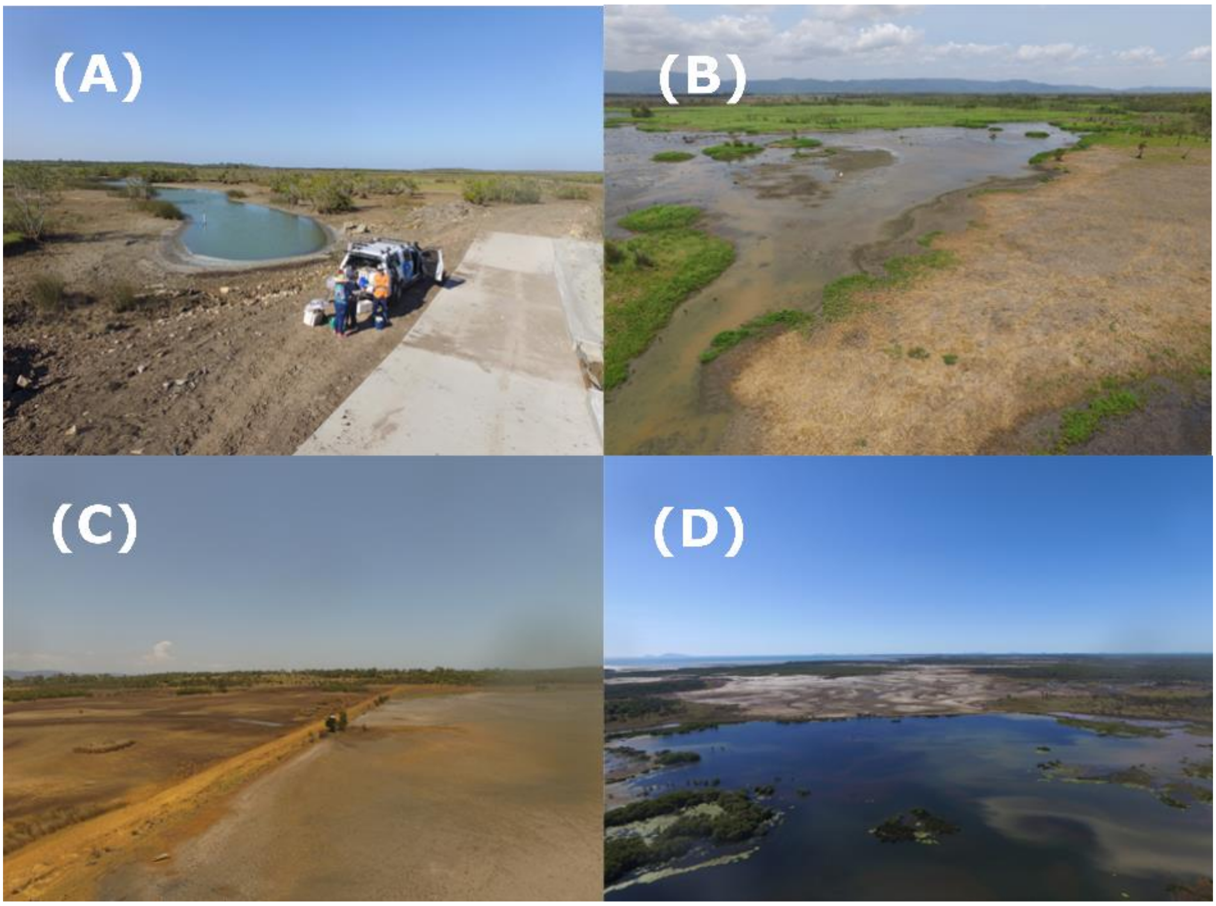

Figure 3: (A) Fish ladder installed on Marklands to allow fish to migrate from estuary into wetland during connection; (B) Tedlands after aerial spraying of water weeds; (C) Lloyds ponded pasture wetland in the late dry season where the wetland is almost completely dry; and (D) Lloyds ponded pasture wetland post wet season after wetland is filled and full of life upstream of the earth wall.

2.0 METHODOLOGY

2.1 Physicochemical monitoring

Logger network
Wetland water depth, temperature and electrical conductivity (EC) were monitored by loggers (CTD-Diver, Eijkelkamp Soil & Water, The Netherlands) permanently located at the outflows (saltwater side of bund wall) of the following sites:

1. Tedlands wetland (149.299319°, -21.562048°) from 21/06/2019 – 15/07/2020.
2. Marklands wetland (149.280020°, -21.529100°) from 15/12/2019 – ongoing.
3. Lloyds wetland (-21.552702°, 149.362834°) from 15/12/2019 – 14/07/2020.

The loggers captured data from the bottom of the water column (10 cm above the soil surface) every 20 minutes and were downloaded as part of monthly routine maintenance visits. Data from the logger at Marklands has not yet been collected.

For each logger, the number of periods (over the entire record) where conductivity was maintained continuously at <16, 16-27, 28-37, 38-55 and >55 mS/cm for periods of <7, 7-13, 14-20, 21-59, 60-89, 90-119 and >120 consecutive days. These thresholds and durations correspond to the introduced macrophyte tolerance thresholds for saltwater exposure examined by Reid *et al* (2018).

Water quality grab sampling
Water quality grab samples were collected sporadically by Reef Catchments between 16/05/2019 and 14/05/2020 from three locations within the Tedlands wetland complex (Figure 4) and tested for the following:

- Total suspended solids
- Turbidity (lab)
- Turbidity (field)
- Ammoniacal nitrogen
- Nitrate-nitrogen
- Nitrite-nitrogen
- Nitrate-nitrite-nitrogen
- Total Kjeldahl nitrogen
- Total nitrogen
- Total phosphorus
- Dissolved reactive phosphorus
- Electrical conductivity (field)
- pH (field)
- Dissolved oxygen (field)
- Temperature (field)

All samples were analytically tested by ALS Environmental, a laboratory that is accredited by NATA for compliance with ISO/IEC 17025 testing standards.

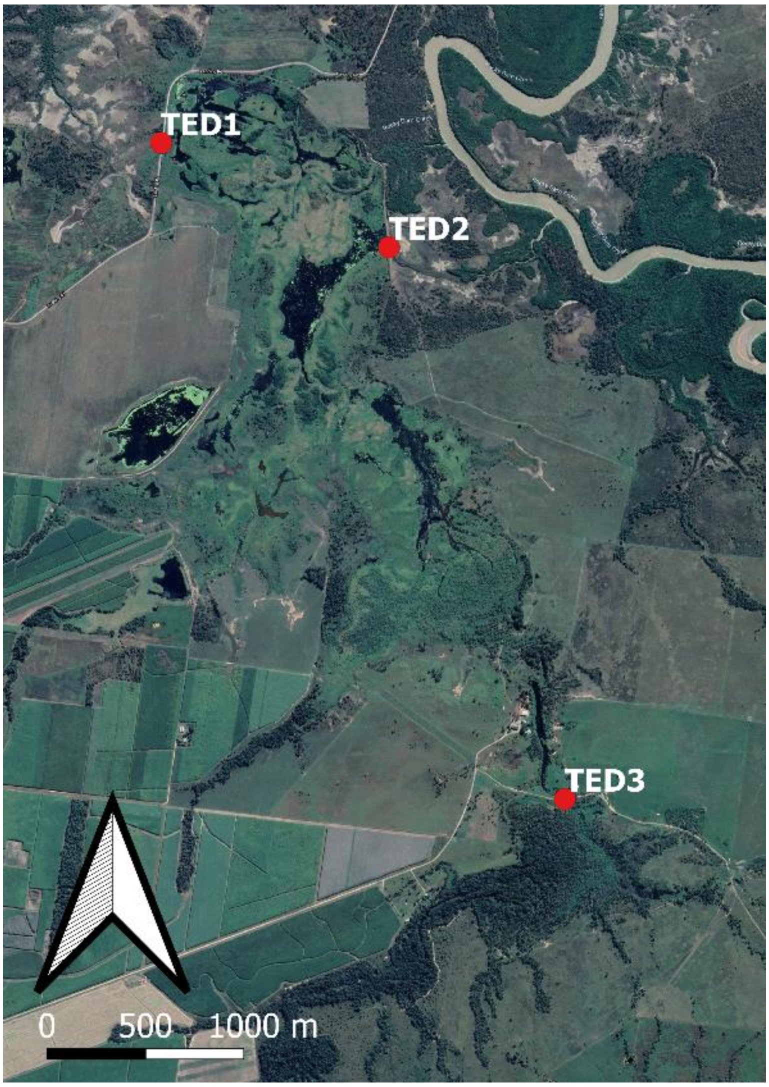

Figure 4: The locations of three water quality sample sites within the Tedlands wetland complex.

2.2 Vegetation monitoring

Aerial imagery of the study wetland area was collected using an unmanned aerial vehicle (UAV) (DJI Phantom 3). UAV's were flown at all three sites in December 2019 and July 2020 in order to encompass changes seen in the wet (January) and dry season (June/July). Given the size of all sites and limited UAV battery life, only parts of the sites could be surveyed (Figure 5). At Tedlands, two parts were imaged, one near the TED1 water quality site and the other near TED2. Individual images were georectified and stitched together using the online platform 'DroneDeploy' (www.dronedeploy.com) to create an orthomosaic image for each survey at each site. The image resolution was set to 0.3 m. A total of 4 stitched orthomosaic images with 3 bands (Red, Green and Blue) were produced. The high tide line or wetland extent was manually digitised using a polygon on each image. Where the boundary line could not be distinguished, the tree line was used as a proxy. This polygon was buffered 5 m, to account for any potential error in delineating the high tide line and each image was clipped to the buffered polygon.

Ground cover types were identified for classification into dominant classes. A training set was created for each orthomosaic image by assigning a minimum of 30 polygons for each ground cover type. In some cases, not all classes were present within an image, for example some images contained no visible aquatic plants or water. In other cases, very small extents of the class were evident in images, such as small patches of acid sulfate soils which resulted is less than 30 training samples for that class. Image classification was performed with the 'Maximum Likelihood Classification' tool in ArcGIS (Version 10.7.1) using equal *a priori* probability weighting. In order to calculate the proportion of each ground cover class, the number of pixels in each class was extracted from ArcGIS. The proportion was calculated by dividing the number of pixels in each class by the total number of pixels (obtained by adding the number of pixels of each class together). In some cases, images contained a black border, where this was applicable it was included in classification as a N/A category. Any areas classified as N/A were removed from the total number of pixels so the proportion encompassed only the wetland extent.

Classification accuracy was assessed against 100 randomly distributed points that were manually classified and independent of the training dataset. Points were created using the 'Create Accuracy Assessment Points' tool in ArcGIS. The distribution of points across each orthomosaic was different between sites, while the position of points remained static within each site between survey events. Classification data was added to these points from the final classified image using the 'Update Accuracy Assessment Points' tool. Each point was then truthed by visually inspecting the image to confirm it had been classified correctly, any errors were manually corrected. A confusion matrix for each site and survey was developed using the 'Compute Confusion Matrix' tool in ArcGIS to assess the accuracy of each classification. Classification accuracy was assessed using Cohen's Kappa (McHugh, 2012) against 100 random points that had been manually classified independent of the training data. A value closer to 1 meaning the classification is more accurate and the map produced is more representative of reality.

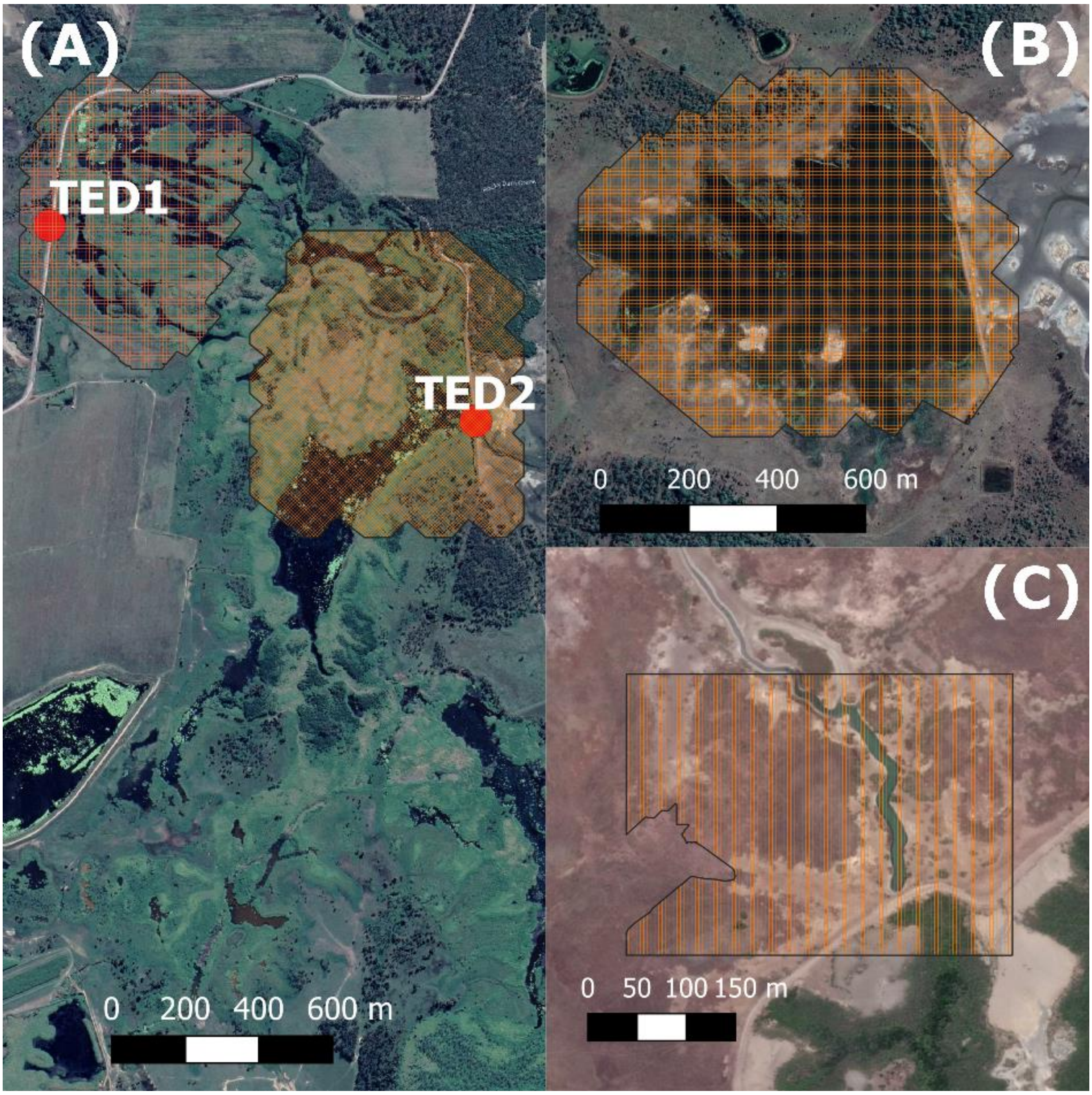

Figure 5: The locations and extent of drone imagery capture within (A) Tedlands, (B) Lloyds and (C) Marklands wetland complexes.

2.3 Biodiversity

Australian Living Atlas Vertebrate Records

All data on vertebrate sightings from within the three wetlands recorded in the Atlas of Living Australia (ALA) were extracted. ALA is a large database that collates sightings of animals from a wide range of organisations and contributors. Records within the database do not provide an exhaustive inventory of all species present or absent at the site and are not the findings of thorough, systematic surveys. Rather they are largely sporadic sightings that may supplement more rigorous surveys.

Fish assemblage

Catchment Solutions (contracted by Reef Catchments) surveyed the fish assemblages at both the Tedlands and Marklands wetlands in August 2019 and May 2020 (McCann & Moore, 2019, 2020), while the former Department of Primary Industries and Fisheries surveyed Tedlands in 2007 (Marsden & Power, 2007). Briefly, boat electric fishing was used to stun and capture fish across a variety of depths, aiming to encompass all accessible habitats. The fork length and total lengths were measured for all forked and non-forked species respectively, for up to 20 individuals. For more detailed methods, see McCann & Moore (2019, 2020) and Marsden & Power (2007).

Birdlife Australia

All data on bird sightings from within Tedlands wetland, as recorded in the Birdlife Australia's Birdata database, were extracted. There were no records available at Lloyds and Marklands. While Birdlife Australia contributes to the ALA database, many records are not submitted, requiring a separate extraction from Birdlife Australia. Similar to the ALA, the database is a collation of records from a wide range of organisations and contributors; however, recreational observations are not included, with preference given to systematic surveys covering at least 2 ha.

2.4 Nitrogen removal estimates

Wetlands can remove nitrogen from surface waters via denitrification. The extent to which nitrogen is removed depends on many factors, including: the concentration and speciation nitrogen inflows; hydraulic loading rate, residence time and efficiency; temperature; wetland size and shape; composition of the ecological community (particularly the vegetation type and density); sediment type and composition; and oxygen concentrations and redox potential (Alldred & Baines, 2016; Land et al., 2016; Vymazal, 2017).

Many of these variables have not been assessed at Tedlands and there is considerable uncertainty in estimating nitrogen removal by these wetlands, attributed to both ecological and methodological factors. We used two published relationships to estimate the plausible nitrogen removal potential by Tedlands wetlands (area = 293 ha) between 2000 and 2019 – the first by Land et al (2016) and the second by Adame et al (2019).

Land et al (2016) approach

Land et al (2016) carried out a meta-analysis to estimate derived equations for estimating denitrification in both natural and artificial wetlands across a range of climates. The meta-analysis was global, recruiting 93 articles with 203 wetlands. We estimated denitrification at Tedlands by applying the best fitting model (R^2=0.72) of denitrification found by Land et al (2016); this model used the hydraulic loading rate, temperature, wetland size and the inflowing nitrogen concentration.

Adame et al (2019) approach

Adame et al (2019) predicted the *potential* denitrification rates for 16 coastal wetlands across North Queensland from inflow nitrate-nitrogen concentrations (R^2=0.46). This regression was used to estimate the potential daily denitrification rate at Tedlands and compared with the inflow nitrate-nitrogen flux (Adame et al., 2019).

Daily inflow nitrogen flux was estimated using the numeric integration method (Ferguson, 1987). Although a flow-regression or a flow-ratio based method for flux estimation may be preferred, there was no correlation between concentration and daily flow (R^2=0.02, $P>0.05$). It was assumed that, for each day, the nitrogen estimated to be delivered to Tedlands is denitrified up to the capacity of the potential denitrification, while loads in excess of the potential denitrification rates are not denitrified. We compared this for denitrification potentials estimated by both the Land et al (2016) approach and the Adame et al (2019) approach.

As there was no flow recorder and instream nutrient monitoring at Tedlands Creek, we used nutrient, temperature and flow data collected from the nearby Sandy Creek at Homebush (https://water-monitoring.information.qld.gov.au/). Sandy Creek has a long term flow recorder (since 1966) and has recent water quality monitoring data. Both catchments drain cane-dominated catchments with similar climates.

Given their close proximity (~35 km) and similar catchment land use, it is likely that the climate and, consequently, rainfall-runoff patterns (i.e., the shape of the hydrograph) and temperature records would be similar between the two creeks. This is further reinforced by the coefficient of variations for annual rainfall-runoff (soil water surplus) totals being very similar (Sandy Creek = 1.05; Tedlands Creek = 1.04), as estimated from rainfall data between 1971-2000 in the Australian Water Resources Information System (AWRIS; Stein et al., 2011). As the AWRIS database only estimates total monthly rainfall-runoff, it is too coarse for use in estimating denitrification as the hydraulic loading from floods and droughts become averaged out. To emulate a more plausible flow record for Tedlands Creek, we scaled down the hydrograph recorded at Sandy Creek at Homebush (https://water-monitoring.information.qld.gov.au/) between 2000 and 2019 by reducing daily flows in proportion to the difference in catchment size.

3.0 RESULTS AND DISCUSSION

3.1 Hydrology and physio-chemistry

The electrical conductivity (EC) on the saltwater side of the bund wall at the Tedlands wetland complex increased steadily from that correlative of ~30% seawater in June 2019 (beginning of record) to that correlative of 100% seawater in August 2019 (Figure 6), where it largely maintained a similar EC until November 2019 (Reid et al., 2018). EC dropped sharply in November 2019 to levels correlative to <10% seawater, coinciding with beginning of high rainfall at the Koumala Hatfields road climate monitoring station (Figure 6).

The EC on the saltwater side of the bund wall at Lloyds wetland complex remained very low; however, was regularly and briefly punctuated with very high conductivity readings (similar to that in marine waters) every month, coinciding with timing of tides greater than 6 m at Half Tide Tug Harbour.

Across the three sampling occasions, the two sites within Tedlands consistently had very low dissolved nitrogen concentrations, while total nitrogen ranged from 0.4-1.2 mg/L and total phosphorus ranged from 0.02 to 0.12 mg/L (Table 1).

Table 1: Water quality monitoring results collected, as grab samples, at the Tedlands wetland complex by Reef Catchments and analysed by ALS Environmental.

Site	Date	pH	Cond (µS/cm)	TSS (mg/L)	Turbidity (NTU)	Ammonia-N (mg/L)	Nitrite-N (mg/L)	Nitrate-N (mg/L)	NNN (mg/L)	TKN (mg/L)	TN (mg/L)	TP (mg/L)	DRP (mg/L)
TED1	26/03/2019	6.75	233	15	11.5	0.09	<0.01	<0.01	<0.01	1.2	1.2	0.12	0.02
TED1	25/06/2019			2	3.7	0.1	<0.01	<0.01	<0.01	0.5	0.5	0.02	<0.01
TED1	16/05/2019			4	4.5	0.07	<0.01	<0.01	<0.01	0.9	0.9	0.04	<0.01
TED3	26/03/2019	7.08	242	6	3.6	0.04	<0.01	<0.01	<0.01	0.8	0.8	0.05	<0.01
TED3	25/06/2019			10	10.1	0.09	<0.01	<0.01	<0.01	0.4	0.4	0.04	<0.01
TED3	16/05/2019			4	4.1	0.07	<0.01	<0.01	<0.01	0.5	0.5	0.02	<0.01

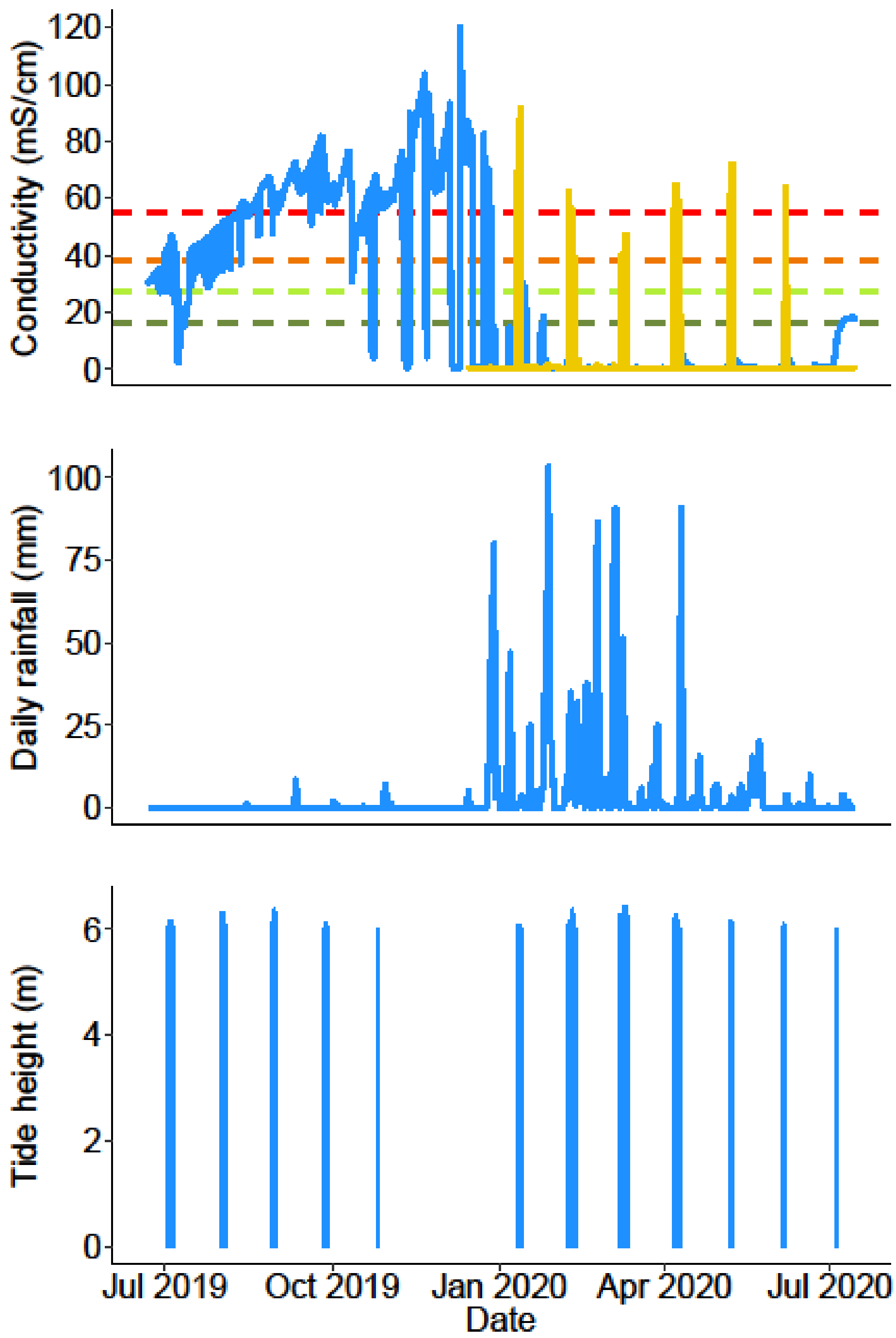

Figure 6: (Top) The electrical conductivity continuously measured at the saltwater side of the bund wall outflows for the Tedlands (blue) and Lloyds (gold) wetland complexes. Red, orange, light green and dark green dashed lines indicate conductivity readings correlative of 100%, 70%, 50% and 30% seawater respectively – weed-salinity thresholds examined by Reid et al (2018). (Middle) The total daily rainfall (middle) as measured at the nearby Koumala Hatfields Roads rainfall station operated by the Bureau of Meteorology. (Bottom) The days where the high tide height was at least 6 m at the nearby Half Tide Tug Harbour tide gauge.

3.2 Biodiversity

At the Tedlands wetland complex, observations recorded within the Atlas of Living Australia identified one gudgeon and six bird species, including the Barking Owl and the Little Falcon (Table 2); while observations from fish surveys observed 15 fish species, including the commercially valued Barramundi and confirming the presence of the Southern Purple-spotted Gudgeon (Table 3). Birdlife Australia recorded 159 species and one hybrid (Table 4).

At the Marklands wetland complex, the Wedge-tailed Eagle was the only species recorded within the Atlas of Living Australia (Table 2); while observations from electric fishing surveys observed 12 fish species, also including Barramundi and the Southern Purple-spotted Gudgeon (Table 3).

Across all wetlands, the aerial imaging classifications showed with moderate to strong agreement (Cohen's Kappa ranging from 0.69 to 0.87; McHugh, 2012). At Tedlands, the wet season aerial imaging exhibited similar coverage of brown grass, green grass and water, but lower coverage of aquatic vegetation. However, this site only covered 30-40% of the entire wetland and may not be representative. At Marklands and Lloyds, both sites exhibited lower brown grass, greater grass coverage and greater water coverage in the wet season relative to the dry season (Table 5).

Table 2: Species recorded within the Atlas of Living Australia at the Tedlands and Marklands wetland complexes, regardless of year or abundance observed.

Wetland	Group	Species	Common name
Tedlands	Fish	*Mogurnda adspersa*	Southern Purple-spotted Gudgeon
	Bird	*Plegadis falcinellus*	Glossy Ibis
		Cisticola exilis	Golden-headed Cisticola
		Haliastur indus	Brahminy Kite
		Chalcites minutillus	Little Bronze-Cuckoo
		Ninox connivens	Barking Owl
		Falco longipennis	Little Falcon
Marklands	Bird	*Aquila audax*	Wedge-tailed Eagle

Table 3: Fish species observed (present) at Tedlands and Marklands wetlands as surveyed using boat electric fishing (Marsden & Power, 2007; McCann & Moore, 2019, 2020).

Common Name	Species	Tedlands	Marklands
Agassizi's glassfish	*Ambassis agassizii*	Present	Present
Long-finned eel	*Anguilla reinhardtii*	Present	Present
Flyspecked hardyhead	*Craterocephalus stercusmuscarum*	Present	Present
Snakehead gudgeon	*Giurus margaritacea*	Present	Present
Mouth almighty	*Glossimia aprion*	Present	Absent
Empire gudgeon	*Hypseleotris compressa*	Present	Present
Midgley's carp gudgeon	*Hypseleotris sp1*	Present	Absent
Barramundi	*Lates calcarifer*	Present	Present
Spangled perch	*Leiopotherapon unicolor*	Present	Present
Tarpon	*Megalops cyprinoides*	Present	Present
Eastern rainbowfish	*Melanotaenia splendida*	Present	Present
Souther purple-spotted gudgeon	*Mogurnda adspersa*	Present	Present
Bony bream	*Nematalosa erebi*	Present	Absent
Rendahl's catfish	*Porochilus rendahli*	Present	Present
Southern platyfish	*Xiphophorus maculatus*	Present	Absent

Table 4: Bird species recorded within the Birdlife Australia database at Tedlands wetland. Count indicates the cumulative number of sightings.

Common Name	Scientific Name	Count
Magpie Goose	*Anseranas semipalmata*	20
Plumed Whistling-Duck	*Dendrocygna eytoni*	3
Wandering Whistling-Duck	*Dendrocygna arcuata*	10
Black Swan	*Cygnus atratus*	27
Radjah Shelduck	*Radjah radjah*	16
Hardhead	*Aythya australis*	11
Australasian Shoveler	*Spatula rhynchotis*	1
Pacific Black Duck	*Anas superciliosa*	32
Grey Teal	*Anas gracilis*	13
Chestnut Teal	*Anas castanea*	3
Australian Wood Duck	*Chenonetta jubata*	7
Cotton Pygmy-goose	*Nettapus coromandelianus*	10
Green Pygmy-goose	*Nettapus pulchellus*	2
Australian Brush-turkey	*Alectura lathami*	1
Brown Quail	*Synoicus ypsilophora*	6
Australasian Grebe	*Tachybaptus novaehollandiae*	19
Spotted Dove	*Streptopelia chinensis*	1
Crested Pigeon	*Ocyphaps lophotes*	7
Peaceful Dove	*Geopelia placida*	8
Bar-shouldered Dove	*Geopelia humeralis*	11
Torresian Imperial-Pigeon	*Ducula spilorrhoa*	2
Topknot Pigeon	*Lopholaimus antarcticus*	3
Pheasant Coucal	*Centropus phasianinus*	8
Eastern Koel	*Eudynamys orientalis*	2
Channel-billed Cuckoo	*Scythrops novaehollandiae*	2
Horsfield's Bronze-Cuckoo	*Chalcites basalis*	3
Little Bronze-Cuckoo	*Chalcites minutillus*	3
Fan-tailed Cuckoo	*Cacomantis flabelliformis*	3

Brush Cuckoo	*Cacomantis variolosus*	4
Pallid Cuckoo	*Heteroscenes pallidus*	1
Australian Bustard	*Ardeotis australis*	7
Lewin's Rail	*Lewinia pectoralis*	1
Buff-banded Rail	*Hypotaenidia philippensis*	3
Purple Swamphen	*Porphyrio porphyrio*	17
Dusky Moorhen	*Gallinula tenebrosa*	16
Eurasian Coot	*Fulica atra*	7
Brolga	*Antigone rubicunda*	18
Black-winged Stilt	*Himantopus leucocephalus*	17
Pacific Golden Plover	*Pluvialis fulva*	3
Red-capped Plover	*Charadrius ruficapillus*	6
Black-fronted Dotterel	*Elseyornis melanops*	18
Masked Lapwing	*Vanellus miles*	29
Red-kneed Dotterel	*Erythrogonys cinctus*	2
Comb-crested Jacana	*Irediparra gallinacea*	23
Bar-tailed Godwit	*Limosa lapponica*	1
Red Knot	*Calidris canutus*	1
Sharp-tailed Sandpiper	*Calidris acuminata*	12
Red-necked Stint	*Calidris ruficollis*	4
Latham's Snipe	*Gallinago hardwickii*	5
Common Greenshank	*Tringa nebularia*	5
Marsh Sandpiper	*Tringa stagnatilis*	4
Little Tern	*Sternula albifrons*	1
Australian Gull-billed Tern	*Gelochelidon macrotarsa*	6
Caspian Tern	*Hydroprogne caspia*	7
Whiskered Tern	*Chlidonias hybrida*	13
Black-necked Stork	*Ephippiorhynchus asiaticus*	2
Australian Pelican	*Pelecanus conspicillatus*	18
Nankeen Night-Heron	*Nycticorax caledonicus*	2
Striated Heron	*Butorides striata*	1
Cattle Egret	*Bubulcus ibis*	18
White-necked Heron	*Ardea pacifica*	3
Great Egret	*Ardea alba*	27
Intermediate Egret	*Ardea intermedia*	26
White-faced Heron	*Egretta novaehollandiae*	19
Little Egret	*Egretta garzetta*	17
Australian White Ibis	*Threskiornis moluccus*	22
Straw-necked Ibis	*Threskiornis spinicollis*	8
Yellow-billed Spoonbill	*Platalea flavipes*	4
Royal Spoonbill	*Platalea regia*	18
Glossy Ibis	*Plegadis falcinellus*	15
Little Pied Cormorant	*Microcarbo melanoleucos*	17
Little Black Cormorant	*Phalacrocorax sulcirostris*	19
Pied Cormorant	*Phalacrocorax varius*	6
Australasian Darter	*Anhinga novaehollandiae*	16
Black-shouldered Kite	*Elanus axillaris*	5
Pacific Baza	*Aviceda subcristata*	3
Wedge-tailed Eagle	*Aquila audax*	1
Swamp Harrier	*Circus approximans*	7
Grey Goshawk	*Accipiter novaehollandiae*	2
Brown Goshawk	*Accipiter fasciatus*	2
White-bellied Sea-Eagle	*Haliaeetus leucogaster*	14
Whistling Kite	*Haliastur sphenurus*	20
Brahminy Kite	*Haliastur indus*	12
Black Kite	*Milvus migrans*	12
Rainbow Bee-eater	*Merops ornatus*	5
Dollarbird	*Eurystomus orientalis*	1
Azure Kingfisher	*Ceyx azureus*	1
Forest Kingfisher	*Todiramphus macleayii*	8
Collared Kingfisher	*Todiramphus chloris*	2
Sacred Kingfisher	*Todiramphus sanctus*	9
Laughing Kookaburra	*Dacelo novaeguineae*	9
Blue-winged Kookaburra	*Dacelo leachii*	9

Nankeen Kestrel	*Falco cenchroides*	10
Australian Hobby	*Falco longipennis*	4
Brown Falcon	*Falco berigora*	8
Red-tailed Black-Cockatoo	*Calyptorhynchus banksii*	3
Galah	*Eolophus roseicapilla*	6
Sulphur-crested Cockatoo	*Cacatua galerita*	1
Red-winged Parrot	*Aprosmictus erythropterus*	2
Pale-headed Rosella	*Platycercus adscitus*	3
Rainbow Lorikeet	*Trichoglossus moluccanus*	6
Scaly-breasted Lorikeet	*Trichoglossus chlorolepidotus*	4
Variegated Fairy-wren	*Malurus lamberti*	1
Red-backed Fairy-wren	*Malurus melanocephalus*	16
Dusky Honeyeater	*Myzomela obscura*	4
Scarlet Honeyeater	*Myzomela sanguinolenta*	1
Helmeted Friarbird	*Philemon buceroides*	5
Noisy Friarbird	*Philemon corniculatus*	2
Little Friarbird	*Philemon citreogularis*	3
Brown Honeyeater	*Lichmera indistincta*	15
Blue-faced Honeyeater	*Entomyzon cyanotis*	4
White-throated Honeyeater	*Melithreptus albogularis*	5
Bar-breasted Honeyeater	*Ramsayornis fasciatus*	2
Yellow Honeyeater	*Stomiopera flava*	13
Lewin's Honeyeater	*Meliphaga lewinii*	1
Mangrove Honeyeater	*Gavicalis fasciogularis*	4
Striated Pardalote	*Pardalotus striatus*	9
Fairy Gerygone	*Gerygone palpebrosa*	1
White-throated Gerygone	*Gerygone olivacea*	2
Large-billed Gerygone	*Gerygone magnirostris*	2
Mangrove Gerygone	*Gerygone levigaster*	4
Black-faced Cuckoo-shrike	*Coracina novaehollandiae*	8
White-bellied Cuckoo-shrike	*Coracina papuensis*	1
Cicadabird	*Edolisoma tenuirostris*	1
Varied Triller	*Lalage leucomela*	3
Rufous Whistler	*Pachycephala rufiventris*	11
Golden Whistler	*Pachycephala pectoralis*	1
Little Shrike-thrush	*Colluricincla megarhyncha*	2
Australasian Figbird	*Sphecotheres vieilloti*	4
Olive-backed Oriole	*Oriolus sagittatus*	3
Black Butcherbird	*Melloria quoyi*	1
Australian Magpie	*Gymnorhina tibicen*	10
Pied Butcherbird	*Cracticus nigrogularis*	7
White-breasted Woodswallow	*Artamus leucorynchus*	10
Spangled Drongo	*Dicrurus bracteatus*	10
Willie Wagtail	*Rhipidura leucophrys*	17
Rufous Fantail	*Rhipidura rufifrons*	1
Grey Fantail	*Rhipidura fuliginosa*	6
Torresian Crow	*Corvus orru*	15
Leaden Flycatcher	*Myiagra rubecula*	12
Magpie-lark	*Grallina cyanoleuca*	14
Spectacled Monarch	*Symposiarchus trivirgatus*	1
Lemon-bellied Flycatcher	*Microeca flavigaster*	4
Mangrove Robin	*Peneothello pulverulenta*	5
Mistletoebird	*Dicaeum hirundinaceum*	10
Olive-backed Sunbird	*Cinnyris jugularis*	8
Chestnut-breasted Mannikin	*Lonchura castaneothorax*	13
Red-browed Finch	*Neochmia temporalis*	1
Double-barred Finch	*Taeniopygia bichenovii*	8
House Sparrow	*Passer domesticus*	1
Australasian Pipit	*Anthus novaeseelandiae*	16
Horsfield's Bushlark	*Mirafra javanica*	3
Zitting Cisticola	*Cisticola juncidis*	1
Golden-headed Cisticola	*Cisticola exilis*	15
Tawny Grassbird	*Cincloramphus timoriensis*	11
Australian Reed-Warbler	*Acrocephalus australis*	1

Fairy Martin	*Petrochelidon ariel*	9
Tree Martin	*Petrochelidon nigricans*	2
Welcome Swallow	*Hirundo neoxena*	12
Black Duck-Mallard hybrid		3

Table 5: The coverage (%) of vegetation, soil and water for the Tedlands, Marklands and Lloyds wetland complexes sites droned (Figure 5) in the wet and dry seasons.

	TED1		TED2		Marklands		Lloyds	
Date (right) Classification (down)	Dec-19	Jul-20	Dec-19	Jul-20	Dec-19	Jul-20	Dec-19	Jul-20
Aquatic Vegetation	NA	16.3	3.9	11.8	0.0	0.0	0.0	4.4
Brown grass	NA	14.2	20.6	24.9	56.4	34.1	17.6	10.0
Green grass	NA	46.4	39.9	35.0	26.2	29.0	3.3	37.1
Soil	NA	1.6	15.4	7.3	13.4	26.6	75.3	8.1
Water	NA	21.6	20.2	21.1	3.9	10.3	3.8	40.4

3.3 Nutrient processing

The mean *potential* denitrification in Tedlands wetland is estimated to be 412 T N/year (SE = 86 T N/year) using the Land et al (2016) model and 683 T N/year (SE = 132 T N/year) using the Adame et al (2019) model (Table 6). Once delivery of nitrogen is accounted for (Figure 7), then the mean annual *actual* denitrification estimated to have occurred over the 2000-2019 period is 12.6 T N/year (SE = 11.5 T N/year) using the Land et al (2016) model and 15 T N/year (SE = 13 T N/year) using the Adame et al (2019) model. This translates to long term estimated efficiencies of 62% and 80% N removal respectively.

Despite limited data, we predict that the Tedlands wetland complex has high potential for nitrogen removal via denitrification. In addition to our modelled estimates, water quality sampling within the wetland indicates very low nitrate-nitrogen concentrations (Table 1), despite draining a catchment largely composed of fertilised sugarcane crops. However, the estimates provided here are very coarse approximations. Should further analysis be desired to more accurately define denitrification, then future data collation should include assessment of: soil characteristics; riverine and groundwater flows into, around and out of the wetlands; inflow and outflow nutrient concentrations across the hydrograph; diurnal oxygen conditions; redox conditions; and vegetation coverage.

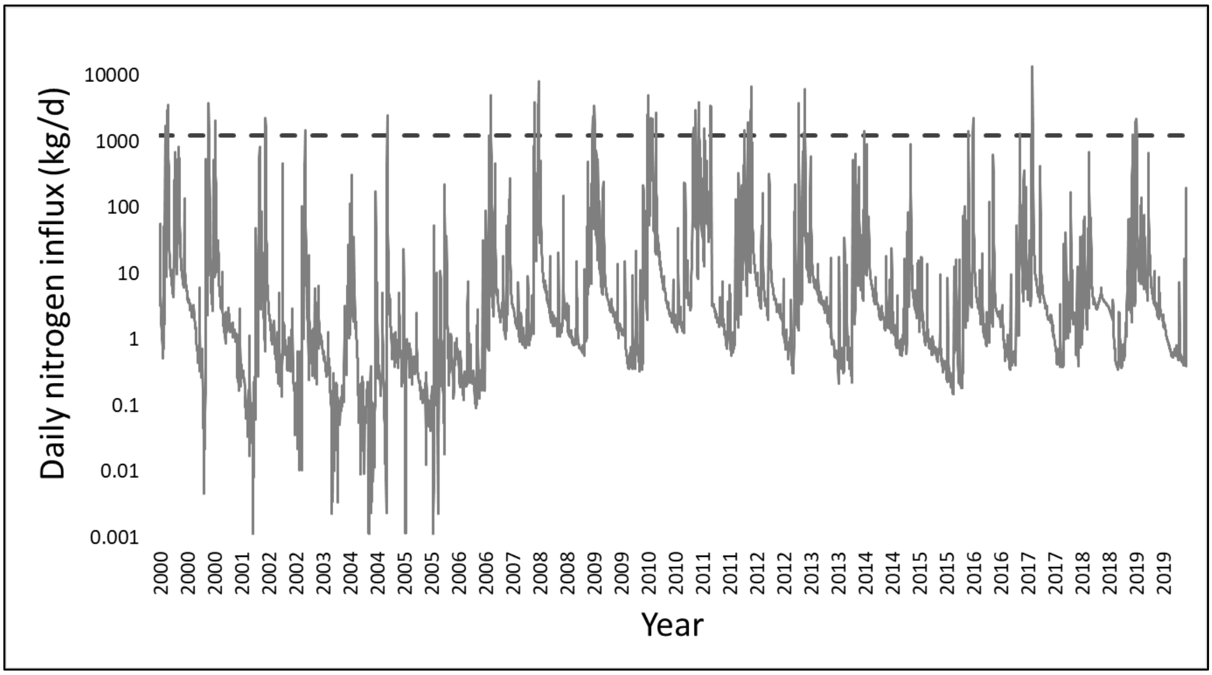

Figure 7: The estimated daily nitrogen flux (kg/d) into Tedlands wetland complex (solid line), and the average potential denitrification rate as predicted using Land et al (2016).

Table 6: Mean monthly nutrient concentrations (TN, total nitrogen; NO_3-N, nitrate-nitrogen; NH_4-N, ammoniacal nitrogen; TP, total phosphorus; OP, orthophosphates; mg/L), and mean monthly denitrification potential ($mg/m^2/hr$) at Tedlands wetlands as estimated from Adame, Roberts, et al (2019) and Land et al (2016) - Dt_{Adame} and Dt_{Land} respectively. Nutrient data is from Water Quality Monitoring Program, Queensland Government, measured at Sandy Creek at Homebush, assumed similar to those at Tedlands.

Month	TN	NO_3-N	NH_4-N	TP	OP	Dt_{Adame}	Dt_{Land}
JAN	1.23	0.38	0.03	0.23	0.14	24.4	20.5
FEB	0.91	0.29	0.04	0.24	0.12	22.1	18.2
MAR	1.05	0.29	0.04	0.21	0.08	22.1	16.8
APR	1.01	0.64	0.02	0.10	0.05	30.1	12.3
MAY	1.04	0.64	0.02	0.11	0.05	30.0	9.7
JUN	1.20	0.74	0.01	0.11	0.04	31.8	11.2
JUL	0.97	0.57	0.02	0.09	0.04	28.7	14.1
AUG	1.45	1.00	0.01	0.12	0.05	35.7	15.0
SEP	1.24	0.74	0.03	0.08	0.04	31.8	15.3
OCT	0.83	0.32	0.02	0.11	0.04	23.0	23.6
NOV	0.81	0.22	0.01	0.27	0.09	19.8	26.1
DEC	0.69	0.22	0.02	0.08	0.03	19.8	26.7

4.0 RECOMMENDATIONS AND CONCLUSION

4.1 Preliminary conclusions

The tidal bund/ponded pasture wetlands examined provide considerable freshwater services and value. The wetlands provide habitat for at least 15 species of fish, including the commercially valued Barramundi. They also provide habitat for over 150 species, including waterbirds, shorebirds and other birds such as the iconic Barking Owl and Little Falcon. In addition, anecdotal and field observations have observed large flocks of birds, which is important for supporting population viability – further work is needed to estimate abundance.

The tidal bund walls also regulate the salinity of estuarine waters outside the bund. During the dry season, conductivity was indicative of 100% seawater for four months, while during the wet season it was indicative of very low salinity brackish and fresh waters. The extent to which this alters the estuarine vegetation assemblages, including weed prevalence, has not been explored. Though weed-salinity tolerance experiments suggest weeds may be able to grow in the wet season and then be killed in the dry season (Reid et al., 2018). However, persistently high salinity downstream due to withheld freshwater flows may also mean that brackish ecological communities are unable to survive.

Indicative estimates of denitrification suggest that the Tedlands wetland complex may remove, on average, approximately 12-15 tonnes of nitrogen each year from discharges to the coastal environment. However, this represents a long term average, and year-to-year estimates could vary, largely influenced by hydraulic loading patterns. Nonetheless, the denitrification is likely substantial and may remove the majority of nitrogen runoff from the catchment if the wetland remained in its present form. The denitrification potential of an alternative situation with mangrove replacing the ponded pasture has not been assessed, though may also be considerable (Kreuzwieser et al., 2003; Lee & Joye, 2006; Shiau et al., 2016).

Clearly, ponded pasture wetlands created by tidal bunds hold/support values, despite being dominated by introduced vegetation and created artificially. If tidal bund walls are removed for the purposes of enhancing alternative values, such as for restoring estuarine habitat for blue carbon benefits, then existing freshwater values will be traded. Any future proposal to remove bund walls should give full consideration to the existing values.

4.2 Future research recommendations

To better improve knowledge on the values provided by Tedlands wetland, the following are recommended:

1. Carry out randomised and consistent vertebrate fauna assessments, beyond fish, at ponded pasture wetlands that also estimate abundance. Vertebrate survey data across wetlands within the GBR catchment is heavily biased towards urban centres and easily accessible areas. This is obscuring understanding of wetland-vertebrate distributions and the biodiversity of GBR wetlands, including those created by tidal bunding for ponded pasture. Without randomised and systematic survey data, it will be difficult to

understand future climate impacts and predict restoration outcomes (Canning & Waltham, n.d., 2020).

2. Carry out on-site assessments of nitrogen and carbon fluxes in multiple ponded pasture wetlands to generate models of the carbon and nitrogen service provision. This would involve collection of soil characteristics; riverine and groundwater flows into, around and out of the wetlands; inflow and outflow nutrient concentrations across the hydrograph; diurnal oxygen conditions; redox conditions; and vegetation coverage. Examination should focus on wetlands draining large, agriculturally-intensive catchments.
3. Assess the impact of freshwater regulation by bund walls on the vegetation assemblages in affected brackish areas. This could involve using long term conductivity loggers and aerial imaging to examine the salinity gradients of brackish waters adjacent to bund walls and in nearby areas not affected by bund walls.
4. Investigate the potential of habitat-enhancement or using green engineering to bolster the biodiversity values within ponded pasture wetlands.
5. Carry out a survey of stakeholders to better identify the economic, social and cultural values held at ponded pasture wetlands.

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